Designing for Usability in Modular Space Habitats: A Space Syntax Perspective

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Abstract

As human ambitions turn toward establishing settlements on the Moon and Mars, the architectural and spatial configuration of these habitats has received comparatively little attention relative to their engineering systems. This paper explores the spatial configuration and architectural usability of modular extraterrestrial settlements, focusing on their potential growth, vulnerability, and navigability. Drawing from architectural theory and Space Syntax methods, we propose a novel framework for evaluating habitat layouts based on two key metrics: intelligibility and vulnerability. Using a combination of analytic tools and simulations – including adapted versions of the "beady-ring" growth model – we assess both small-scale configurations and larger aggregated settlements. We introduce a new vulnerability metric based on spatial types and configurational redundancy, allowing us to quantify how module failure can fragment a habitat system. Our findings confirm five core hypotheses, including the inverse relationship between structural resilience and spatial intelligibility as modular settlements scale, and the applicability of Space Syntax theories to non-terrestrial environments. We argue that without deliberate planning, accretive modular growth leads to declining usability, and we advocate for intentional and informed planning interventions, to sustain human-centered design at larger scales. This work provides a foundational methodology for evaluating and guiding the spatial evolution of off-world settlements.

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Keywords and phrases Space Syntax, architectural usability, intelligibility, lunar habitats, Mars habitats, modular design, human-centered computer simulation

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1 Introduction

There is a growing interest in the prospect of human settlements on the Moon and Mars. Evidence for this surge in attention can be found across multiple domains: in media coverage of high-profile proposals, such as Elon Musk's vision of a million-person colony on Mars [12]; in a steady increase in academic publications; in Google Trends data since 2004; and in the proliferation of policy documents, conferences, and design competitions [7] addressing

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extra-terrestrial habitation. This growing discourse is mirrored by an expansion of scientific research into the technical challenges such settlements might face. For instance, a recent systematic review [10] considered over seventy studies focused on lunar and Martian regolith simulants for plant growth, underscoring the significant interest in sustaining life off-world. However, while technical issues such as agriculture, radiation shielding, and thermal control dominate much of the literature, fewer studies explore the spatial configuration of these habitats – and the usability and vulnerability implications of their growth over time. Both these concepts will be defined in the next section.

When it comes to imagining how a lunar or Martian habitat might be designed and function, most visions converge around a common approach: modularity. As early as 1989, NASA reports described habitat subsystems as including *"life support and thermal control systems, pressure vessels and internal structure, communications and information management systems, and interior outfitting,"* and emphasized that *"the constructible habitat has egress hatch ports for connection . . . "* [3]. Subsequent designs have largely followed this logic, favoring a modular "stick-and-ball" approach (to borrow a phrase from chemistry), in which domed or cylindrical habitation units are connected incrementally. Some proposals are single-storied, others multi-level; some are subsurface, fully or partially regolith-covered; but the principle of accretive modularity remains a frequently shared constant.

In the early stages, a base is likely to begin with a single habitat with additional modules delivered on subsequent missions. Over time, and with increased functionality, such a base may reach or exceed the scale of the International Space Station, or current Antarctic research settlements. While in-situ construction methods are anticipated, most projections assume standardized interfaces and metrics across modules. What this implies is a spatial configuration that evolves incrementally – often unpredictably – with modules added as needed rather than through comprehensive master-planning.

Coming from a combined background in architecture and human-computer interaction, the authors of this paper argue that current visions of modular habitat-systems are predominantly shaped by engineering-driven definitions of utility and function. While these designs address essential environmental and mechanical needs, they often overlook the spatial, perceptual, and experiential dimensions that are fundamental to architecture. We propose a layered model of habitat usability and functionality in which higher-order qualities – such as legibility, comfort, spatial resilience, and navigability – are dependent on the successful resolution of more basic technical challenges (Figure 1). This framework underscores the need to treat spatial configuration not as an afterthought, but as a critical component of successful design.

