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Towards a human-centred framework for conceptualization of lunar surface solutions

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Abstract

It has been 50 years since astronauts last walked on the lunar surface during the Apollo programme. The aim of NASA's lunar exploration programme, Artemis, to which the European Space Agency (ESA) and several national space agencies are contributing, is to establish a sustainable human presence by 2028. The goal is to "go forward to the Moon" and use what is learned on and around the Moon to take the next giant leap, sending astronauts to Mars.

ESA and commercial partners are currently preparing the development of a European Large Logistics Lander (EL3). The EL3 is being designed to allow various missions with different options for its payloads, such as scientific payloads, crew supplies, or unpressurised rovers to support human expeditions. A cargo deployment solution that fulfils EL3's mission requirements and allows easy interaction by astronauts has yet to be designed, however it is essential to the success of future missions involving human interaction. The lunar surface poses several challenges due to its unique environmental conditions such as reduced gravity levels, harsh thermal conditions, peculiar illumination, limited field of view and range of motion due to the extravehicular activity suits, as well as mental and physical fatigue. All these challenges need to be considered and tackled when designing technology for future lunar and planetary explorers.

This paper aims to present a novel human-centred design methodology that combines elements of standard space systems engineering with approaches from the design engineering domain related to concept development to generate creative and innovative design solutions for the lunar surface such as reliable logistics supply systems for the EL3.

The following design process was adopted; first, multiple concepts were generated during group brainstorm sessions, after that a trade-off analysis was performed to narrow down the set of concepts in a systematic manner. The weighted trade-off criteria included: operations risk, development risk, safety and feasibility. Feedback was gathered through a multiple-stakeholder approach including operations engineers, astronaut instructors, managers and scientists from the European Astronaut Centre (EAC) and the EL3 study team. The concepts were then refined iteratively to finally select three viable cargo deployment concepts, whose operations could then be tested in a representative virtual reality environment.

In conclusion, this work provides a novel approach for early-stage design studies which shows potential for the concept development of prospective novel lunar surface systems.

Keywords: Human Spaceflight, Moon, Human-Centred Design, Lunar exploration, Lunar Lander, Cargo Deployment Solutions

Acronyms/Abbreviations

CAD: Computer-Aided Design
C&DH: Command and Data Handling
CoM: Center of Mass
EAC: European Astronaut Centre
ECSS: European Cooperation for Space Standardization
EL3: European Large Logistics Lander
ESA: European Space Agency
EVA: Extravehicular Activity
HLS: Human Landing System
ISRU: In-situ resource utilization
LDE: Landing Descent Element

LRO: Lunar Reconnaissance Orbiter
LSAM: Lunar Surface Access Module
MBSE: Model-Based System Engineering
NASA: National Aeronautics and Space Administration
TRL: Technology Readiness Level
VR: Virtual Reality

1. Introduction

Humanity's understanding of the Moon has undergone a substantial evolution since the days of Apollo. While the first astronauts to walk the lunar surface were met by a barren wasteland, robotic missions, such as the Lunar Reconnaissance Orbiter (LRO), have since then painted a different picture [1]. It is now strongly implied that permanently shadowed craters on the polar regions of the Moon hold significant quantities of water [2] and that the unique lighting [3] and thermal conditions [4] in these areas are favourable for power production and other forms of in-situ resource utilization (ISRU) activity. Moreover, its proximity to Earth places the Moon within theoretical reach of relatively fast and routine access (compared to future exploration destinations such as Mars). Such factors are increasingly lending credence to proponents of human space exploration who advocate for the establishment of lunar outposts as a "*historical starting point for human expansion off-planet*" [5]. Against this backdrop, the stage appears set for a new generation of lunar missions, that will exceed Apollo in their scope and ambition by virtue of longer stay times, reusable infrastructure and eventually permanent surface bases to achieve a sustainable human presence on the Moon.

The feasibility of a sustained human presence on the Moon will be heavily dependent on the development of reliable logistical solutions for delivery of crew supplies and other forms of cargo to the lunar surface. Recent years have seen a number of both public and private actors from around the world taking up this challenge, giving rise to a spectrum of design concepts ranging from the 325 kg light Astrobotic Peregrine Lander [6] to the towering SpaceX Starship Human Landing System (HLS) [7]. In line with this trend, ESA is currently in the process of designing the European Large Logistics Lander (EL3), an autonomous lunar landing vehicle capable of delivering a wide range of payloads to the Moon, with an initial launch window planned between 2028 and 2029. Once taken into service, the EL3 is expected to form the backbone of Europe's pathway toward sustainable human exploration of the Moon [8], [9].

A key challenge hampering the development of EL3, and other comparable solutions, stems from the lack of an established design framework tailored to the unique context of human-machine interactions on the Moon. Whilst prior studies on the design of lunar surface solutions have taken place, issues concerning human factors and ergonomics, such as those surrounding the delivery and reception of cargo, have typically been left unaddressed.

To fill this gap, the aim of this work is to propose an innovative human-centred design methodology that combines elements of standard space systems engineering with approaches from the design engineering domain related to concept development to generate creative and novel design solutions for the lunar surface. In doing so, it seeks to shift the spotlight from purely technical issues to relevant human factors, including astronaut safety and usability.

To demonstrate the viability of this methodology, this paper documents its employment during the development and evaluation of novel design ideas for EL3 cargo unloading. In a first step, initial design concepts for viable cargo delivery solutions were generated during a brainstorming session. Based on various criteria such as risk, safety, and feasibility, the concepts were then narrowed down using a systematic trade-off analysis, followed by feedback from domain experts at the European Astronaut Centre (EAC) and the EL3 team in a multi-stakeholder approach. The design was iteratively refined, based on the feedback received, until three viable cargo deployment concepts were generated. Following the selection, the identified concepts were implemented in a representative virtual reality environment to further evaluate the proposed cargo deployment solution's design. As a result of this work, a framework for future design studies is established as well, allowing for an early operational evaluation of design solutions for the EL3 and other relevant projects [10].

The remainder of this paper is structured as follows: Section 2 elaborates the backdrop and provides an overview of relevant prior work. Section 3 describes the novel methodology used to generate innovative yet feasible cargo concept solutions. The cargo deployment ideas generated, as well as an informal list of requirements originating from the context analysis performed during the iterative design process, are then described in section 4. Section 5 presents a discussion on the adopted methodology and the resulting cargo deployment concepts. Furthermore, the limitations related to the proposed design approach and lessons learnt are elaborated upon. Finally, conclusions and recommendations for future work are outlined in section 6.

2. Related Work

Whilst the long-term ambition of the ongoing lunar exploration is to establish a sustainable and self-sufficient human presence, the progress towards this goal will likely be gradual and unfold over stages, with early outposts being dependent on supplies delivered from Earth [11]. It has been suggested, for instance, that the renewed push for the Moon ought to start out with precursor robotic missions deployed to the lunar surface in the early 2020's with the aim of installing supporting ground systems ahead of the first human landing [12]. Existing literature identifies a long list of provisions required for outfitting such outposts on their path to sustainability, including water extraction facilities and processing plants for ISRU fuel manufacturing, large structures for plant cultivation, metal extraction and processing tools, sanitations and recycling solutions, appliances for ceramics manufacture and use, as well as major hardware like coils of pipe and wiring, pumps, electrical heaters and LED lights [13]–[16]. All in all, relevant enquiries into long-duration habitation have anticipated that outfitting a sustainable lunar outpost will require the delivery of between 200 to 600 m^3 of pressurized cargo, weighing in excess of 50 tons [17].

