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What Space Architects Can Learn from System Failure Cases to Make Risk-Conscious Design Decisions

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When formulating the design information of space system concepts, space architects need to be aware of the consequences and implications of the design decisions they make, as there are many ways space systems can fail—small defects can lead to catastrophic consequences, and the remoteness of the sites would impose prohibitive costs to fix issues in the fortunate cases where issues are discovered. To learn from mistakes, this paper leverages cases of system failures in construction and spaceflight projects due to built-in defects—or *embedded pathogens*. Depicting the sequence of defective processes traveling across system hierarchy and project timeline, the case studies illustrate that each failure case is plagued with multiple paths of latent failures—*pathogen threads*—propagating and reaching the artifact. By extracting the design decisions that directly or indirectly contributed to the system failures, this paper discusses the effects of physical and organizational *strains.* These strains, both intentional and unintentional, undermine the safety, quality, and integrity of the system if handled inadequately. They are induced by design solutions exacerbated by underlying organizational factors that cause the design-induced strains to end up as embedded pathogens. We show how defective design decisions as well as inadequately managed design solutions can be incubated into system failures. This paper concludes by underscoring the importance of communicating and managing design-induced strains throughout the project lifecycle to prevent them from causing system failures in space system development, deployment, and operation.

Acronyms

ECLSS = Environmental control and life support system
FLAPP = Framed and layered accident pathogen propagation
FRAM = Functional resonance analysis method
HFACS = Human factors analysis and classification system
HST = Hubble Space Telescope
MCO = Mars Climate Orbiter
STAMP = Systems-theoretic accident model and processes
STS = Space Transportation System
TMO = Temporary multi-organization

I. Introduction

Various space architecture designs have been conceptualized and developed throughout history, and the momentum to materialize them to reality has become stronger than ever, as evident in the array of private companies developing commercial space station concepts and research institutes investigating technologies to construct extraterrestrial settlements. Formidable challenges and technological gaps exist in implementing and maintaining space architecture projects: the harsh environmental conditions of space demand careful consideration of constructability; the remoteness of the sites makes it infeasible to make frequent, or any, visits to repair issues; and if left unaddressed, small design defects can lead to catastrophic consequences. In this light, space architects, who are responsible for facilitating the decision-making process of formulating the design of the frontiers of extraterrestrial

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human activities, must make the “right” design decisions to maximize the quality and functionality of the end-product, while minimizing potential risks of defects and failures.

A *design decision* is a *decision* by responsible decision-makers (e.g., owner, client, designer, or engineer) to select a design solution from alternatives [1–4] and make an “irrevocable allocation of resources, in the sense that it would take additional resources, perhaps prohibitive in amount, to change the allocation[5]”. Design alternatives can include materials, physical form and functions of components, their configurations, and other quantitative and qualitative design variables.[6,7] Every aspect of developing space architecture concepts involves such decisions, from the site layout of a lunar settlement to the dimensions of door handles in an orbital space station.

Design decisions made in the early phase of the system lifecycle can affect various downstream aspects, including constructability, operability, and maintainability. Specifically, inadequate decisions can result in latent failures, or resident pathogens,[8] which can remain unnoticed and eventually resurface as system failures and accidents when combined with local triggers. In space architecture, such pathogens embedded in the form of built-in defects in the artifacts—the physical architecture or constructed system installed on its operational site—are especially challenging to detect and remove once launched and installed off Earth. To be precise, an *accident* in safety research is defined as an unplanned and undesired but not necessarily unforeseen event resulting in an unacceptable loss involving injuries, human lives, or property.[9] For example, a fatal aircraft crash is an accident involving losses in human life and the aircraft. A *system failure*, in contrast, refers to a system not meeting its system requirements. A commercial airline failing to operate on schedule is a system failure where the unsatisfied requirement of the air transportation system is to transport passengers from origin to destination according to the published flight schedule. Every accident is a system failure involving nonconformance of safety-related system requirements, whereas not all system failures result in losses significant enough to be considered accidents.

Although there are only a handful of flight-proven space architecture projects and the prospective design decisions to be made in future projects are likely novel and unprecedented, the history of spaceflight projects now spans more than half a century, and when it comes to architecture and construction projects, their history stretches over millennia. Throughout those histories, humans have made countless failures and accidents, and it is not difficult to find cases where faulty design decisions were part of the picture. The objective of this paper is to provide lessons that space architects can learn from cases of construction system failures that happened on and off Earth, to aid them in making risk-conscious decisions in formulating the designs of off-world built environments. Here, we use the term *construction system failures* to describe the system failures caused by the defective outputs of *construction systems*, i.e., the sociotechnical systems that develop and produce constructed systems. To derive lessons from system failure case studies, this paper focuses on the design decisions contributing to the pathogens identified in each of the failures in our case set and extracts the underlying properties that can be translated into prospective design decisions to be made in future space architecture projects.

II. Design Decisions Behind System Failures

A. Embedded Pathogens in Construction and Space System Failures

Responding to the complex challenges that various domains in the society constantly present, the safety research community has produced various causation models to analyze accidents from systems-based perspectives, including the Swiss Cheese Model,[10] functional resonance analysis method (FRAM),[11] AcciMap,[12] and systems-theoretic accident model and processes (STAMP).[13] However, one feature of construction systems that remains to be addressed is the time dimension, which is necessary to describe the dynamic and ephemeral nature of the project organizations.[14] The project teams in construction can be considered as temporary multi-organizations (TMOs), where multiple teams from different organizations form a temporary coalition for the duration of the project.[15–17]

To capture the transient nature of construction project organizations and the system-wide mechanisms that allow design defects to end up materializing in the artifact, in our previous work we developed a failure analysis framework with an explicit focus on two dimensions: project timeline and system hierarchy.[18] The basic structure of the framework, namely the framed and layered accident pathogen propagation (FLAPP) model, consists of *frames*—snapshots of certain periods of time in the project lifecycle to describe defective processes—and *layers*—hierarchical division to separate the players, different processes (information and physical), the artifact, and the physical environment.[18] Figure 1 presents a conceptual illustration of the FLAPP model, where a sequence of defective information and physical processes traverses through frames and layers and eventually reaches the artifact and injects an embedded pathogen. This simplified depiction represents how a flawed design decision can propagate downstream, become fabricated and installed as specified, and take a physical form in the constructed system. Tracking such paths of failure leads us to consider the paths of propagation as *pathogen threads*—each thread containing one or more defective processes upstream and ending with an interaction with the artifact.