We suggest that after meeting basic engineering and survival functions (shelter, safety, and so forth), the next most critical task is to solve – or at least balance – the spatial configurational functions (Layer II of the pyramid). It is this second layer that is most directly impacted by the challenge of evolving, sprawling, accretive growth. Our paper seeks to address the often-overlooked importance of this configurative level of modular settlement design, and to apply established methods for examining urban spatial complexity to the outcomes of their development over time.

Many of the largest proposed habitat designs remain relatively "simple" in spatial terms, in that they function – and are often conceived – as singular buildings rather than as true settlements [9][28]. We argue that a structured method for scaling complexity from individual habitats to larger, interconnected settlements – while maintaining acceptable architectural usability – is currently lacking. In response, we propose a novel habitat vulnerability measure, based on simple spatial types and their configurational redundancy, that quantifies the usability impact of a single module loss. Vulnerability is here defined both as a local risk – the configurational consequence of losing an individual module – and as a global metric of systemic resilience.

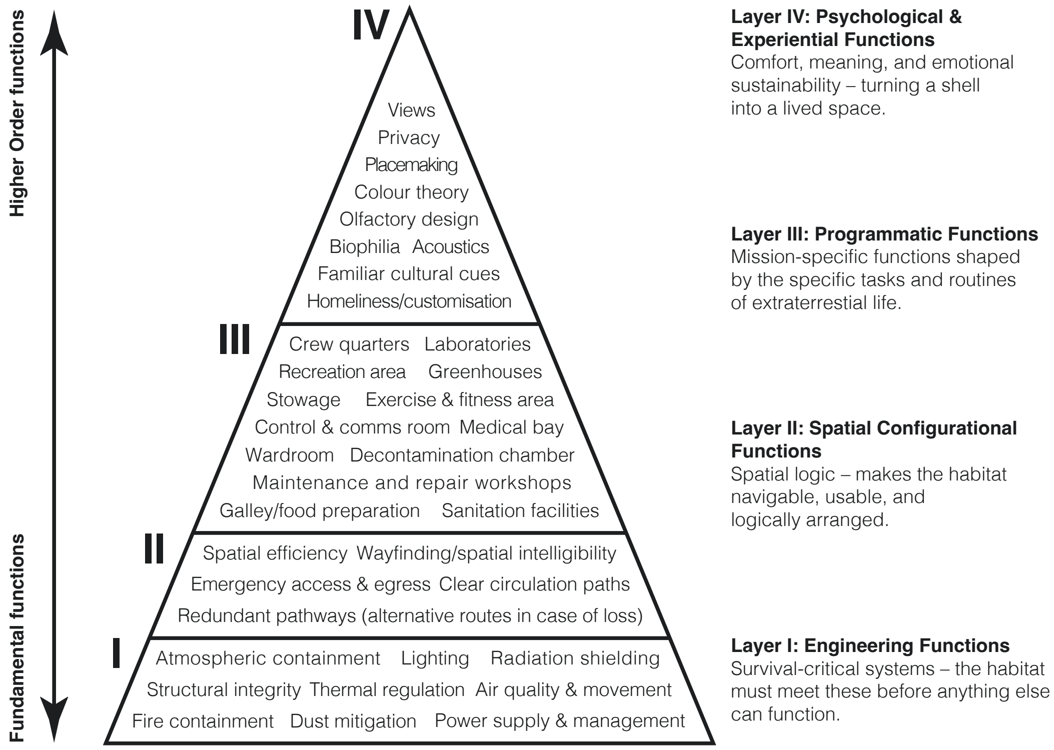

Figure 1 A functional hierarchy of extraterrestrial habitat architecture (after Hillier's theory of generic building function [14]). Note this is an indicative rather than exhaustive list of functions.