Establishing and maintaining logistics supply chains robust enough to underpin such an endeavour is a non-trivial matter. Above all, current activities in space are largely limited by transportation costs. As Kutter explains, "*it costs $4000 to $10000 per kilogram to get from Earth to low earth orbit. It costs four times as much to get to [geostationary orbit] GEO and nine times as much to get to the lunar surface"*[13]. Facing such economic considerations, space agencies around the world have been experiencing a growing demand for reliable and efficient logistic landing and cargo deployment solutions. Jones et al. sum up this situation, arguing that "*the human exploration of space can be seen as an investment in a new space infrastructure, most of which will be logistical*" [18]. Indeed, studies suggest that minimizing the costs of lunar surface infrastructure is in large part directly related to the design of a cargo delivery and landing craft [19] and that designing efficient cargo offloading and transportation solutions will be critical for the effectiveness of future lunar surface missions [20].

The past two decades have seen several initiatives arising in this vein. Notably, NASA's Constellation programme engaged in conceptual design of the Lunar Surface Access Module (LSAM) [21]. With a projected payload capacity of roughly 14-20 tons [17], the LSAM was intended to accommodate a host of prospective missions, including delivery and deployment of scientific experiments, supply of materials for lunar habitats, and crew to the lunar surface [22], [23].

Following the Constellation programme's cancellation due to budgetary constraints [24], NASA launched a series of initiatives aiming at producing more affordable lunar landing solutions via closer collaboration with the private sector. The Lunar Catalyst programme, for instance, seeks to provide technical support to companies designing light lunar landers for future lunar cargo delivery services [25], [26]. Similarly, NASA's Lunar Delivery Challenge is asking teams around the world to submit innovative ideas and concepts to unload cargo from lunar landers [27].

Going a step further, the Next Space Technologies for Exploration Partnerships (NextSTEP) initiative provides funding for industry partners involved in more extensive human spaceflight projects, including the design and development of new reusable human landing systems for future Artemis missions [28], [29]. In April 2021, NASA selected the Starship HLS concept by SpaceX as the most suitable solution for this purpose, awarding its authors a full development contract [30]. To maintain a climate of competition, another company will be selected for funding to produce an additional human landing solution in the near future [31].

Much like the other lunar lander concepts described above, the EL3 design efforts have been revolving predominantly around issues concerning technical feasibility and integration into future mission infrastructure [22], [32]. In contrast, less attention is paid to human factors and ergonomics surrounding the interaction of crew members with the lander itself, especially in connection with cargo unloading.

This can be largely attributed to the fact that designing efficient human-machine interfaces for the lunar context constitutes a uniquely challenging undertaking. The singular environmental conditions of the Moon, in combination with the still largely undefined missions' concept of operations, translate into complex and oftentimes ambiguous design requirements, all against a backdrop of an evolving engineering development. Whilst NASA has explicitly stated that advancing low-technology readiness level (TRL) solutions for human-robotic science operations represents a key aspiration of the Artemis programme [33], it is arguable whether conventional design approaches represent the most optimal employment of contemporary design methodologies for tackling such a complex and dynamic problem-space.

When confronted with some of the complex challenges surrounding human-machine interactions in the past, scholars have typically been arguing in favour of combining traditional systems engineering approaches with elements of human-centred design. Lee et al. reflect on this synergy, stating that "*designers and engineers are uniquely positioned to help address these challenges by inventing new problem-solving methodologies in times of need"* [34]. Thomas Both follows a similar line of reasoning, arguing that human-centred and systems-thinking methods all fit within an effective design approach and can work in conjunction to address complex problems [35]. The importance of a human-centric approach in engineering was further elaborated by Owen et al., who advocate for planning teams to *"uncover user-centered needs, recognize insightful relationships, capture ideas as they develop, organize large amounts of information optimally for concept development, and develop solutions appropriate to the real (and natural) complexity of problems*"

Aside from human-centred and systems-thinking approaches, related methodologies from the design engineering domain could be relevant for the early-stage concept development of space systems and human-machine interaction concepts. As documented in German engineering standards from the 1970s [36], and further expanded on in fundamental theoretical work by Pahl and Beitz [37] and Roozenburg and Eekels [38], from the 1950s onwards a systematic approach to engineering design has been developed [39] to tackle the complex challenges related to new product development in an unpredictable commercial and technological context. These methodologies were designed to operationalise the development of new solutions for multiple-stakeholder problems within a commercial context while considering the limitations and advantages of the developing entity as well as trends and developments in technologies and market conditions. Similarities between the context intended and that of the subject of this paper indicate that adaptation of these methodologies to the development of human space systems could be of interest.

As Ramos et al. explain, broadening the scope of systems engineering in this manner can result in the classical notion of *systems* being replaced by complex "*systems of systems*" [40], which in turn introduces a level of intricacy that may be difficult to handle in large engineering projects. Efforts to navigate this new problem landscape are increasingly crystalizing as various forms of Model-Based Systems Engineering (MBSE). The core idea behind MBSE is to develop visual models of the domain of interest, capturing key project aspects while simplifying or omitting less relevant features [41]. Such a model can feature both social and technological contexts, helping engineers to coordinate and incorporate an extensive and wide-ranging set of requirements, including flexibility, sustainability, real-time capability, adaptability, expandability, reliability or usability [42].

The approach by which such a model ought to be conveyed remains a topic of debate. Lutfi and Valerdi, for instance, suggest that drawing on elements of Virtual Reality (VR) could help develop system models capable of facilitating early design evaluations and analyses with less cost and effort than what would be feasible using traditional means [43]. However, further work is needed in order to arrive at a more well-defined and applicable approach. As argued by Lee et al., developing and curating a new methodology that enables designers and engineers to create human-centred systems where the needs of the user and the system can be simultaneously met remains a key goal for future efforts in this domain [44].

Moreover, the integration of VR for the purpose of creating a virtual model is aimed at enhancing the standard MBSE approach which is still largely lacking a significant level of multidisciplinary collaboration in a common shared work environment. In fact, the time and effort required for training, the deep level of understanding required by the modelling language, the complexity of the models adopted, and the limited flexibility of the tools results in a situation where the MBSE design approach has yet to see any widespread adoption by the industry [45]. Indeed, most of the time, especially in the space sector where large complex systems or "*systems of systems*" must be developed, a model-based approach typically crystallises into another form of a document-based method. Lindblad et al. postulated that the non-total adoption and successful realisation in the space sector of fully operational MBSE processes and tools [46] lay in the integration of heterogenous engineering applications from the design to the production and ultimately inspection steps of products across the production network [45].

It is here then, in the intricate and largely unexplored territory of lunar human-machine interaction design, where the main subject of this enquiry resides. Facing novel challenges that need to be tackled at both the human and engineering level, one is left with little choice but to rethink, adapt and - if necessary - break the status quo of established design methods. The following sections will elaborate this process in detail, outlining a novel approach to generate design solutions for future lunar landing systems.

