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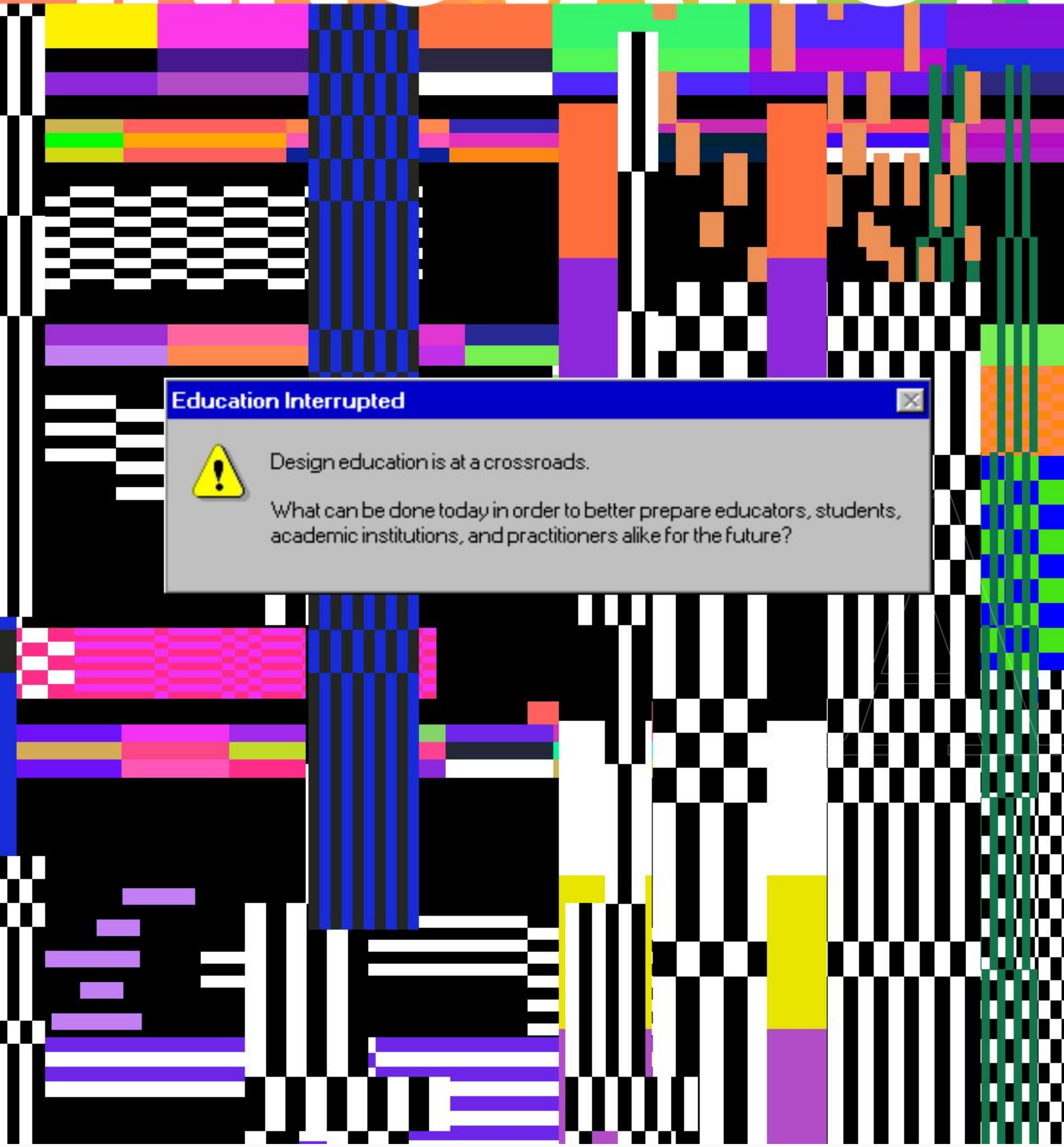
INNOVATION