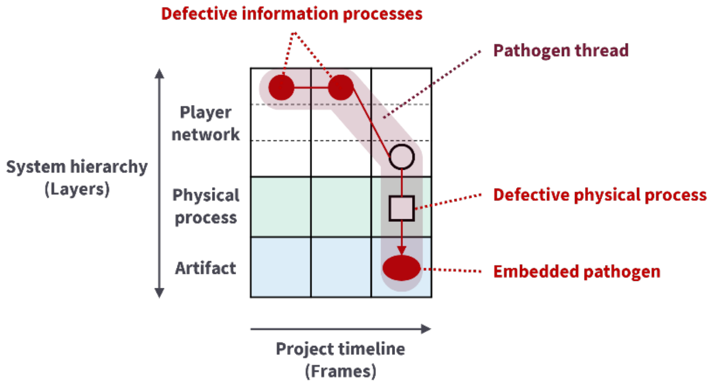

Figure 1. Conceptual illustration of pathogen threads.

While we developed the FLAPP model to reflect the characteristics of construction systems, its frame and layer structure can also illustrate design-induced failures in the space domain, since the sociotechnical systems and project phases involved in spaceflight projects are similar enough to those in construction projects. Organizational networks in spaceflight projects often exhibit the critical features of TMOs: being a temporary organization—the team is formed only for the duration of the project, and they are not guaranteed to work together on another project again—and a multi-organization—the organizational network consists of participants representing multiple organizations, each with their own operational and managerial control. The sociotechnical systems that run construction and spaceflight projects both develop and operate physical artifacts through information and physical processes. The project lifecycle phases in both domains generally follow similar steps: development of concepts, specifications, and design information (planning and design in construction; concept development and design in spaceflight), physical formulation of the artifact (fabrication and installation in construction; fabrication, system assembly, and integration in spaceflight), and system checkout (building commissioning in construction; system testing, verification, and validation in spaceflight) followed by operation, maintenance, and decommissioning.[19,20]

B. Construction and Space System Failure Cases

The particular types of system failures that we are most interested in involve defects in design, fabrication, or installation, that end up embedded in the artifact. In the context of space architecture, once launched and installed on an extraterrestrial site, be it low Earth orbit, the lunar south pole, or the Martian surface, such embedded pathogens are difficult to detect, require prohibitive costs to fix, and could easily lead to catastrophic consequences if left unaddressed. Hence, it is important to learn from these types of failures to prevent similar mistakes.

Table 1 summarizes the basic information about the cases of construction and space system failures we studied, which include three space systems, four buildings, and three civil engineering structures. The three space system accidents exhibit similar mechanisms of propagation and injection of embedded pathogens to the terrestrial accidents, confirming our supposition that space systems may fail in similar ways to terrestrial systems (and may of course also fail in unique ways).[21] In all of the listed cases , defective information or components that were produced during the planning, design, or construction phase ended up in the artifact, remained unresolved due to other defective processes, and, combined with a multitude of triggering factors, eventually surfaced as system failures. The failures led to several different consequences: malfunctioning resulting in eventual costly repair and refurbishment (HST and Sydney Opera House); loss of primary asset (MCO and Arecibo Telescope); and loss of lives (Columbia, Kansas City Hyatt Regency, Charles de Gaulle Airport, Algo Centre Mall, Minneapolis highway bridge, and Sasago Tunnel).

Including spaceflight and civil engineering cases in the case set, which might appear irrelevant to an architect in a conventional sense, is essential for learning from failures that involved inadequate system-level design decisions in general, as we have yet to define the professional boundary of space architects. It is safe to say, compared to terrestrial structures, the design of space architecture requires stricter adherence to "form follows function" with less margin for flexibility. Extraterrestrial systems are highly integrated with structural, mechanical, thermal, and software subsystems and are subject to tighter constraints in size and mass, performance, and safety. Such aspects of space architecture inevitably set the role and responsibilities of a space architect apart from the conventional profession of an architect, and leave the boundaries between architects and engineers, architecture and civil, aerospace, and mechanical engineering blurred and undefined.

Admittedly, the listed case set is skewed toward structural failures. While the severity of a failure is not proportionate to the potential for learning,[22] system failures with severe consequences tend to attract more public interest compared to minor and inapparent failures, often resulting in detailed documentation. Because our study required detailed and publicly available accounts of failure cases, many eligible cases involved structural failures that led to major and obvious consequences. It is important to note that, even when the apparent consequences are the same, i.e., structural collapse, the failures involve various kinds of inadequacies, such as lack of holistic perspective, defunct design review, poor fabrication quality, and flawed inspection procedures. We can hypothesize their contribution to nonstructural failures from the instances we see in the HST case: flawed inspection procedures that relied on a single measurement device led to the incorrect attribution of test result anomalies;[23] and the case of Sydney Opera House: lack of holistic perspective led to the absence of acoustic consideration during the initial design of the outer shell structure.[24] Case studies on minor defects and errors (e.g., malfunctioning, quality deficiencies, and nonconformance) would be beneficial for gaining insights irrespective of severity, which we anticipate in future work.

Table 1. Construction and space system failure cases.

Failure Case	Year	Type	Location	Built in	Main Narrative
Hubble Space Telescope (HST) optical systems failure[23,25]	1990	Orbital spacecraft	Low Earth Orbit	1990 (launch)	The verification of the primary mirror solely relied on a mis-calibrated measurement device, resulting in a fabrication error.
Mars Climate Orbiter (MCO) mishap[26–31]	1999	Orbital spacecraft	Earth-Mars space	1998 (launch)	One of the software files used incorrect units, leading to substantial discrepancy of the trajectory and loss of the spacecraft.
Space Shuttle Columbia STS-107 re-entry failure [Columbia][32–34]	2003	Orbital transport vehicle	Earth-Low Earth Orbit	1979	A foam debris detached from the External Tank during launch, hit and breached the wing edge of the Orbiter, resulting in breakup during re-entry.
Sydney Opera House acoustics failure [SOH][24,35–37]	1973-2020	Building (concert hall)	Australia	1973	The spherical shell was built with limited volume to accommodate the required functions, resulting in poor acoustic performance of the hall.
Kansas City Hyatt Regency walkway collapse [KCHR][38,39]	1981	Building (hotel)	Missouri, US	1980	An improper design change made to the joints suspending the walkway bridges caused them to collapse into the hotel atrium.
Charles de Gaulle Airport Terminal 2E collapse [CDG][40–43]	2004	Building (airport)	France	2003	A section of the tube-shaped terminal shell structure collapsed inward due to design deficiencies and poor concrete quality.
Algo Centre Mall roof collapse [Algo][44]	2012	Building (shopping mall)	Canada	1980	None of the owners addressed the water leakage from the defective waterproofing system, leading to the corrosion of the steel structure and collapse of the roof.
Minneapolis I-35W highway bridge collapse [Minn][45]	2007	Bridge	Minnesota, US	1967	Underdesigned gusset plates, overlooked by multiple design reviews and inspections, failed and caused the bridge to collapse.
Sasago Tunnel ceiling collapse [Sasago][46,47]	2012	Tunnel	Japan	1977	Adhesive anchor bolts supporting the ceiling panels gradually lost their load-carrying capacity.
Arecibo Telescope collapse [Arecibo][48]	2020	Radio telescope	Puerto Rico, US	1963	The end of the cables suspending the instruments slipped out from the sockets due to uneven fabrication quality and gradual deformation of zinc in the sockets.