3. Methods

From the outset, the goal in formulating an approach for this study was to pool the diverse resources and experiences brought together by an interdisciplinary team within EAC. It was decided to adopt an approach which borrows both from the design engineering domain, more specifically methodologies described by the VDI standard 2221 [36], and further works by Pahl and Beitz [37] and Roozenburg and Eekels [38] related to concept development and from space system engineering methods, namely European Cooperation for Space Standardization (ECSS) standards [47]. This section provides a retrospective view of the activities and methods applied.

As illustrated in Figure 1, an iterative approach was adopted for the conceptual design of a cargo offloading system for the EL3.

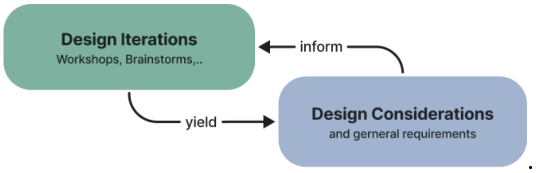


Fig. 1 Iterative design process adopted for the design of a cargo deployment system for the EL3.

A semi-structured, multidisciplinary approach based on the VDI standard 2221's first two phases in the design cycle was employed [36]. Based on the principles of the double diamond (see Fig. 2), intuitive methods such as brainstorming, 'How Might We's' and association were used for divergent concept generation with the aim to find a multitude of solution principles which are unconventional or innovative. Convergent processes such as intuitive clustering, dot-voting and a trade-off analysis were used to home in on the ideas with the most promise.

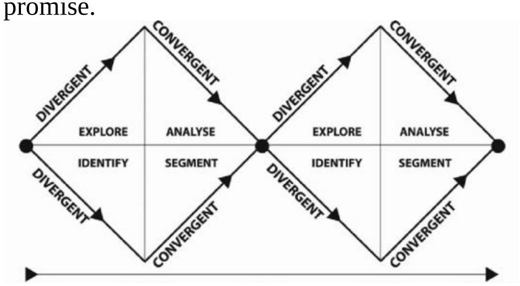


Fig. 2 The double diamond approach [48].

Throughout the process, the approach itself was discussed by the team to evaluate if the existing plan was suitable given the unforeseeable nature of creative problem solving, and adjustments were made when necessary. Specifically, direction was given to the level of abstraction on which the team was working. When it seemed that the discussion was being excessively weighed down by technicalities, the discussion was nudged to achieve a higher level of abstraction. For example, a discussion about how one might lower objects to the lunar surface was lifted to a higher level of abstraction by asking 'how might one move objects? This opened the discussion and allowed for more unconventional and innovative ideas to be found. Alternating between higher and lower levels of abstraction throughout this iterative process allowed the team to evaluate a large number of ideas and ensure that promising solutions were not left behind due to collective or individual tunnel vision.

Due to the intuitive nature of this synthesis stage, it is challenging to provide detailed specifications of each step followed. In fact, the synthesis stage is well-documented as a creative phase and although methodologies can provide hints and inspiration, no one-size-fits-all step-by-step plan can be given [38]. Figure 3 provides an overview of the activities and various types of guided brainstorms and discussions that were performed, while highlighting some of the methods and creative tools which were employed.

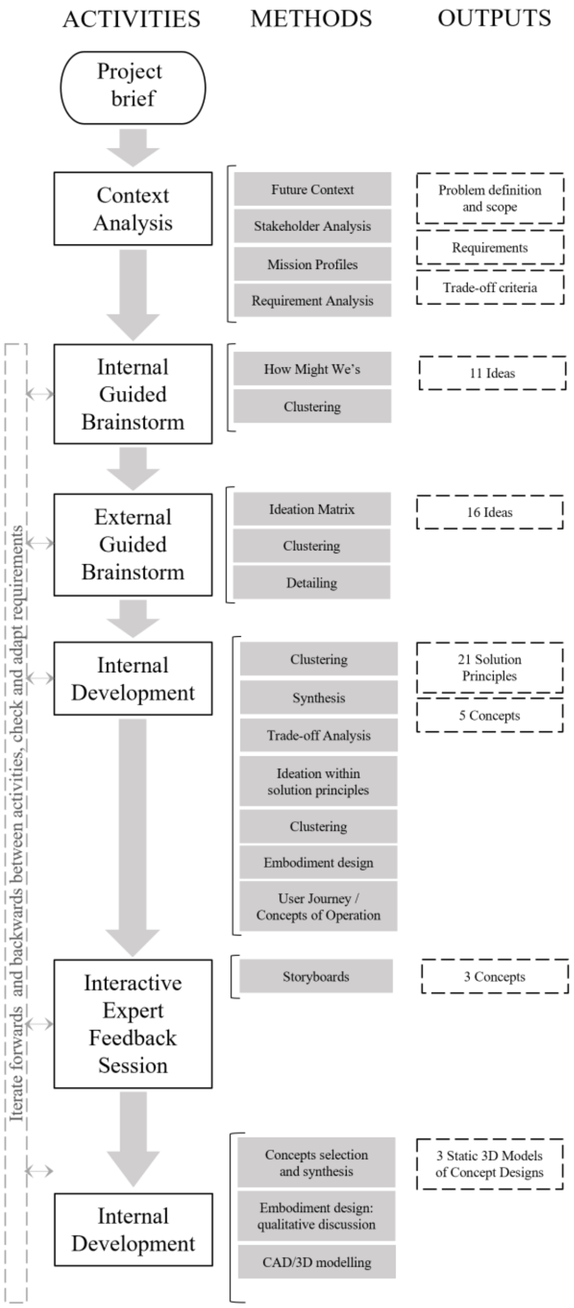


Fig. 3 Iterative design process adopted for the design of a cargo deployment system for the EL3 outlining all the activities, methods and related outputs.

Documentation of the sessions was done using online real-time collaboration tools with functions similar to those of a digital whiteboard. This allowed team members and experts to join from various locations despite restrictions imposed during the COVID-19 pandemic.

3.1 Context Analysis

After formalizing the objectives, a short analysis of the external context of the intended design, including its expected use cases, other lunar infrastructure currently under development and potential mission profiles, was performed. Subsequently a stakeholder analysis and an inventory of technical requirements formed the basis for a list of requirements and an initial formulation of trade-off criteria by which future concepts could be evaluated. This concluded the 'context analysis' activity, but the findings were revisited at every subsequent step; they were never seen as unchangeable or complete. Instead, the activities in the concept development phase were also used to further refine and substantiate the definitions resulting from the context analysis.

3.2 Internal Guided Brainstorm

The first internal brainstorm overlapped with the context analysis and was done during the same session with the same participants, the core project team. The main goal was to document initial ideas and preconceptions about what a potential solution might look like. Discussing potential solutions and different perspectives also allowed further detail to be added to the context analysis, problem definition and project scope through critical discussion of assumptions and unknown factors. This led to either making decisions (e.g., deciding for the given scope to exclude the handling of the cargo after it reached the lunar surface) or defining objectives for information finding. Several ideas and thoughts were discussed and clustered in groups that seemed representative of distinctive thoughts; this resulted in 11 idea clusters.