EDUCATION PAPER

EXPERIMENTING WITH DESIGN THINKING AND SYSTEM ENGINEERING METHODOLOGIES

USING A COMMERCIAL CISLUNAR SPACE DEVELOPMENT PROJECT AS AN EXAMPLE

1. Introduction

In today's world, many human-made systems have failed to meet the needs of the broader population as macro trends such as climate change, inequality, and the proliferation of new technologies continue to change how we live, work, and play. Without having to look far, individuals can easily notice the shortcomings of transportation, healthcare, education, government, and many more human-made systems that are designed to serve the public. As in the past, designers and engineers are uniquely positioned to address these complex issues by inventing new problem-solving methodologies in times of need.

Based on Charles Owen's framework in his 1998 paper "Design, Advanced Planning and Product Development" and Thomas Both's article "Human-Centered, Systems-Minded Design" from the *Stanford Social Innovation Review,* an opportunity exists to combine human-centered design approaches with System Engineering methodologies in order to solve system design challenges in a human-centered way. Owen and Both's research have inspired questions: How might we embed a layer of human touch into the System Engineering method? How might we create a human-centered system design methodology incorporating quantitative and qualitative techniques? This study will demonstrate the similarities and differences of both methodologies on a principle level by applying their processes and tools to a commercial cislunar space development project.

2. Literature and Methodology Review

2.1 Design Thinking

The commonly accepted industry term for human-centered design methods is "Design Thinking," which was coined by John E. Arnold in his book *Creative Engineering* in 1959. L. Bruce Archer also mentioned the term in his book *Systematic Method for Designers* in 1965. At the time, research on developing creativity techniques was rapidly growing and the core concepts of Design Thinking were adopted by design and innovation consultancies such as IDEO, Continuum, frog design, and others to assist corporate clients in discovering new market opportunities.

At a high-level, Design Thinking involves four problem-solving steps: inspiration, ideation, implementation, and iteration. The first step of inspiration involves in-depth research through techniques such as interviews and ethnography, followed by data synthesis to uncover latent needs. Once problems are clearly defined, a diverse team of experts is assembled to generate ideas that will be down-selected for implementation. Lastly, a prototype for these ideas will be created and tested with users to obtain feedback, which will inform the next iteration of the prototype.

The hallmark of Design Thinking is this continuous cycle of convergence and divergence around the exploration, synthesis, and actualization of ideas. Design Thinking is now widely applied to many industries to solve design challenges that range from new product development,

Methodology	Design Thinking	System Engineering
Technique	Qualitative	Quantitative
Process	Diverge & Converge	Decomposition & Integration
Mental Model	Human-centered	Function-centered
Scale	Primarily small-scale projects	Primarily large-scale projects
Key Steps	Inspiration (e.g., research, interview), ideation (e.g., brainstorm, design) and implementation (e.g., prototype, test, refinement, manufacturing) Note: This was adapted from IDEO Method Cards (2003).	Input and output; requirements analysis and loop; functional analysis/allocation; synthesis; design loop; verification and balance (*System Engineering Fundamentals*, 2001)

Table 1. Summary of Design Thinking and Systems Engineering

brand design, interaction, service experience, and socially impactful projects.

2.2 System Engineering

System Engineering is a language and method that enables communication among engineering disciplines on large-scale complex projects. If we use a simple metaphor, in various engineering disciplines, engineers solve the problem for either 0 or 1, whereas in Systems Engineering engineers tackle the problem area between 0 and 1.

The term "Systems Engineering" can be traced back to Bell Labs in the 1940s, but the discipline was formalized after World War II when it was applied to national science projects such as the Apollo space program under President John F. Kennedy. "System engineering is a robust approach to the design, creation, and operation of systems. In simple terms, the approach consists of identification and quantification of system goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design, verification that the design is properly built and integrated, and post-implementation assessment of how well the system meets (or met) the goals" (NASA, 2017).