The cases show that system failures in construction and space are often plagued with multiple instances of pathogen threads occurring throughout system lifecycles, from design and construction, system verification and commissioning, and during operation and maintenance. Different threads can originate from different decisions made by different actors during different project phases. Table 2 lists the instances of pathogen threads in each case, which we categorized into five different types depending on when the thread interacted with the artifact during the system lifecycle: initial injection (initial planning, design, and construction), pathogen exposure (system verification and commissioning), missed opportunities (operation and maintenance), well-intended aggravation (refurbishment and modification), and pathogen activation (immediate trigger during operation).

In the following sections, we derive the design decisions contributing to the system failures by identifying the design solutions corresponding to each instance of pathogen threads identified in the cases.

Table 2. Instances of pathogen threads in each failure case.

Failure Case	Pathogen Thread Type	Instances
HST	1. Initial injection	• Fabrication and integration of a misfabricated mirror
	2. Pathogen exposure	• Telescope operation commenced without correction
MCO	1. Initial injection	• Development and integration of a defective ground software
	2. Pathogen exposure	• Spacecraft operation commenced without correction
	3. Missed opportunities	• Discrepancy in trajectory and spacecraft attitude observed • Emergency trajectory maneuver not performed
	4. Well-intended aggravation	• Spacecraft maneuvered away from nominal trajectory
	5. Pathogen activation	• Excessive friction with the Martian atmosphere
Columbia	1. Initial injection	• Fabrication and installation of defective foam ramp • Fabrication and installation of defective wing edge panels
	2. Pathogen exposure	• Shuttle commenced without fixing foam vulnerability
	3. Missed opportunities	• Assessment of panel mass loss did not determine strength loss • Repeated observations of foam detachment • Damage assessment dismissed the foam debris impact
	5. Pathogen activation	• Exposure to harsh flight conditions
Sydney Opera House	1. Initial injection	• Fabrication and installation of unsatisfactory hall interior
	2. Pathogen exposure	• Concert hall commissioned with acoustic problems
Kansas City Hyatt Regency	1. Initial injection	• Fabrication and installation of defective beam-rod joints
	2. Pathogen exposure	• Hotel operation commenced without detecting the defect
	5. Pathogen activation	• Load of a crowd larger than usual but within expected range
Charles de Gaulle Airport	1. Initial injection	• Fabrication and installation of defective concrete shells
	2. Pathogen exposure	• Airport terminal commissioned without correcting the defect
	5. Pathogen activation	• Rapid temperature drop adding stress to concrete
Algo Centre Mall	1. Initial injection	• Installation of defective waterproofing system
	2. Pathogen exposure	• Building operation commenced without fixing the defect
	3. Missed opportunities	• Repeated observations and complaints of water leaks • Multiple repairs did not fix the water leak
Minneapolis I-35W bridge	1. Initial injection	• Fabrication and installation of defective gusset plates
	2. Pathogen exposure	• Opened to traffic without detecting the defect
	3. Missed opportunities	• Inspections and evaluations did not detect the design defect
	4. Well-intended aggravation	• Renovations increased bridge weight
	5. Pathogen activation	• Construction materials inappropriately stockpiled on bridge
Sasago Tunnel	1. Initial injection	• Installation of defective anchor bolts and ceiling panels
	2. Pathogen exposure	• Opened to traffic without detecting the defect
	3. Missed opportunities	• Routine inspections did not detect the installation defect • Past repair works did not address the installation defect
Arecibo Telescope	1. Initial injection	• Fabrication and installation of defective wire-sockets
	2. Pathogen exposure	• Telescope commissioned without correcting the defect
	3. Missed opportunities	• Routine inspections did not address cable slips • Additional structure installed without redundancy
	4. Well-intended aggravation	• Updates increased structure weight

C. Relevant Design Decisions

For each of the pathogen threads, we can derive the design solutions associated with their instantiations, i.e., the selected design options or alternatives that directly or indirectly caused the defective process or action, or the defective design solutions that the pathogen thread communicated or implemented. Table 3 lists the design decisions and the resulting design solutions that contributed to the pathogen threads in the system failure cases. To observe the breadth of design decisions contributing to the failures, we assigned a non-exhaustive, tentative set of categories of design variables: physical layout, dimensions, choice of component, material, mathematical parameter, software architecture, process architecture, and modification. As we study additional cases, we expect to require additional types and perhaps an alternative categorization. Another dimension we assigned to the design variables is whether they are controlled and implemented locally or globally, i.e., whether the variable is tied to the component or subsystem-level (e.g., dimension of the gusset plates in the bridge truss) or whether it can only be determined at the system-level (e.g., asymmetrical overall geometry of the MCO spacecraft). A design variable defined locally does not necessarily indicate that it has no system-wide effects (e.g., underdesigned gusset plates can cause structure-wide collapse).

Table 3. Design decisions and solutions contributing to the pathogen threads.

Failure Case	Contributing Design Solutions	Type of Design Variables	
HST	Configuration of the reflective null corrector	Physical layout	Local
	Precise dimensions of the primary mirror	Dimensions	Local
	Confined configuration of the Optical Telescope Assembly	Physical layout	Global
	Single-point failure verification method	Process architecture	Global
MCO	Software using SI units	Mathematical parameter	Local
	Complex software architecture	Software architecture	Global
	Asymmetrical geometry of the spacecraft	Physical layout	Global
Columbia	Configuration of bipod connections	Physical layout	Local
	Structural properties of wing-edge thermal protection	Choice of component	Local
Sydney Opera House	Geometry of the outer shells	Physical layout	Global
	Configuration of hall interior installations	Physical layout	Global
Kansas City Hyatt Regency	Offset hanger rods	Physical layout	Local
	Concealed placement of the beam-rod connections	Physical layout	Global
Charles de Gaulle Airport	Geometry of the outer shell	Physical layout	Global
	Configuration of shell support structures	Physical layout	Global
Algo Centre Mall	Configuration of waterproofing system	Physical layout	Local
	Concealed configuration of the roofing structure	Physical layout	Global
	Placement of parking on the rooftop	Physical layout	Global
Minneapolis I-35W bridge	Gusset plate dimensions	Dimensions	Local
	Concealed placement of the gusset plates in bridge truss	Physical layout	Global
	Additional installation of components	Modification	Global
Sasago Tunnel	Use of adhesive anchor bolts for ceiling panel support	Choice of component	Local
	Concealed configuration of ceiling panels	Physical layout	Global
	Designed load distribution of ceiling panels	Physical layout	Global
Arecibo Telescope	Splayed out configuration of cable wire ends	Physical layout	Local
	Concealed configuration of cable-socket components	Physical layout	Local
	Safety factor of the cable system	Mathematical parameter	Global
	Use of zinc for sockets supporting cable ends	Choice of material	Local
	Nonredundant cable configuration	Physical layout	Global
	Additional installation of components	Modification	Global

In the case of Space Shuttle Columbia for example, one of the *initial injection* threads is the "fabrication and installation of defective foam ramp". The inadequate design decision that was implemented through this thread was the "configuration of bipod connections," which was formulated without appropriate integration of structural and thermal considerations.[32] The design solution undermined the foam ramp integrity, which was communicated and remained unaddressed in other pathogen threads, including "repeated observations of foam detachment" and "damage assessment dismissed the foam debris impact."