3.3 External Guided Brainstorm

Once the project scope and problem definition were well defined and the first idea clusters had been generated, a guided external brainstorm was organized with 11 interns, trainees and EAC staff from a wide variety of backgrounds. Three members of the core project team acted as facilitators. This large group allowed the team to approach the problem as openly as possible by including perspectives from different fields of expertise. After a plenary introduction, participants were split into three groups, each with their own facilitator. Participants were asked to freely write down all their ideas for logistics solutions. Once the stream of ideas slowed down, facilitators used either pre-arranged or impromptu tools to ignite the discussion and cause new ideas to be generated. For instance, a matrix was prepared in which participants were challenged to think about solutions that could work for certain types of cargo with specific requirements (fragile/non-fragile and small/large). An example of an impromptu tool used by facilitators would be to highlight an idea which was written down and ask all participants to freely associate new ideas based on it. This process generated over 100 digital post-its with ideas and thoughts within the span of a few hours. Then each group created clusters which represented idea groups to filter out ideas which would already clearly not be suitable for further development (for example highly unrealistic ideas or ideas outside the project scope) and to combine duplicate ideas. In total, 16 clusters were generated.

3.4 Internal Development

Subsequently, progress was made internally by the team. First, the clusters from both previous brainstorms were combined into 21 solution principles. These solution principles have a high level of abstraction, describing some key aspect of a possible approach to solving the problem without defining how this would be achieved technically speaking. For example, a solution principle might be to have a system which propels the payload from the top of the lander to the lunar surface for astronaut pickup. The solution principles often have a higher level of abstraction than the ideas, meaning that one principle can represent multiple ideas. Such as when both the idea for a catapult system and for a rocket-propelled system fell under the principle of cargo ejection. Part of this process included synthesizing ideas from the brainstorms and refining them with specific considerations derived from technical requirements, trade-off criteria and project goals.

It was however not feasible to define embodied designs for 21 solution principles for evaluation due to the available resources. Instead, it was decided to use a trade-off analysis to identify the most promising solution principles that should be advanced through the early steps embodiment design stages. Using weighted criteria based on insights from the context analysis and the two previous brainstorms, a spreadsheet with a short description and rough sketch to explain each solution principle was created. The selected trade-off criteria were risk, safety, and feasibility. Risk was further specified and divided into risk of failure during operation and risk of failure during the development; safety specifically refers to astronaut crew safety, while feasibility refers to whether the concept fulfils EL3's mission requirements. The following weights from 1 to 4 (weight 1: lowest importance, weight 4: highest importance) were assigned to each trade-off criteria, safety (weight: 4), risk of failure during development (weight: 3), risk of failure during the operation (weight: 2), and feasibility (weight: 1).

To account for the wide range of interpretations that could be made based on these rough descriptions and to benefit from the multi-disciplinary environment, both the team and three EAC staff members rated the concepts by filling in the spreadsheet. After combining the results, all participants in this analysis met virtually to discuss them. It was found that the quantified results generally matched individual expectations, and after some critical discussion it was decided to move forward with the 5 most feasible and highest scoring concepts.

These 5 concepts were developed further by the core project team, defining a preliminary embodied design concept, describing the function, structure and creating illustrated storyboards showing the intended concept of operations with each concept. These outputs were then used in the next interactive expert feedback session.

3.5 Interactive Expert Feedback Session

The next session included EAC staff from the astronaut training team. The EAC experts' feedback represented an important factor in the development of the design concept thanks to their first-hand knowledge of human spaceflight operations and insight into the real constraints, challenges and priorities for space systems meant for astronaut interaction. This session consisted of an introduction by the core project team, followed by an open discussion in which experts were asked open questions to elicit critical feedback on each concept.

3.6 Internal Development

Inputs from this session were then used to further narrow down the concepts to a total of three. These 3 selected concepts were then detailed further. After iterating their embodiment design, CAD models were made to represent the concept designs. The interested reader is referred to Nilsson et al. [10].

4. Results

In this section the outcomes of the iterative design process, explained in section 3, are presented. The initial context analysis was important to define the problem and scope of the project as well as identify potential mission profiles, stakeholders, requirements and constraints to subsequently formulate design concept trade-off criteria.

An informal list of requirements important for the cargo deployment system conceptualisation resulted from the abovementioned context analysis:

- Center of Mass (CoM): *the center of mass of the lander shall be kept low to ensure structural stability.*
- Fairing fit: *the cargo deployment system shall be contained in the predefined fairing envelope of Ariane 6-4* [49].
- Mass: *the cargo deployment system shall not exceed the allocated mass budget.*
- Cargo:
  - *the cargo deployment system shall support the integration of pressurised cargo for the delivery of e.g., life support items or fuel* [9].
  - *the cargo deployment system shall allow for fragile payloads to be integrated and delivered safely.*
  - *the cargo deployment system shall accommodate different sizes of payloads* [9].
- Scalability*: the cargo deployment system shall allow for scalability with increased lunar surface activity.*
- Interfaces: *the cargo deployment system shall provide for required interfaces for night survivability, thermal control, power, Command and Data Handling (CD&H)* [49].
- Payload capacity: *the cargo deployment system shall allow for the maximum allocated payload capacity of 1800kg* [9].
- Mechanical loads*: the cargo deployment system's structure shall be able to withstand all mechanical loads e.g., launch, descent, touchdown loads.*
- Environmental constraints: *the cargo deployment system shall be resilient against regolith dust contamination* [50].

As at the time of writing it remains unclear whether and to what extent human intervention will be required to operate the cargo deployment system, a certain degree of human-machine cooperation was assumed. Below is the resulting list of associated assumptions:

- Working volume clearance*: astronaut crew shall be able to access the working area and be able to comfortably move and reach required items.*
- Clearance from sharp edges and fragile equipment: *astronaut crew shall be aware of sharp edges and fragile instrumentation as well as equipment and have enough space to move and work freely.*
- Physical and mental fatigue:
  - *astronaut crew operations shall consider the acceptable energy consumption limit for physical activities in 1/6g conditions of 234Kcal/h* [51].
  - *astronaut crew operations duration shall not exceed 8 hours* [51].
- Safety: *astronaut crew safety shall always be ensured during operations* [51].
- Manual backup system: *astronaut crew shall be able to avail of manual backup cargo deployment system in case maintenance is required.*
- Usability*:*
  - *the cargo deployment system shall be simple.*

- ○ *if required, appropriate interfaces to control (remotely) the cargo deployment system shall be integrated.*

Following the in-depth context analysis, the first internal brainstorm session where the design challenge was rephrased into the following '*How Might We'*, namely *'How might one move objects and people?'* and *'How might one move cargo off the landing and descent element of the EL3?'* a set of 11 loosely defined ideas for potential operating principles of cargo deployment systems without any definition of form, architecture or embodied design was produced. These ideas are listed below:

1. Gravity-driven
2. Robotic
3. Magnetic
4. Spring-loaded mechanisms
5. Propelled by human
6. Pulleys
7. Pressure-driven
8. Conduit-based
9. Vertical displacement (e.g., ladder, jumping, jetpack)
10. Carried by human
11. Vehicles