Most complex systems and engineering management issues will utilize system thinking principles to organize and solve challenges. In contrast to Design Thinking, System Engineering is geared toward projects that require significant consideration for systems architecture and the integration of subsystems. "System architecture is the embodiment of concept, and the allocation of physical & informational function to elements of form, and the definition of relationships among the elements and with the surround context" (Crawley et al., 2016).

2.3 Comparing Two Methodologies

Design Thinking and System Engineering each have their advantages and disadvantages. Instead of ranking the two methodologies, it is more important to understand the context for which the methods should be suitably and accurately applied. Table 1 summarizes the key characteristics of both methodologies.

3. Design Process

3.1 Project Context and Brief

Cislunar space represents a prime environment for future business opportunities that improve life on Earth through the use of space. In the project, an interdisciplinary team identified opportunities to expand the economic sphere beyond the Earth's surface and developed a novel concept for a commercial cislunar business. The study applied the aforementioned Design Thinking approach and System Engineering methodologies to generate the preliminary design architecture of a lunar energy grid that would provide power to NASA's future space missions based on a call for proposals from the 2020 RASC-AL competition. The project team consisted of four experts with

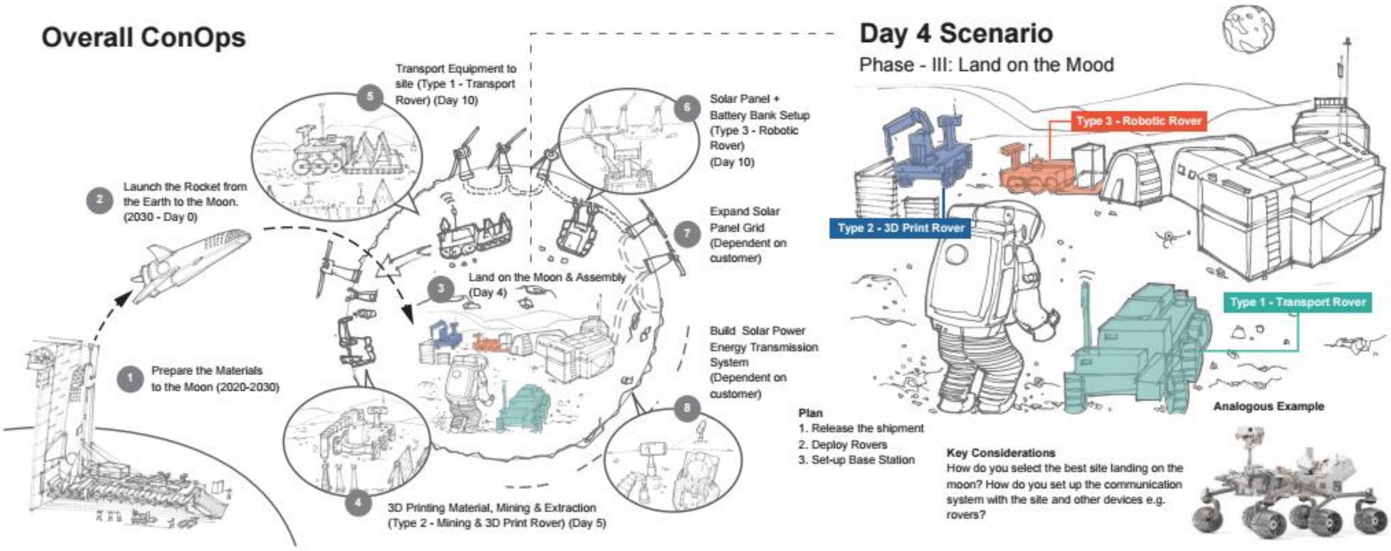


Figure 1. The overall ConOp of a commercial cislunar space development project (*left*) and a detailed scenario view of Phase III by adding key considerations and an analogous example (*right*).

experiences across industrial design, electrical engineering, aerospace engineering, business, and finance. The project accomplished the allocation and derivation of a lunar energy grid and its subsystems by combining Design Thinking tools with two important frameworks from System Engineering: concept of operation (ConOp) and Object-Process Methodology (OPM).