In the Sasago Tunnel case, "routine inspections did not detect the installation defect" was one of the *missed opportunities* threads. This instance sheds light on two design decisions that likely affected the cost and quality of the inspections: the choice of adhesive anchor bolts as the components supporting the ceiling panels, and the layout configuration of ceiling panels. The long-term material behavior and structural mechanism of the adhesive anchor bolts were not well understood at the time of construction, which made it difficult to establish appropriate inspection cycles and maintenance plans, and the degradation of the adhesives could not be detected by simple visual inspections.[46] The physical layout of the ceiling panels did not allow easy access to the bolts, functioning as a technical and financial barrier to performing detailed inspections.

III. Incubating Design Decisions into System Failures

A. Design-Induced Physical and Organizational Strains

While some of the design solutions that played roles in the instantiation of pathogen threads are clearly erroneous (e.g., the load distribution design of the ceiling panels of Sasago Tunnel that did not include all necessary loads in its calculation), others are not necessarily defective or erroneous by themselves, but are rather reasonable and justifiable if observed in isolation. In the Algo Centre Mall case, the decision made early in the design phase to place the parking on the rooftop turned out as inadequate because the effects of additional weight and vibration of vehicles combined with exposure to precipitation were not reflected in the structural reinforcement, waterproofing system design, and maintenance plans. The asymmetric spacecraft geometry of the Mars Climate Orbiter only ended up contributing to the discrepancy of the trajectory because necessary knowledge about the characteristics of spacecraft attitude control was not communicated from the development team to the operations team.

In considering what made the design solutions "problematic" if not "wrong," we can think of the kinds of *strains*—effects that could undermine the safety, quality, and integrity of the system if handled inadequately—that the design solutions induced, either directly to the physical artifact or indirectly to the project organization. In the Minneapolis highway bridge case, one of the *physical strains* was induced by the design solution of gusset plate dimensions, which resulted in decreased load capacity of the truss joints, negatively affecting the overall structural integrity of the system (i.e., the bridge). In the same accident case, the placement of the gusset plates (located under the bridge) had no apparent effect on the structural integrity (no instance of physical strain), but the fact that the plates were not easily accessible and observable from the top of the bridge ultimately led to the bridge operator needing additional operational steps and attention to recognize them as necessary inspection items and to observe and detect their irregularities. We can consider such extra effort as an *organizational strain* induced by the design solution, which would eventually lead to the instantiation of pathogen thread elements if not properly addressed (the actual maintenance operation did not include the gusset plates as inspection items and contributed to the eventual collapse of the bridge).

While the choice to place the gusset plates in inconspicuous locations is self-explanatory (the purpose of the gusset plates is to support the truss joints under the bridge), there are obvious design choices that inherently demand additional resources, considerations, and operational steps—inevitably inducing organizational strains—to maintain the overall system performance and integrity and to prevent the design solution from causing undesired problems and complications. Some design solutions only lead to either physical or organizational strains: in the case of Sydney Opera House, the geometry of the outer shells did not directly diminish the acoustic performance of the halls (no physical strain) but reduced the internal volume and options to accommodate functional requirements, resulting in an organizational strain. Other solutions can induce both physical and organizational strains: the asymmetric spacecraft geometry of MCO resulted in undesired deviation in spacecraft attitude due to the asymmetrical effects of the solar pressure (physical strain), which needed to be accounted for to maintain the planned trajectory with proper monitoring based on the accurate knowledge of the spacecraft (organizational strain).

The physical and organizational strains explain *what* made the design decisions "problematic." When we further examine *why* the decision-makers chose the design solutions that would strain the physical and organizational systems, we observe three modes of awareness regarding the consequential implications of inducing the strains: 1) the designers were unaware of the negative consequences due to their lack of knowledge, expertise, or critical information—the strains were completely unnoticed; 2) they were actively aware of the implications and made a voluntary choice to live with the strains as a result of various considerations, such as trade-offs and prioritization of other factors; 3) they were aware of the strains but underestimated the consequential implications due to the lack of holistic perspectives.

Table 4 lists the physical and organizational strains induced by the contributing design solutions and their modes of awareness in each of the system failure cases.

Table 4. List of physical and organizational strains induced by the design solutions.

Case	Design Solutions	Physical Strains	Organizational Strains	Awareness
HST	Configuration of the reflective null corrector	N/A (no apparent negative effect on the device performance)	Additional operational steps and attention required for proper setup and calibration	Under-estimated
	Precise dimensions of the primary mirror	N/A	Additional operational steps and attention required for precise fabrication	Actively chosen
	Confined configuration of the Optical Telescope Assembly	N/A	Additional operational steps and attention required to detect anomalies	Under-estimated
	Single-point failure verification method	N/A	Additional operational steps and attention required for thorough verification	Under-estimated
MCO	Software using SI units	Deviation in output values	Additional operational steps and attention required to verify units	Unnoticed
	Complex software architecture	N/A (no apparent negative effect on system performance)	Additional operational steps and attention required to detect anomalies	Under-estimated
	Asymmetrical geometry of the spacecraft	Deviation in spacecraft attitude from solar pressure	Additional consideration required to maintain the planned trajectory	Actively chosen
Columbia	Configuration of bipod connections	Decreased material integrity	Additional operational steps required to monitor and inspect the integrity of components	Under-estimated
	Structural properties of wing-edge thermal protection	Decreased thermal and structural capacity	Additional operational steps required to monitor and inspect the integrity of components	Under-estimated
Sydney Opera House	Geometry of the outer shells	N/A (no direct effect on acoustic performance)	Reduced internal volume to accommodate functional requirements	Actively chosen
	Configuration of hall interior installations	Decreased acoustic performance	N/A	Actively chosen
Kansas City Hyatt Regency	Offset hanger rods	Decreased structural capacity	N/A	Unnoticed
	Concealed placement of the walkway beam-rod connections	N/A (no apparent effect on structural integrity)	Additional steps and attention required to detect anomalies	Unnoticed
Charles de Gaulle Airport	Geometry of the outer shell	Decreased structural capacity	Additional steps and attention required to ensure sufficient overall structural integrity	Under-estimated
	Configuration of shell support structures	Decreased structural capacity	N/A	Unnoticed
Algo Centre Mall	Configuration of waterproofing system	Diminished watertightness	N/A	Under-estimated
	Concealed configuration of the roofing structure	N/A (no apparent effect on structural integrity)	Additional operational steps and attention required to detect anomalies	Unnoticed