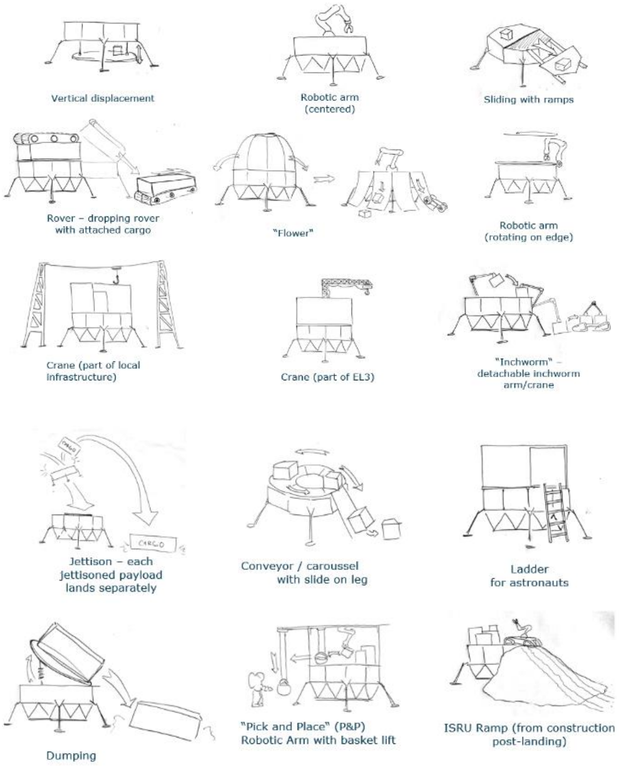
The second brainstorm session produced a set of slightly more detailed ideas. In fact, these ideas included descriptions of the operating principles which could be used to estimate the suitability of the concepts in terms of the selected trade-off criteria.

The following ideas were generated:

1. Crane
2. Inflatable or non-inflatable rolling ball
3. 'Origami-like' unfolding structure/mechanism
4. Ladder
5. 'Shootables'
6. Local infrastructure
7. 'Dumping'
8. Rail crane
9. Transportation system
10. Robotic arm
11. Auger transportation
12. In-flight deployment
13. Moving carousel with compartments / conveyor
14. Robotic arm (rotating on edge)
15. Jettison
16. Inflatable or non-inflatable coiled tube, the 'snake concept'

Following an internal development phase, 21 so called solution principles were generated (see Fig. 4). These abstract ideas of operating principles that do not consider the cargo shape or embodied solution are listed below:

1. Vertical displacement
2. Centred robotic arm
3. Sliding with ramps
4. Rover
5. 'Flower' concept
6. Robotic arm (rotating on edge)
7. Crane (part of local infrastructure)
8. Crane (part of EL3)
9. 'Inchworm'
10. Jettison
11. Conveyor
12. Ladder
13. 'Dumping'
14. Pick and Place (P&P)
15. ISRU ramp
16. Projection
17. 'Shootables'
18. Zipline
19. Inflatable robotic arm
20. Inflatable ball
21. 'Snake concept' coiled tube



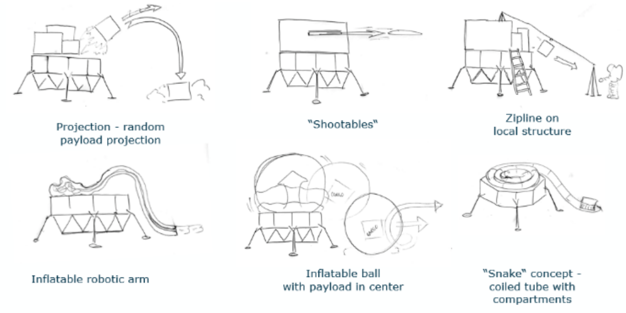


Fig. 4. Illustrations of the 21 solution principles.

Consequently, a set of 5 concepts was generated (see Fig. 5), namely:

1. Center-platform revolving elevator
2. Extendable sliding plank
3. Delta-printer type construction with extendable booms
4. Flipping robotic arm attached on the edge of the Landing Descent Element (LDE) of the EL3
5. Winch-based lowering mechanism

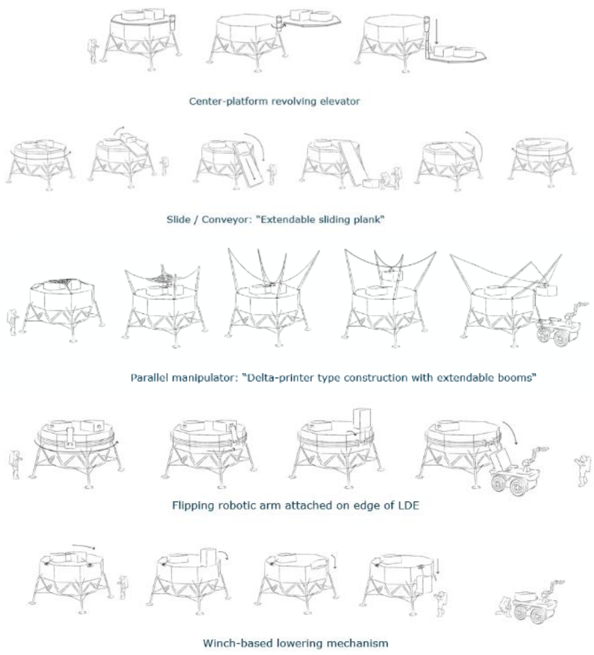


Fig. 5 Illustrations of the 5 concepts: center-platform revolving elevator, extendable sliding plank, delta-printer type construction with extendable booms, flipping robotic arm attached on edge of the Landing Descent Element (LDE) of the EL3, winch-based lowering mechanism.

Finally, following the interactive expert feedback session, 3 concepts were produced. These included a detailed description of a design, including the operating principle, high-level system architecture, embodiment of the design concept and concept of operations. These concepts are:

1. Robotic arm (see Fig. 6)
2. Winch-based pulley system (see Fig. 7)
3. Ladder (see Fig. 8)

In Figure 6, the robotic arm concept is illustrated including its operating principle and embodiment of the design concept.

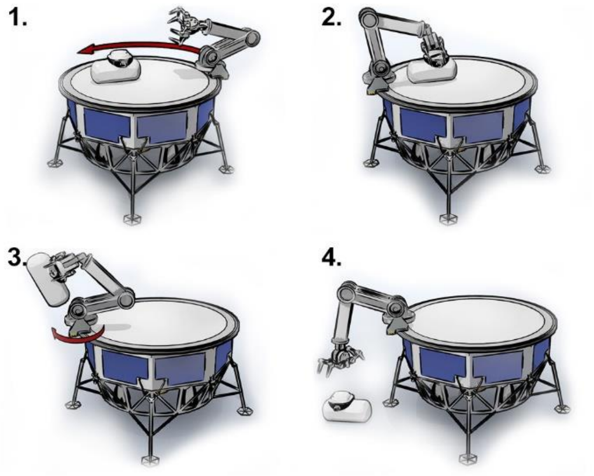


Fig. 6 Robotic arm capable of orbiting along the edge of the LDE of the lander.