3.2 ConOp for Systems Design & Scenario Exploration

A concept of operation (ConOp) is a verbal statement or graphic to describe a complex system. The ConOp includes a sequence of phases, an estimated timeline for deployment, and an overview of important system characteristics shown in a quantitative and qualitative way. According to Edward Crawley (2019), professor of aeronautics and astronautics and engineering systems at MIT, "The ConOp is an important component in capturing expectations, forming requirements and developing the architecture of a project or system" (slide 61). ConOp is a tool commonly used in stakeholder meetings and discussions during the early concept development stage for the military, aerospace industry, and government services. In short, ConOp can be viewed as a system blueprint that guides the implementation of a complex project.

The project team followed a step-by-step process to create a ConOp for a lunar energy grid (Figure 1, left). First, the team generated the key technical requirements for the system and its subsystems to deliver value for all stakeholders involved. When developing the ConOp, the team considered critical questions that inform the system architecture: How can the lunar grid capture, store, and transmit energy? What technologies are necessary for the energy system to work?

Next, the team entered a radical ideation stage where each member had an important role: the designer rapidly visualized concepts that emerged, the engineers stress tested concepts for technical feasibility, and the business expert evaluated the viability of the system for the burgeoning space industry. During this stage of brainstorming, the sequence of phases and timeline for deployment began to serve as valuable constraints that brought more fidelity to the ConOp. The team began to consider more detailed questions for the subsystems of the energy grid: Who should operate the lunar rovers for solar panel deployment? Where will the rovers transport the solar panels on the moon's surface? What is the transportation capacity and energy needs for each rover?

The final stage of ConOp development was to identify analogous examples that could inspire the design of subsystems (Figure 1, right). Both detailed scenarios and examples brought higher fidelity for the whole system map. Typically, a ConOp is a single diagram that communicates an abstracted view of a system, but it does not immerse stakeholders in the detailed design. In contrast, the experimental ConOp that was developed consisted of valuable information to convey a more nuanced picture of how a system functions for its stakeholders. Through this process of rapid concept generation and inquiry, the project team was able to envision a lunar energy grid that was radically different from existing archetypes in the space industry. The ConOp was a blank canvas, and the project team became the paintbrush.

3.3 Integrating User Journey within OPM System Modeling

Object-Process Methodology (OPM) is a modeling tool to represent a complex system in a graphical and textual way by showing the structural relationships between two fundamental elements: object and process. An object is a physical or informatical element that exists, while processes are elements that transform (create, destroy, or change the state of) the objects. OPM was initially developed for Systems Engineering and can be used to model a wide range of topics ranging from complex systems, information, social issues, and natural disasters to product design challenges.

OPM is a valuable tool to communicate the structure and behavior of a system to stakeholders on a large-scale project. It was recently adopted in 2014 as ISO 19450, a global standard language for system modeling. The project team used OPM to create a representation of the energy system depicted by their experimental ConOp, which displayed critical components such as the lunar rovers, lasers, laser transmission energy, and others. Within each component, there are multiple subsystems, elements, and processes.

The team also made an important modification to the standard OPM diagram of the lunar energy grid by adding a layer to depict a user journey within the system. Figure 2 illustrates how OPM and user journeys can be combined to empower a system designer in balancing the user journey against a system architecture and vice versa. Many iterations of a system design can be created to achieve a future state that would meet key stakeholder needs and system requirements. Furthermore, the tool can assist system planners and designers in capturing a comprehensive user journey from both an emotional and functional perspective.