This work is guided by the following hypotheses, which are dependent on two key concepts, which we use extensively in this paper: *intelligibility* and *usability* which we will first define, before presenting the hypotheses. Intelligibility objectively measures how maze-like or confusing a layout is likely to be [14] and has been predictive of people becoming lost in complex environments. This leads to our definition of *habitat usability*, which we adopt from Krukar et al. [21] in which they present a formal model for understanding usability and user experience in an architectural context. They define a usable building one which is *"understood, learned [or learnable] and liked by their users, so they are able to do what they want, or need, to do effectively, efficiently and with satisfaction"*. We suggest that modular habitats must adhere to these principles to be considered *usable* and that *"learn[ability]"* is simply intelligibility.

- **H1** As simple, modular habitats aggregate beyond a certain size, intelligibility and usability will decrease without intentional and informed planning.
- **H2** Aggregations of modular habitats will have inherent vulnerabilities that can be captured through a combination of spatial and graph-theoretic analyses, providing a new measure of habitat vulnerability.
- **H3** As habitat-settlements increase in size, habitat vulnerability will naturally tend to decrease.
- **H4** Space Syntax theories and analytic methods, established in architecture, urban and built environment disciplines, can be applied to investigate both habitat vulnerability and habitat usability.
- **H5** For habitats to be effectively scaled up, from building-scale to small settlement-scale to city-scale, a strong theoretic basis for planning growth is required. [17]

Our paper is unique in applying Space Syntax methods and theories, currently used in architecture and urban planning (Section 2.2), to extraterrestrial settlements. In so doing, we demonstrate how modular habitats, as they aggregate and evolve into larger settlements, must be understood not only as technical systems but also as spatial configurational ones, and that their design must address both technical and spatial requirements.

2 Background and literature review

In this section, we will briefly introduce different types of habitat designs, establish how large a settlement is likely to grow, and also introduce the relevant Space Syntax concepts that can be applied to the analysis of such aggregations of habitats or settlements.

2.1 Modularity and existing habitat designs

As mentioned above, NASA's descriptions of habitat subsystems are focused primarily (and understandably) on the functional [3][5][4]. The consensus seems to be that early settlements will most likely consist of modular habitats linked together, via pressurized passages or tunnels, to form larger aggregations [13]. The modules being linked can be sorted into three sub-categories; hard-shell modules; inflatable or expandable habitats (essentially pressurized structures with their internal volume increasing after deployment); and lastly, structures made of in-situ resources (ISRU). These are termed classes-I, II and III respectively [19]. Prototype examples of class-I include the Habot module (habitat + robot), a pressured rigid vessel (with the ability to move) and a basic module diameter of 3.75m [6]. The Habot comes in multiple different types, with varying pressure port angles, which is of significance when considering layout possibilities.

Prototype examples of class-II include the "planetary surface habitat and airlock unit", a 3.65m diameter inflatable fabric structure [13] and the MB10 habitat [28], a three-storey inflatable structure which should reach a diameter of 26m when fully deployed. In another paper [28], Sinn presents a hypothesized aggregation of 19 such units in a densely packed honeycomb arrangement. Finally, the NASA TransHab project describes a hybrid type module combining a rigid core and inflatable exterior. It provides a four-storey, 3.35m wide inflatable habitat [18]. For spherical modules, Vogler [29] suggests that 4.0m diameter should be the minimum size. It appears that most deployable units are initially conceived of as being between 3m-4m in diameter. Class-III examples can be built using a number of construction methods applied to the ISRU, including 3D printing and brick-making [20][31][30].

All of the above examples permit a reconfigurable aggregation of modules. We have based our simulations on the Habot module, as it seems the best documented in terms of the range of different module-types and as it offers a variety of connector-layouts. Our next challenge was to consider how large an extraterrestrial city might reasonably be. Outside of the rich world of science fiction, we have struggled to find any considered discussion of how expansive an aggregation of modules might ultimately become. Pabila [26] suggests that they may expand to fill entire craters on Mars: *"The natural shape of the impact crater creates predetermined sized cities, or states that would spread to fill the crater."* Beyond the latter, some clue might be found in a presentation by Elon Musk in 2017 when he presented an artists' visualization of what a Martian city might look like [25] (Figure 2).