Case	Design Solutions	Physical Strains	Organizational Strains	Awareness
	Placement of parking on the rooftop	Increased structural load	Additional consideration required to counteract the increased loads	Under-estimated
Minneapolis I-35W	Gusset plate dimensions	Decreased structural capacity	N/A	Unnoticed
	Concealed placement of the gusset plates in the bridge truss	N/A (no apparent effect on structural integrity)	Additional operational steps and attention required to detect anomalies	Under-estimated
	Additional installation of components	Increased structural load	Additional verification required to ensure the structure can maintain its integrity	Actively chosen
Sasago Tunnel	Use of adhesive anchor bolts for ceiling panel support	Progressive loss of structural capacity	Appropriate maintenance plans required to address long-term degradation	Unnoticed
	Concealed configuration of ceiling panels	N/A (no apparent effect on structural integrity)	Additional operational steps and attention required to detect anomalies	Under-estimated
	Designed load distribution of ceiling panels	Decreased structural capacity	N/A	Unnoticed
Arecibo Telescope	Splayed out configuration of cable wire ends	N/A (maximizes structural capacity)	Expertise and high technical skills required to fabricate as designed	Under-estimated
	Concealed configuration of cable-socket components	N/A (necessary for structural integrity)	Additional operational steps and attention required to detect anomalies	Actively chosen
	Safety factor of the cable system	Decreased structural capacity	Additional operational steps and attention required to detect anomalies	Unnoticed
	Use of zinc for sockets supporting cable ends	Progressive loss of structural integrity via zinc flow	Appropriate maintenance plans required to address long-term zinc flow	Unnoticed
	Nonredundant cable configuration	Decreased structural capacity	N/A	Unnoticed
	Additional installation of components	Increased structural load	Additional verification required to ensure the structure can maintain its integrity	Actively chosen

B. Underlying Organizational Factors

Given that some of the physical and organizational strains are intentional and not all strains immediately lead to system failures, we need to consider the factors behind how the strains actually turned into accident pathogens and eventually contributed to the outbreak of failures and accidents. Here, we focus on the contributions of inadequate organizational factors. Human and organizational factors have long been studied and acknowledged as one of the predominant underlying causes of failures in various domains, including aviation accidents,[49] structural failures,[50] and space mission failures.[51] The human factors analysis and classification system (HFACS), originally developed for aviation safety, provides a hierarchical taxonomy to classify various instances of human and organizational factors that contributed to incidents.[52,53] Using the subcategories in the "Organizational influences" category from HFACS, we can attribute the design decisions to issues in resource management, organizational climate, and organizational process.

Looking at the instances of design decisions, we can attribute which organizational factors affected the design-induced strains and turned them into pathogen threads. Table 5 provides the instances of such organizational factors identified in the system failures cases. Design decisions can become part of the failure causation due to both the nature of the design solutions that could induce physical or organizational strains and the inadequate organizational factors that make the strains turn into embedded pathogens.

Table 5. Instances of inadequate organizational factors observed in the accident case set.

Organizational Influence		Instances	Examples of Inadequacies
Resource management	Human resource management	Absence of necessary expertise	Wire fabrication [Arecibo]
		Inadequate allocation of expertise	Design change without acoustic consultation [SOH]
		Incompetence in risk identification	Structural design of concrete shell [CDG]
		Insufficient sharing of knowledge	Long-term material properties [Sasago]
		Insufficient staffing	Monitoring of spacecraft [MCO]
		Loss of historical knowledge	Record of repair history [Sasago]
	Monetary/budget resource management	Insufficient budget allocation	Repair works of water leaks [Algo]
Organizational climate	Organizational structure	Temporary communication structure	Documentation of structural calculations [Minn]
		Lack of communication channels	Quality assurance specifications [HST]
		Multi-level subcontracting structure	Communication of critical design change [KCHR]
		Siloed responsibilities	Upgrade of instruments [Arecibo]
		Structural discontinuity	Mid-project transfer of authority and responsibilities [SOH]
	Organizational culture	Inadequate problem-resolution philosophy	Communication of test results [HST]; Normalization of foam debris [Columbia]
		Blind beliefs/invalid assumptions	Bridge inspection guidelines [Minn]
		Overconfident feasibility	"Operational" view of the experimental vehicle [Columbia]
Organizational operations	Organizational procedures	Ill-defined decision-making procedure	Damage criticality assessment criteria [Columbia]
		Insufficient specification of procedures	Test result review policies [HST]
		Violation of formal procedures	Report of issues and anomalies [MCO]
		Out of the scope of standard procedures	Completion inspection standards [KCHR]
		Lack of formal communication protocol	Communication of original design intent [KCHR]
	Organizational operations	Schedule & workload pressure	Communication of critical design change [KCHR]
		Socioeconomic pressure	Routine inspection plans [Sasago]
		Sub-standard work quality	Inspection of water leaks [Algo]
		Out of the scope of normal operation	Inspection of concrete shell [CDG]
		Improper omission of operation	Bridge load rating prior to opening [Minn]
	Organizational oversight	Lack of holistic supervision	Approval parking configuration [Algo]

IV. Lessons for Space Architects

Through the analysis of failure cases in both construction and spaceflight, we identified the design-induced strains that characterize problematic design decisions and the organizational factors that turn the problems into pathogen threads and embedded pathogens, which, if left unaddressed, will eventually break out as system failures (Figure 2).While limited in number, the current case set shows that the design decisions involving the physical layout of components are the most prevalent, contributing to both structural and nonstructural failures, and that the distinction of local and global design variables does not appear to be presenting significant value, as both are contributing equally to the pathogen threads (Table 3). As we study additional cases, it might be possible to indicate which type of design decisions and strains are more likely to generate pathogen threads so that we can inform space architects of likely strains and consequences by looking up the same type of design decisions made in the past.