In Figure 7, the winch-based pulley system concept is illustrated.

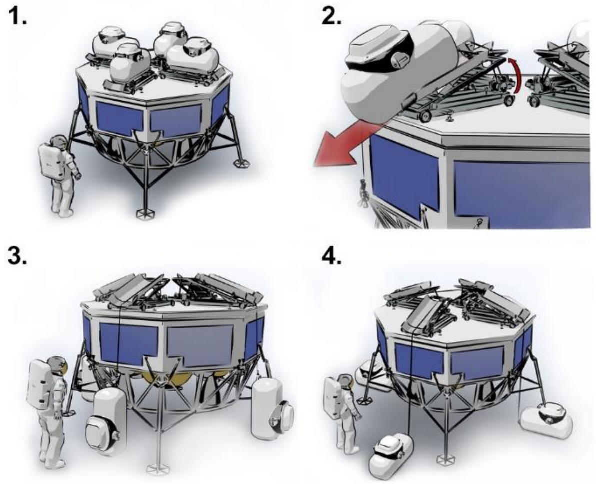


Fig. 7 Winch-based pulley system with cradles concept.

In Figure 8, the ladder concept is illustrated including the concept of operation with an astronaut in the loop.

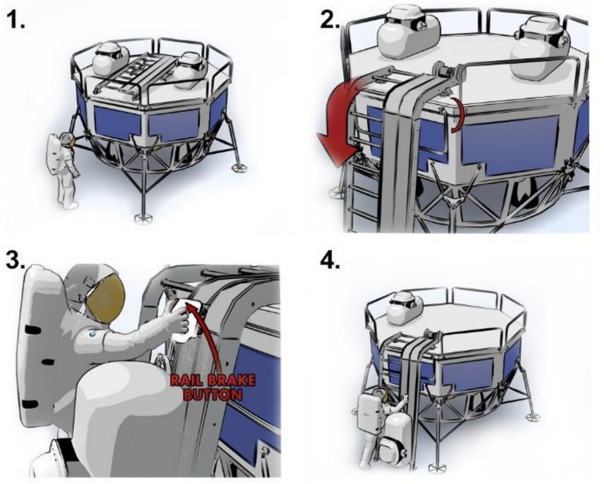


Fig. 8 Advanced ladder concept.

5. Discussion

Space system design is complex and involves a large number of stakeholders, which need to navigate high levels of uncertainty, fluctuations in budget and shifting mission priorities. The direct involvement of astronauts in the early-stage design of human space systems by space agencies is limited if not non-existent. Instead, systems engineers coordinate engineering teams to deliver on functional system requirements, including human factors, set against constraints. However, due to the rather static and generalised inclusion of human factors, this approach may allow for the development of sub-optimal concepts, or for blind spots related to specific human factors design considerations in the early stages to cause unnecessarily costly design changes further on in the testing and technical design stages.

In order to prevent such blind spots from arising, the aim of this work has been to propose an innovative human-centred design methodology that combines elements of standardised space systems engineering with approaches from the design engineering domain. Specifically, in a bid to facilitate the development of creative and novel, yet feasible, design solutions, this paper has sought to demonstrate the viability of the proposed methodology in the context of human space systems for the lunar surface. By employing low-cost visualisations to elicit user feedback, rapid iterative development of design ideas was enabled at the very beginning of the development process. Gathering input from both users and experts at such an early conceptualisation phase was found to evoke new and unconventional ideas which consequently translated into more well-rounded and better optimised concepts.

Such a user-centred design approach ensured that the concept design, its prospective context of use, and potential user interactions were all considered, thereby minimising the risk of inadvertently neglecting or trivialising relevant human factors that could otherwise translate into expensive late-stage design adjustments.

The design engineering methodologies adopted in this work are particularly suitable for the early concept design of highly complex systems intended for human interaction. For one, the iterative approach allows for learning during the design development, which is essential when dealing with complex problems that involve significant unknowns. Secondly, freely switching between levels of abstraction, as design methods encourage, allows for an efficient evaluation of several highly differentiated solution principles. Thirdly, embracing the creative and intuitive sides of innovative concept development and providing tools to guide these processes can help break past convention and find the most suitable solution for a specific problem. This is particularly relevant in a context defined by the fast pace of technological advancements, where conventions must be questioned in order not to hold on to inefficiencies caused by the paradigm of outdated technologies.

Evidently, the adopted approach facilitated the creative output of the interdisciplinary engineering and design teams during this early phase of the concept development of a cargo offloading system for EL3. It also led to enhanced group work as the approach adopts and integrates intuitive methods from the design engineering domain, e.g., guided brainstorms, ‘how might we’s’, double diamond approach and switching between levels of abstraction.

A barrier to the successful implementation of such a mixed approach is scepticism from established professionals who are used to working with a conventional system engineering approach. To effectively include experts in the process, attention must be given to convey the objective of workshops and brainstorm sessions clearly and concisely while underlining the benefits of the mixed approach.

Another limitation of the approach may be that it is more labour intensive and hence time-consuming, especially during early-phase design studies due to the work required in preparing, conducting and documenting the outcome of the various brainstorm sessions.

A factor which was found to determine the type, applicability and value of resulting concepts is the level of detail in the requirements and reference mission profiles which are provided in the project brief. It seems doubtful that any design process can produce a solution that meets a requirement with less ambiguity than the ambiguity of the requirement. So, if no detailed information is provided, for example if ‘cargo’ is not defined with any specifications, then it is not possible to develop concepts which are specialised in their design for the unique intended application. Although a certain value might be found in more general designs that can be applied in a wide range of contexts and applications, it is not sure that this would weigh up against the value of a specialised design which can meet very specific requirements efficiently.

In this study, only limited specifications were available. Notably, it was not clear what types of cargo would be transported, what the destination of the cargo would be once delivered to the lunar surface and whether astronaut crew time would be available for the handling of cargo or whether the deployment and transportation of cargo on the lunar surface should be entirely automated. Therefore, the concepts resulting from the study can only be illustrative, serving to highlight the value of the employed design process. It should be noted however, that the three selected concepts feature different levels of autonomy; the ladder is fully manual, while the robotic arm and the winch-based pulley system can be either hybrid, thus requiring a certain degree of human intervention, or in combination with a transportation system potentially fully autonomous.

It is also noteworthy that the evaluation of concepts on the basis of rudimentary descriptions, rough sketches and visualisations cannot act as replacement for the actual testing and optimisation of a concept during its embodiment design, technical design and integration phases. Evaluations during the concept design serve to focus on the most promising directions and concepts for solution principles. Doing so at a high level of abstraction allows for rapid evolution of a design with a limited investment of resources. However, this process always relies on a high level of assumptions and intuitive or qualitative assessments. Therefore, the evaluations including grades derived from the trade-off analysis should not be seen as an indication of the actual system's performance once it is built.

The concepts which resulted from the mixed approach adopted in this work are innovative and have received positive expert feedback. This is a promising result which shows the potential value inherent in the combination of concept development methodologies from the design engineering domain with established space system engineering methodologies. Especially for early-stage development of space systems, this approach can ensure that many possible solution principles are evaluated at an early stage and ideas are progressed towards testable embodied designs in a structured and well-supported manner.