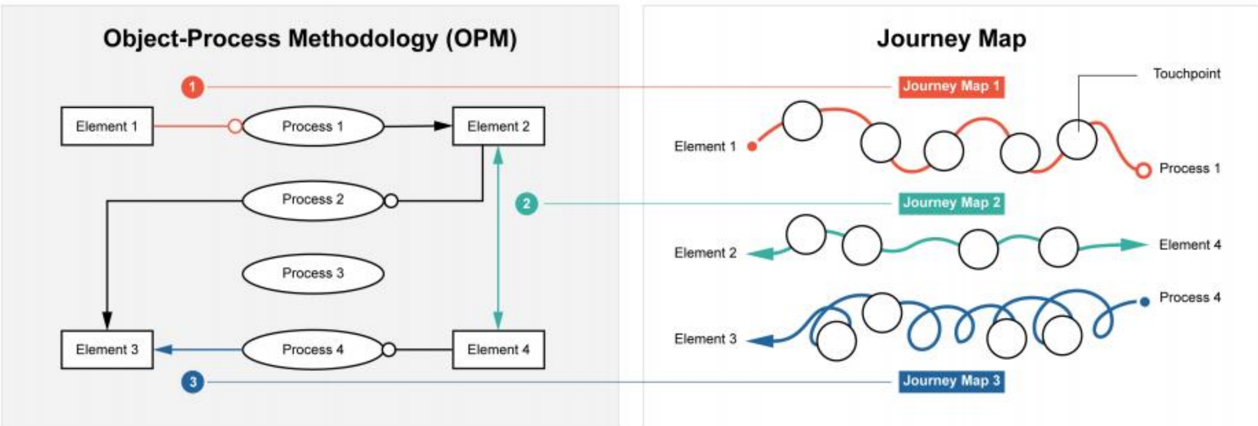


Figure 2. Combining the Object-Process Methodology (OPM) and user journey map.

4. Extending System Engineering to Human-Centered Design

For designers, cislunar space is not a typical environment for a human-centered design challenge. Space systems are unique because they may not have precedents and safety trumps nearly all other requirements. NASA does not design a space system by first asking what an astronaut desires for the experience. Instead, NASA will ask systems engineers to coordinate engineering teams to deliver on functional system requirements set against constraints.

This approach is not immediately compatible with Design Thinking, where designers often begin a project by building empathy with end users to create solutions that address both functional and emotional needs. As projects grow in complexity, designers will need tools to diagnose problems from a systems perspective and to design for systems that positively influence human behavior.

The experimental ConOp helps designers to illustrate both an abstract and a deconstructed view of a system. By following the same brainstorm process as the project team and stepping away from norms, designers have the freedom to conceive radically new systems that may transform companies and industries. The OPM system modeling tool allows a designer to make tradeoffs between the user journey and a system's structure and functionality. OPM also empowers a designer to better facilitate the creative output of engineering and design teams on system-related projects.

Bringing together two methodologies is a challenging task due to the radically different contexts in which they were born, but one characteristic that bridges the current direction of Design Thinking and the discipline of Systems Engineering is the need for better designed human systems. The methods proposed in this paper aim to support the design community in expanding its impact in the field of systems innovation. As stated by Olivier de Weck, professor of aeronautics and astronautics and engineering eystems at MIT in his book, "Designing the design process becomes a significant concern for large-scale projects" (De Weck et al., 2016, p.127).

5. Conclusion

The project has led to critical questions to take this study further: What should be the criteria for determining whether a project or opportunity space is suitable for application of these two methodologies? What are the conditions necessary for a new methodology to emerge? The answers to these questions will enable designers and engineers to better solve the world's system-related issues in the decades to come.

Systems Engineering emerged from NASA's lunar missions as a discipline to address engineering design challenges in the most extreme conditions. In these missions, the requirements for space engineering systems to guarantee safety and success for all key stakeholders involved meant that the functional attributes of a space system took precedent over the human experience. Design Thinking has emerged from the field of industrial and product design, where designers focus on creating products that address emotional needs in conjunction with the functional needs of users. Therefore, the goal is to develop and curate a new methodology that enables designers and engineers to create human-centered systems where the needs of the user and the system can be simultaneously met.

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