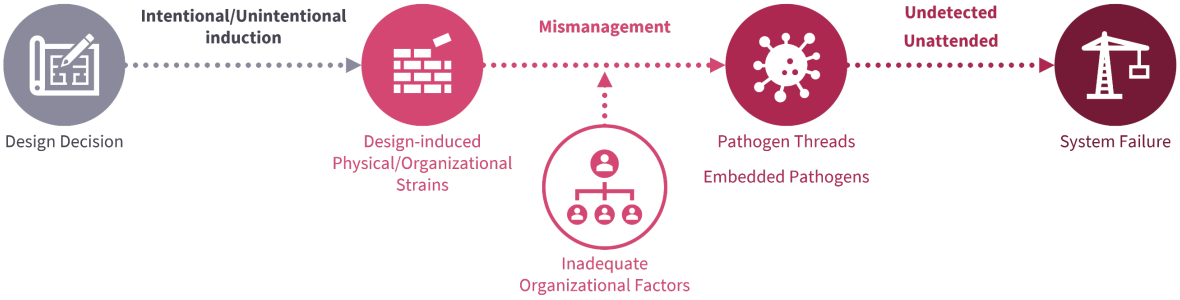

Figure 2. Schematic of incubation of design decisions into system failures.

When we place them in the context of space architecture, our findings underline the importance of being actively aware of the potential physical and organizational strains that can be induced by the design solutions that space architects will choose, and being mindful of the effects of organizational factors in space architecture project organizations, as seemingly safe and harmless design can turn otherwise because of unhealthy organizational settings, or a minor design defect can be amplified into a catastrophic failure through the contributions of defective organizational factors. Applying the types of design variables to space architecture concepts, we can consider the potential strains that could be induced into space architecture projects by prospective design decisions.

Table 6 shows the observed instances of physical and organizational strains induced by the different types of design decisions and lists examples of prospective design decisions of the same types that could induce similar strains in orbital and surface habitats like the Lunar Gateway,[54] Project Olympus,[55] Mars Ice Home,[56] and Hassel's Mars Settlement.[57] For example, the selection of material for regolith-based shell structures for surface habitats (choice of material) could affect long-term structural integrity if the mechanical properties were not understood well (physical strain), and the compositions and characteristics of the material could increase the level of expertise and technical difficulties required to control the quality of on-site fabrication (organizational strain); The placement of environmental control and life support system (ECLSS) components in hidden/hard-to-access locations in the habitat modules (physical layout) would inevitably induce the need of additional operational steps and attention for regular inspection and maintenance (organizational strain); The safety factors (mathematical parameter) would directly dictate the structural capacity of the structure (physical strain), and since the introduction of safety factors in the calculation would likely occur early in the design phase, it could require substantial effort to detect its inadequacy later in the project phase, accompanied by prohibitive costs of correction (organizational strain).

From the discussion of design-induced strains and the inadequate organizational factors, space architects can learn that, in addition to ensuring the removal of design errors and unintended physical strains, they must also be aware of the strains that the design choices would intentionally and unintentionally induce, especially the organizational strains, as some of them are inevitable and others are actively chosen. Particularly, extraterrestrial systems would likely suffer from organizational strains induced by choices of materials and components without sufficient understanding of long-term properties and performance. While the abundance of experience in terrestrial systems has allowed the study and understanding of long-term behaviors of many materials and technologies, the history has also been long enough to expose system failures due to inadequate monitoring of unproven materials or products, as seen in Sasago Tunnel (degradation of anchor bolt adhesives) and Arecibo Telescope (deformation of zinc resulting in cable slips). With the field of space architecture still in its infancy, we can expect to observe many organizational strains stemming from the lack of understanding of long-term behaviors, since many if not most materials, components, and technologies are yet to be tested in the long run.

Table 6. Potential strains induced by prospective design decisions in space architecture projects.

Types of Design Variables		**Observed Instances of Design-Induced Strains**		**Examples of Applicable Design Decisions in Orbital/Surface Habitats**
		Physical	***Organizational***	
Physical layout	**Global**	▪ Decreased performance (structural, acoustic) ▪ Increased load (structural)	▪ Additional operational steps and attention required to detect anomalies ▪ Reduced options to satisfy functional requirements ▪ Additional consideration to counteract design constraints	▪ Geometry of regolith-based shell structures [surface] ▪ Concealed configuration of module foundation structures [surface]
	Local	▪ Decreased performance (structural, watertightness)	▪ Additional operational steps and attention required to detect anomalies ▪ Expertise required for the quality control of fabrication	▪ Configuration of windows (structural weak points) [orbital/surface] ▪ Confined placement of ECLSS components [orbital/surface]
Dimensions	**Local**	▪ Decreased performance (structural)	▪ Additional operational steps and attention required for precise fabrication	▪ Dimensions of module shell beams and stringers [orbital/surface]
Choice of component	**Local**	▪ Progressive loss of performance (structural, thermal)	▪ Appropriate plans required to monitor and address performance degradation	▪ Choice of window sash components [orbital/surface]
Material	**Local**	▪ Progressive loss of performance (structural)	▪ Appropriate plans required to monitor long-term behavior	▪ Material for inflatable modules [orbital/surface] ▪ Material for regolith-based shell structures [surface]
Modification	**Global**	▪ Increased load (structural)	▪ Additional verification required to ensure the structure can maintain its integrity	▪ Additional installation of modules, airlocks, and other instruments [orbital/surface]
Mathematical parameter	**Global**	▪ Decreased performance (structural)	▪ Additional operational steps and attention required to detect anomalies	▪ Designed load distribution of module envelope structure [orbital/surface]
	Local	▪ Deviation in output (numerical)	▪ Additional operational steps and attention required to verify units	▪ Safety factors of module foundation structures [surface]
Software architecture	**Global**	▪ N/A	▪ Additional operational steps and attention required to detect anomalies	▪ Software architecture of power distribution system [orbital/surface]
Process architecture	**Global**	▪ N/A	▪ Additional operational steps and attention required for thorough verification	▪ Quality control method of on-site module installation [surface]

As the primary decision-makers in the design formulation process, space architects, along with other personnel with systems engineering and quality assurance responsibilities, should recognize the consequential implications of such strains. It is then crucial to communicate with the entire project organization about the necessity and criticality of properly managing the strains throughout the development and operation of the system, to realize the implementation of space systems, without defects and failures, that can provide the desired functions and capabilities.

The concept of pathogen threads and design-induced strains presented in this paper can serve as the starting point for further discussions on the quantification and prioritization of the contributions of different design decisions and strains. Furthermore, we can leverage the dataset of inadequacies for deriving and planning key actions to manage the strains and implementing a project-wide mechanism to monitor the proper handling of strains throughout the system lifecycle.

V. Conclusion

The development and implementation of space architecture concepts involve great excitement about addressing novel design challenges and realizing the visionary future of expanding the human presence beyond Earth, but also come with the need for adequate identification and management of various risk factors and technical challenges. To explore the lessons we can learn from previous mistakes, this paper leveraged case studies of real-world system failures in construction and spaceflight projects, extracted the contributing design decisions, and identified the instances of design-induced strains and inadequate organizational factors, which together can create risk-prone project environments where embedded pathogens can flourish. This knowledge base on how design decisions can go wrong provides illustrative guidance for considering the consequences and implications of the prospective design decisions to be made in future space architecture projects.