6. Conclusions and Future work

The purpose of this paper is then not to advocate for the presented method as a comprehensively applicable approach to designing future lunar surface solutions. Rather, this paper has sought to demonstrate its promise and viability during the early phases of conceptual development.

Indeed, the ability to reward creative and intuitive problem solving while surfacing matters concerning human factors and ergonomics, in combination with the high degree of flexibility in terms of allowing varying levels of abstraction, all add up to a method that fills a void in conventional approaches to iterative ideation and evaluation of early-stage lunar surface solutions.

One might object that the high level of abstraction employed by conceptual sketches has likely steered the workshop discussions towards high-level overarching themes at the expense of some of the more specific features that might nevertheless be of key concern later in the design process. Further work is therefore needed in order to integrate elements of the presented method into comparatively more advanced phases of design and development. It seems reasonable to assume that as the development matures, increasingly robust design tools will have to be employed and adapted to the unique context of lunar surface solution design.

Virtual reality is emerging as a particularly promising platform in this vein. VR refers to three dimensional computer-generated environments and artifacts that can be simulated and interacted with in a realistic manner. Such computer simulations may typically be produced at a fraction of the time and cost it would take to build a real-world counterpart, enabling efficient visualisation, modelling and assessment of prospective design solutions under realistic and controlled experimental conditions.

Drawing on VR technology, forthcoming design efforts will be directed at developing usage scenarios centred around the proposed cargo unloading solutions, making them available for further evaluation by relevant space engineering experts. Centring future user studies around such VR scenarios will help communicate design ideas with a higher degree of fidelity than what could be achieved using the conventional sketches employed in this study, thus narrowing the gap between abstraction and detail, resulting in more accurate and well-defined user feedback.

Early experimentation conducted in this vein has already yielded numerous constructive insights, with participants commenting on matters such as the ideal placement of lights on the lander, ergonomic aspects of the cargo containers and potential safety hazards associated with the cargo unloading workflow [10].

The modelling of relevant VR scenarios and their subsequent testing thus forms a vehicle for representation, demonstration, interpretation and deep analysis of the proposed cargo unloading solutions. According to the Stanford Encyclopaedia of Philosophy [52], this cognitive process constitutes the basis of a so-called "model-based reasoning", which, in turn, has been described as central to MBSE [53]. Consequently, another aspiration of this work is to lay the foundation for the adoption of a MBSE approach, exploiting early conceptual models as a means for information exchange in order to coordinate complex sociotechnical work across large teams, thus contributing to the evolution of MBSE interoperability required to fully adopt a model-based approach in the context of space projects [45], [46]. Ultimately, this research aspires to provide engineers and designers with the best means possible to develop human space systems in which the needs of the astronaut and the system can be concurrently met.

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References

[1] S. Jin, S. Arivazhagan, and H. Araki, “New results and questions of lunar exploration from SELENE, Chang’E-1, Chandrayaan-1 and LRO/LCROSS,” *Advances in Space Research*, vol. 52, no. 2, pp. 285–305, Jul. 2013, doi: 10.1016/j.asr.2012.11.022.

[2] A. Colaprete *et al.*, “Detection of Water in the LCROSS Ejecta Plume,” *Science (1979)*, vol. 330, no. 6003, pp. 463–468, Oct. 2010, doi: 10.1126/science.1186986.

[3] P. Gläser, J. Oberst, G. A. Neumann, E. Mazarico, E. J. Speyerer, and M. S. Robinson, “Illumination conditions at the lunar poles: Implications for future exploration,” *Planet Space Sci*, vol. 162, pp. 170–178, Nov. 2018, doi: 10.1016/j.pss.2017.07.006.

[4] D. A. Paige *et al.*, “Diviner Lunar Radiometer Observations of Cold Traps in the Moon’s South Polar Region,” *Science (1979)*, vol. 330, no. 6003, pp. 479–482, Oct. 2010, doi: 10.1126/science.1187726.

[5] P. Spudis and A. Lavoie, “Using the resources of the Moon to create a permanent, cislunar space fairing system,” Sep. 2011. doi: 10.2514/6.2011-7185.

[6] M. Coleman, “NASA Scientist over the Moon with homegrown radish research,” 2020. https://www.jpl.nasa.gov/news/nasa-scientist-over-the-moon-with-homegrown-radish-research (accessed Aug. 01, 2022).

[7] E. Seedhouse, “Starship,” in *SpaceX*, Cham: Springer International Publishing, 2022, pp. 171–188. doi: 10.1007/978-3-030-99181-4_9.

[8] N. Gollins, S. Timman, M. Braun, and M. Landgraf, “Building a European lunar capability with the European large logistic lander,” 2020.

[9] W. C. Carey *et al.*, “European access to the lunar surface: EL3 mission options,” in *72nd International Astronautical Congress*, Dubai, UAE, Oct. 2021.

[10] T. Nilsson *et al.*, “Using Virtual Reality to Design and Evaluate a Lunar Lander: The EL3 Case Study,” in *CHI Conference on Human Factors in Computing Systems Extended Abstracts*, Apr. 2022, pp. 1–7. doi: 10.1145/3491101.3519775.

[11] J. N. Pelton, “Space Habitats, Space Colonies and the New Space Economy,” in *The New Gold Rush*, Cham: Springer International Publishing, 2017, pp. 141–157. doi: 10.1007/978-3-319-39273-8_8.

[12] M. Smith *et al.*, “The Artemis Program: An Overview of NASA’s Activities to Return Humans to the Moon,” in *2020 IEEE Aerospace Conference*, Mar. 2020, pp. 1–10. doi: 10.1109/AERO47225.2020.9172323.

[13] B. F. Kutter and G. F. Sowers, “Cislunar-1000: Transportation supporting a self-sustaining Space Economy,” Sep. 2016. doi: 10.2514/6.2016-5491.

[14] Y. Fu *et al.*, “How to Establish a Bioregenerative Life Support System for Long-Term Crewed Missions to the Moon or Mars,” *Astrobiology*, vol. 16, no. 12, pp. 925–936, Dec. 2016, doi: 10.1089/ast.2016.1477.

[15] A. Ellery, “Leveraging in situ resources for lunar base construction,” *Canadian Journal of Civil Engineering*, vol. 49, no. 5, pp. 657–674, May 2022, doi: 10.1139/cjce-2021-0098.

[16] W. Siegfried, “Return to the moon - A program to benefit Earth,” Sep. 1995. doi: 10.2514/6.1995-4061.

[17] R. L. Howard, “A Joinable Undercarriage to Maximize Payload (JUMP) Lunar Lander for Cargo Delivery to the Lunar Surface,” Aug. 2019. doi: 10.2514/6.2019-4141.

[18] C. (Jr.). Jones, H. Franklin, and S. Feldman, “Lunar base logistics and precursor missions,” Nov. 1991. doi: 10.2514/6.1991-4140.

[19] G. R. Woodcock, “Space transfer concepts and analyses for exploration missions, phase 4,” *NAS 1.26*, 1993.

[20] B. Donahue, “Logistics impacts on lunar and Mars lander design,” Nov. 1991. doi: 10.2514/6.1991-4139.