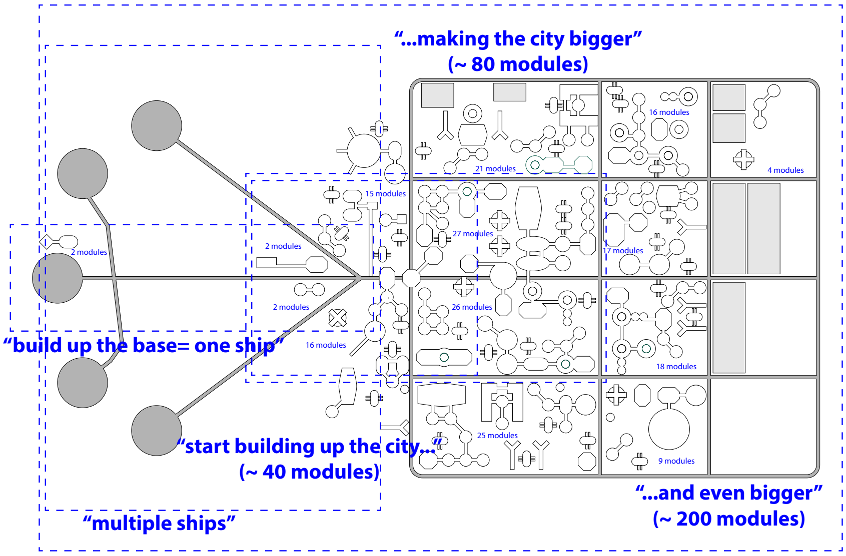

Figure 2 Visualization of Musk's impression of the growth stages of a Martian city, taken from his presentation at the International Astronautical Conference (IAC) 2017 at Adelaide [25]. The superimposed text are annotated quotes from his talk, showing that his vision of a "bigger city" seems to approximate 200 separate modules/habitats.

Setting aside the physical dimensions of the modules in Musk's presentation for the time being, a simple count of the number of modules at each stage of growth provides us with some insights. The settlement's initial phase expands from "one ship" to 40 modules. Expansion stage two doubles the size to 80 modules, whilst the latter "city-state" is depicted as reaching 200 modules. Notably, not all modules are shown as being physically connected, although it is reasonable to assume the presence of subterranean tunnels, or established external pathways between proximal airlocks. Given the lack of any other data, we have decided to simulate habitat aggregations for up to 200 modules. Such an approach captures the early-stage architectural level challenges of settlement growth and configuration, and as such helps to identify key architectural constraints and risks that any such habitat is likely to face in its more vulnerable formative years.

2.2 Relevant Space Syntax concepts

To better understand the growth of such extraterrestrial settlements, we can turn to architectural and urban theories such as Space Syntax. Space Syntax is a framework of architectural theories, spatial representations, analytic methods and software tools, primarily developed at University College London from the 1970s onward by Bill Hillier and colleagues. It seeks to understand the relationships between spatial configurations found in the built environment and people's use of, movement through and social interactions within them [15]. Space Syntax tools and methods are widely applied across different scales from simple to complex buildings, neighborhoods and small settlements, through to large cities and geographic regions.

Fundamentally, Space Syntax methods decompose any built environment into different types of spatial representations or "primitives," typically either convex spaces (spaces containing only mutually visible location pairs [15]), axial lines (longest lines of sight/movement, [27]), or isovists (visibility fields [1][23][24]). These spatial units are then typically represented as graphs, with spaces becoming nodes and edges representing spatial relations such as adjacency, accessibility, and/or visibility. This approach allows the extraction of graph-based metrics, many of which have been shown to correlate with observed use or behavior, such as occupancy rates, pedestrian flow [16], getting lost [8], and architectural function. Whilst a comprehensive review of Space Syntax is beyond the scope of our paper, we use a selection of Space Syntax concepts: Hillier's space types; isovist field analyses and intelligibility; and "beady-ring" settlements. Below we briefly explain each in turn, and discuss how they are relevant to the modeling and analysis of aggregations of space habitats.