While we do not intend the sample size of the qualitative case studies to be large enough to present statistical significance, our future work will include additional failure cases with increased diversity and extended scope to enhance the library of relevant design decisions and instances of design-induced strains both physical and organizational. With an extended knowledge base, we can construct potential scenarios of system failures based on the potential design decisions and organizational settings in future projects and derive general principles and recommendations for the successful realization of space architecture concepts.

Space architects, or any decision-makers responsible for the formulation and delivery of design information, need to consider both the implications of the design solutions and the functioning of the project organization that communicates and materializes the design. On top of employing various design-for-safety principles and existing quantitative and qualitative risk identification tools to formulate and select better design alternatives, the discussion presented in this paper underscored the importance of retaining the information about the considerations and decisions behind the design solutions. While the outline of the roles and responsibilities of space architects remain vague, their active engagement throughout the system lifecycle would facilitate the communication and management of design-induced strains necessary to prevent the outbreak of failures down the road and to deliver successful designs that can expand the boundary of human civilization.

References

[1] Scott, M.J., and Antonsson, E.K., “Arrow’s Theorem and Engineering Design Decision Making.” *Research in Engineering Design - Theory, Applications, and Concurrent Engineering*, Vol. 11, No. 4, 1999, pp. 218-228. doi:10.1007/S001630050016/METRICS.

[2] Hansen, C.T., and Andreasen, M.M., “A Mapping of Design Decision-Making.” *Proceedings of DESIGN 2004, the 8th International Design Conference*, 2004, pp. 1409-1418.

[3] Zeiler, W., Savanovic, P., and Quanjel, E., “Design Decision Support for the Conceptual Phase of the Design Process.” *International Association of Societies of Design Research*, 2007.

[4] Zhuang, J., Hu, M., and Mousapour, F., “Value-Driven Design Process: A Systematic Decision-Making Framework Considering Different Attribute Preferences from Multiple Stakeholders.” *Journal of Solar Energy Engineering*, Vol. 139, No. 2, 2017. doi:10.1115/1.4035059/392476.

[5] Matheson, J.E., and Howard, R.A., “An Introduction to Decision Analysis.” In: *The Principles and Applications of Decision Analysis*. Strategic Decisions Group, Menlo Park, CA, 1983, pp. 17-56.

[6] Radford, A.D., and Gero, J.S., “On Optimization in Computer Aided Architectural Design.” *Building and Environment*, Vol. 15, No. 2, 1980, pp. 73-80. doi:10.1016/0360-1323(80)90011-6.

[7] Kwak, M.J., Hong, Y.S., and Cho, N.W., “Eco-Architecture Analysis for End-of-Life Decision Making.” *International Journal of Production Research*, Vol. 47, No. 22, 2009, pp. 6233-6259. doi:10.1080/00207540802175329.

[8] Reason, J., “The Contribution of Latent Human Failures to the Breakdown of Complex Systems.” *Philosophical Transactions of the Royal Society of London Series B*, Vol. 327, No. 1241, 1990, pp. 475-484. doi:10.1098/rstb.1990.0090.

[9] Leveson, N., *Safeware: System Safety and Computers*. Addison-Wesley, 1995.

[10] Reason, J., “Human Error: Models and Management.” *British Medical Journal*, Vol. 320, No. 7237, 2000, pp. 768-770. doi:10.1136/bmj.320.7237.768.

[11] Hollnagel, E., *FRAM, the Functional Resonance Analysis Method: Modelling Complex Socio-Technical Systems*. Ashgate, 2012. doi:10.1201/9781315255071.

[12] Svedung, I., and Rasmussen, J., “Graphic Representation of Accident Scenarios: Mapping System Structure and the Causation of Accidents.” *Safety Science*, Vol. 40, No. 5, 2002, pp. 397-417. doi:10.1016/S0925-7535(00)00036-9.

[13] Leveson, N., “A New Accident Model for Engineering Safer Systems.” *Safety Science*, Vol. 42, No. 4, 2004, pp. 237-270. doi:10.1016/S0925-7535(03)00047-X.

[14] Love, P.E.D., Gunasekaran, A., and Li, H., “Concurrent Engineering: A Strategy for Procuring Construction Projects.” *International Journal of Project Management*, Vol. 16, No. 6, 1998, pp. 375-383. doi:10.1016/S0263-7863(97)00066-5.

[15] Stringer, J., “Operational Research for ‘Multi-Organizations.’” *Journal of the Operational Research Society*, Vol. 18, No. 2, 1967, pp. 105-120. doi:10.1057/jors.1967.23.

[16] Lehtiranta, L., “Risk Perceptions and Approaches in Multi-Organizations: A Research Review 2000-2012.” *International Journal of Project Management*, Vol. 32, No. 4, 2014, pp. 640-653. doi:10.1016/j.ijproman.2013.09.002.

[17] Cherns, A.B., and Bryant, D.T., “Studying the Client’s Role in Construction Management.” *Construction Management and Economics*, Vol. 2, No. 2, 1984, pp. 177-184. doi:10.1080/01446198400000016.

[18] Igarashi, T., and Marais, K., “Construction System Failures: Frame Notation of Project Pathogens and Their Propagation Across Time and System Hierarchy.” *32nd Annual INCOSE International Symposium*, Vol. 32, No. 1, 2022, pp. 419-433. doi:10.1002/IIS2.12940.

[19] *NASA Systems Engineering Handbook*, NASA SP-2016-6105 Rev2, 2016.

[20] Guo, H.L., Li, H., and Skitmore, M., “Life-Cycle Management of Construction Projects Based on Virtual Prototyping Technology.” *Journal of Management in Engineering*, Vol. 26, No. 1, 2010, pp. 41-47. doi:10.1061/(asce)0742-597x(2010)26:1(41).

[21] Igarashi, T., and Marais, K., “Modeling Extraterrestrial Construction System Failures: Lessons Learned and a Framework Based on Terrestrial Construction.” *AIAA SciTech Forum 2022*, 2022. doi:10.2514/6.2022-2492.

[22] Hollnagel, E., *Safety-I and Safety-II: The Past and Future of Safety Management*. Ashgate, 2014.

[23] Allen, L., Angel, J., Roger P., et al., *The Hubble Space Telescope Optical Systems Failure Report*. NASA-TM-103443, 1990.

[24] Jordan, V.L., “Acoustical Design Considerations of the Sydney Opera House.” *Journal and Proceedings of The Royal Society of New South Wales*, Vol. 106, No. 2, 1973, pp. 33-53.

[25] Rodney, G.A., *Hubble Space Telescope: SRM/QA Observations and Lessons Learned*. NASA-TM-105505, 1990.

[26] Mars Climate Orbiter Mishap Investigation Board, *Mars Climate Orbiter Mishap Investigation Board Phase I Report*. 1999.