[21] J. F. Connolly, “Constellation program overview,” Oct. 2006. Accessed: May 19, 2022. [Online]. Available: https://cyberspacelabs.com/ConstellationProgramOverview.pdf

[22] W. K. Hofstetter, P. D. Wooster, T. A. Sutherland, and E. F. Crawley, “Design Options for NASA’s Lunar Surface Access Module,” Oct. 2006. doi: 10.2514/6.IAC-06-D2.7.06.

[23] M. Cohen, “From Apollo LM to Altair: Design, Environments, Infrastructure, Missions, and

Operations," Sep. 2009. doi: 10.2514/6.2009-6404.

[24] N. Arockiam, W. Whittecar, and S. Edwards, "Space Launch System Accelerated Booster Development Cycle," 2012.

[25] L. Dawson, *The Politics and Perils of Space Exploration*. Cham: Springer International Publishing, 2021. doi: 10.1007/978-3-030-56835-1.

[26] S. Tkatchova, "Interplanetary Settlement and In Situ Exploration," in *Emerging Space Markets*, Berlin, Heidelberg: Springer Berlin Heidelberg, 2018, pp. 49–72. doi: 10.1007/978-3-662-55669-6_4.

[27] A. Heiney, "NASA Challenge Seeks Ideas to Unload Lunar Cargo," 2020. https://www.nasa.gov/feature/nasa-challenge-seeks-ideas-to-unload-lunar-cargo (accessed Aug. 03, 2022).

[28] J. C. Crusan *et al.*, "Deep space gateway concept: Extending human presence into cislunar space," in *2018 IEEE Aerospace Conference*, Mar. 2018, pp. 1–10. doi: 10.1109/AERO.2018.8396541.

[29] G. Chavers, L. Watson-Morgan, M. Smith, N. Suzuki, and T. Polsgrove, "NASA's Human Landing System: The Strategy for the 2024 Mission and Future Sustainability," in *2020 IEEE Aerospace Conference*, Mar. 2020, pp. 1–9. doi: 10.1109/AERO47225.2020.9172599.

[30] CNBC, "Bezos' Blue Origin loses NASA lawsuit over SpaceX $2.9 billion lunar lander contract," Nov. 04, 2021. https://www.cnbc.com/2021/11/04/bezos-blue-origin-loses-lawsuit-against-nasa-over-spacex-lunar-lander.html (accessed May 26, 2022).

[31] J. Foust, "NASA to support development of second Artemis lunar lander," Mar. 23, 2022. https://spacenews.com/nasa-to-support-development-of-second-artemis-lunar-lander/ (accessed May 26, 2022).

[32] M. Duggan, J. Engle, T. Moseman, X. Simon, and K. Manyapu, "A crewed lunar lander concept utilizing the SLS, Orion, and the cislunar Deep Space Gateway," in *2018 IEEE Aerospace Conference*, Mar. 2018, pp. 1–10. doi: 10.1109/AERO.2018.8396422.

[33] R. Weber, B. Cohen, and S. Lawrence, "The Artemis III Science Definition Team Report," *Lunar and Planetary Science Conference*, 2021. https://www.nasa.gov/sites/default/files/atoms/files/artemis-iii-science-definition-report-12042020c.pdf (accessed May 28, 2022).

[34] S.-H. Lee, J. Liu, J. Rudnik, O. Weck, J. F. Coughlin, and J. Chapman, "Experimenting with Design Thinking and System Engineering Methodologies: Using a Commercial Cislunar Space Development Project as an Example," 2020.

[35] C. Owen, "Design, advanced planning and product development," 1998.

[36] V.D.I., "VDI 2221 Design of technical products and systems - Model of product design," *VDI Guidelines*. Verein Deutscher Ingenieure, p. 56, Nov. 2019. [Online]. Available: https://www.vdi.de/richtlinien/details/vdi-2221-blatt-1-entwicklung-technischer-produkte-und-systeme-modell-der-produktentwicklung

[37] G. Pahl and W. Beitz, *Engineering Design*. London: Springer London, 1996. doi: 10.1007/978-1-4471-3581-4.

[38] N. F. M. Roozenburg and J. Eekels, *Productontwerpen, structuur en methoden*, 2nd ed. Amsterdam: Boom Lemma Uitgevers, 1998.

[39] J. Jänsch and H. Birkhofer, "The development of the guideline VDI 2221 - the change of direction," 2006.

[40] A. L. Ramos, J. v. Ferreira, and J. Barcelo, "Model-Based Systems Engineering: An Emerging Approach for Modern Systems," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 42, no. 1, pp. 101–111, Jan. 2012, doi: 10.1109/TSMCC.2011.2106495.

[41] L. Jacobson and J. G. B. Rumbaugh, *The UnifiedModeling Language Reference Manual*. Addison-Wesley Longman, 1999.

[42] D. Rhodes, "Addressing systems engineering challenges through collaborative research," *SEARI—Systems Engineering Advancement Research Initiative*, 2008.

[43] M. Lutfi and R. Valerdi, "Framework for Integration of Virtual Reality into Model Based Systems Engineering Approach," 2021, pp. 131–139. doi: 10.1007/978-3-030-80091-8_16.

[44] S.-H. Lee *et al.*, "A Systematic Thinking Design Research Approach Combining the ConOps with Design Scenario--Use Commercial Cislunar Space Development Project as an Example," 2020.

[45] L. Lindblad, M. Witzmann, and S. vanden Bussche, "SYSTEMS ENGINEERING FROM A WEB BROWSER: TURNING MBSE INTO INDUSTRIAL REALITY," 2016. Accessed: Aug. 22, 2022. [Online]. Available: https://www.valispace.com/wp-content/uploads/2021/02/Lindblad-SECESA-2016-Valispace-web-browser-engineering.pdf

[46] H. Eisenmann, J. Miro, and H. P. de Koning, "MBSE for European Space-Systems Development," *INSIGHT*, vol. 12, no. 4, pp. 47–53, Dec. 2009, doi: 10.1002/inst.200912447.

[47] ESA, “ECSS-E-ST-10C Rev.1 – System engineering general requirements.” 2017. [Online]. Available: https://ecss.nl/standard/ecss-e-st-10c-rev-1-system-engineering-general-requirements-15-february-2017/

[48] A. Abdel-Hadi and A. Harb, “Anticipating possible future visions in interior architecture,” 2018, pp. 155–163. doi: 10.1201/9781315166551-15.

[49] L. Duvet *et al.*, “European access to the lunar surface: EL3,” in *72nd International Astronautical Congress*, Dubai, UAE, Oct. 2021.

[50] NASA, “NASA-STD-3001 Technical Brief on Lunar Dust ,” Dec. 2021.

[51] NASA, “Human Integration Design Handbook (HIDH),” 2014. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/human_integration_design_handbook_revision_1.pdf

[52] Stanford Encyclopedia of Philosophy, “Models in Science,” 2006. http:/plato.stanford.edu/entries/models science (accessed Jun. 19, 2022).

[53] R. I. G. Hughes, “Models and Representation,” *Philos Sci*, vol. 64, no. S4, pp. S325–S336, Apr. 1997, doi: 10.1086/392611.