[27] Mars Climate Orbiter Mishap Investigation Board, *Report on Project Management in NASA by the Mars Climate Orbiter Mishap Investigation Board*. 2000.

[28] Euler, E.A., Jolly, S.D., and Curtis, H.H., “The Failures of the Mars Climate Orbiter and Mars Polar Lander: A Perspective from the People Involved.” *24th Annual AAS Guidance and Control Conference*, 2001.

[29] NASA, *Mars Climate Orbiter Arrival Press Kit*. 1999.

[30] McNamee, J.B., “The 1998 Mars Surveyor Lander and Orbiter Project.” *The Space Congress Proceedings*, Vol. 19, 1998.

[31] Young, T., Arnold, J., Brackey, T., et al., *Mars Program Independent Assessment Team Report*. 2000.

[32] Columbia Accident Investigation Board, *Columbia Accident Investigation Board Report Volume I*. 2003.

[33] Ciannilli, M.A., “Columbia Vehicle History.” NASA, 2023. Accessed March 6, 2024. https://public.ksc.nasa.gov/columbia/columbia-vehicle-history/

[34] External Tank Working Group, “Space Shuttle STS-107 Columbia Accident Investigation External Tank Working Group Final Report—Volume I.” In: *Columbia Accident Investigation Board Report*. Vol IV, 2003, pp. 239-395.

[35] Murray, P., *The Saga of Sydney Opera House: The Dramatic Story of the Design and Construction of the Icon of Modern Australia*. Taylor and Francis, 2003.

[36] Kirkegaard, R.L., Gulsrud, T.E., and McCreery, S., “Acoustics of the Sydney Opera House Concert Hall Part Two: The Acoustician’s Perspective.” *Proceedings of 20th International Congress on Acoustics*, 2010.

[37] Taylor, L., and Claringbold, D., “Acoustics of the Sydney Opera House Concert Hall Part One: The Client’s Perspective.” *Proceedings of the 20th International Congress on Acoustics*, 2010.

[38] Luth, G.P., “Chronology and Context of the Hyatt Regency Collapse.” *Journal of Performance of Constructed Facilities*, Vol. 14, No. 2, 2000, pp. 51-61. doi:10.1061/(ASCE)0887-3828(2000)14:2(51).

[39] Marshall, R.D., Pfrang, E.O., Leyendecker, E. V, and Woodward, K.A., *Investigation of the Kansas City Hyatt Regency Walkways Collapse*. 1982. doi:10.6028/NBS.BSS.143.

[40] Daou, H., Abou Salha, W., Raphael, W., and Chateauneuf, A., “Explanation of the Collapse of Terminal 2E at Roissy–CDG Airport by Nonlinear Deterministic and Reliability Analyses.” *Case Studies in Construction Materials*, Vol. 10, 2019, pp. e00222. doi:10.1016/j.cscm.2019.e00222.

[41] El Kamari, Y., Raphael, W., and Chateauneuf, A., “Reliability Study and Simulation of the Progressive Collapse of Roissy Charles de Gaulle Airport.” *Case Studies in Engineering Failure Analysis*, Vol. 3, 2015, pp. 88-95. doi:10.1016/j.csefa.2015.03.003.

[42] Raphael, W., Faddoul, R., Feghaly, R., and Chateauneuf, A., “Analysis of Roissy Airport Terminal 2E Collapse Using Deterministic and Reliability Assessments.” *Engineering Failure Analysis*, Vol. 20, 2012, pp. 1-8. doi:10.1016/j.engfailanal.2011.10.001.

[43] Bennhold, K., “Cost of Fallen French Terminal Rises.” The New York Times. 2005. Accessed March 20, 2024. https://www.nytimes.com/2005/02/10/business/worldbusiness/cost-of-fallen-french-terminal-rises.html

[44] Bélanger, P.R., *Report of the Elliot Lake Commission of Inquiry*. 2014.

[45] National Transportation Safety Board, *Collapse of I-35W Highway Bridge: Minneapolis, Minnesota, August 1, 2007*, NTSB/HAR-08/03, 2008.

[46] Konda, T., Nishimura, K., Niwa, J., et al., *Tonneru tenjo-ban no rakka-jiko ni kansuru chosa-kento-iinkai hokokusho [Report of the Research & Examination Committee for Tunnel Ceiling Collapse Incident (Japanese)].* 2013.

[47] Ministry of Land, Infrastructure, Transport and Tourism of Japan, *Sasago Tunnel Ceiling Collapse on the Chuo Expressway (Sequence of Events and Countermeasures).* 2013. Accessed November 22, 2022. https://www.mlit.go.jp/road/road_e/s3_maintenance.html

[48] Abruzzo, J., Cao, L., and Ghisbain, P., *Arecibo Telescope Collapse Forensic Investigation*. Thornton Tomasetti, 2022.

[49] Wiegmann, D., Faaborg, T., Boquet, A., Detwiler, C., Holocomb, K., and Shappell, S., *Human Error and General Aviation Accidents: A Comprehensive, Fine-Grained Analysis Using HFACS*. DOT/FAA/AM-05/24, 2005.

[50] Ren, X., Terwel, K.C., and van Gelder, P.H.A.J.M., "Human and Organizational Factors Influencing Structural Safety: A Review." *Structural Safety*, Vol. 107, 2024, 102407. doi:10.1016/j.strusafe.2023.102407.

[51] Newman, J.S., "Failure-Space: A Systems Engineering Look at 50 Space System Failures." *Acta Astronautica*, Vol. 48, No. 5-12, 2001, pp. 517-527. doi:10.1016/S0094-5765(01)00071-6.

[52] Shappell, S., Detwiler, C., Holcomb, K., Hackworth, C., Boquet, A., and Wiegmann, D.A., "Human Error and Commercial Aviation Accidents: An Analysis Using the Human Factors Analysis and Classification System." *Human Factors*, Vol. 49, No. 2, 2007, pp. 227-242. doi:10.1518/001872007X312469.

[53] Salmon, P.M., Cornelissen, M., and Trotter, M.J., "Systems-Based Accident Analysis Methods: A Comparison of Accimap, HFACS, and STAMP." *Safety Science*, Vol. 50, No. 4, 2012, pp. 1158-1170. doi:10.1016/j.ssci.2011.11.009.

[54] Connell, D., "Gateway, NASA" 2024. Accessed February 21, 2024. https://www.nasa.gov/mission/gateway/

[55] ICON, "Project Olympus," 2023. Accessed February 21, 2024. https://www.iconbuild.com/projects/project-olympus

[56] Space Exploration Architecture, "Mars Ice Home," Accessed February 21, 2024. http://www.spacexarch.com/mars-ice-home

[57] Hassell, "NASA 3D Printed Habitat Challenge," Accessed February 21, 2024. https://www.hassellstudio.com/project/nasa-3d-printed-habitat-challenge