2.2.1 Hillier's space types

In this paper, we introduce (and extend) Hillier's concepts of *a*-, *b*-, *c*-, and *d*-space types [14]. He developed these classifications to distinguish connected spaces within a spatial system based on their contributions to connectivity, function, and movement. An a-space is a space with a single link or a dead end. *b*-spaces contain more than one link and are part of tree-like sub-systems. A *c*-space has more than one link and lies on a single ring or loop of circulation. Finally, a *d*-space must have more than two links and forms part of at least two overlapping rings. Importantly for our work, Hillier's definitions (Table 1) are derived from a graph-based theorizing of how the removal of each type affects the overall spatial network. In short, these classifications reflect the potential of each space to fragment a system's configuration.

Table 1 Definitions of space-link types, their roles, and the impact of their removal.

Type	Definition	Role in System	Impact of Removal
a-space	A space with a single link – a dead end.	Terminal point with no through-movement.	No effect on connectivity; system size reduced.
b-space	More than one link, part of a tree-like sub-system.	Local connector providing access to dead ends.	Removal fragments system; severity depends on node degree.
c-space	More than one link, part of a single ring.	Local integrator increasing local intelligibility.	Ring collapses into tree; no full fragmentation.
d-space	More than two links, part of overlapping rings.	Global connector maintaining system-wide integration.	High impact; may reduce redundancy and increase depth.

Although not explicitly conceived with settlement vulnerability in mind, Hillier's framework implicitly begins to capture it; yet it lacks the necessary precision for assessing functional vulnerability in complex, modular systems such as space habitats. In the course of our work, it became clear that the removal of certain *b*-, *c*-, and *d*-spaces had a greater impact on the resultant/remaining spatial network than others. Not all spaces of a given type are equal; and so, a distinguishing sub-categorization of Hillier's original definitions became necessary.

We term these special-case subsets b^*-, c^*-, and d^*-spaces, and collectively refer to them as *star-hub spaces*. In each case, the * distinction reflects the addition of a branch connector that does not alter the base classification of the space, but significantly increases the degree of system fragmentation that would result from its removal. These sub-classifications are defined as follows:

- A b^*-space is a *critical tree connector* – a key branching point in a tree configuration, whose removal causes the system to fragment into more than two parts.
- A c^*-space is a *critical ring connector*.
- A d^*-space is a *critical multi-ring connector*, where the space links multiple rings or ring-tree interfaces, meaning that their removal would result in widespread disconnection or potential system failure.

Finally, as we began testing habitat layouts, we identified an entirely new spatial category. This type is similar in form to a *b*-space, in that it has more than one link and exists within a tree configuration – but rather than accessing a dead end, it serves to connect two or more ring configurations. In doing so, it acts as an essential bridge within the overall configuration. We therefore classify it as an *e*-space (or *essential space*) and its more critical variant as an e^*-space. This particular spatial type appears especially relevant to the challenges of complex extra-terrestrial settlement design and system vulnerability. In summary, it is clear that Hillier's taxonomy of space types has potential to become highly useful for extraterrestrial settlement design analysis, despite not having been conceived with such an application in mind.

2.2.2 Isovist fields, integration, and intelligibility

An isovist represents the geometric bounds of space directly visible from a single location, providing a simple unit of spatial experience [1]. From that unit a number of geometric and relational metrics can be extracted [2]. If isovists are calculated throughout a spatial system (typically but not exclusively represented in plan form), their visual links and overlaps can be used to form dense sets of data. Such fields (commonly visualized as colored spectra) describe both locally experiential qualities and broader spatial relations in the system. Whilst numerous Space Syntax measures can be developed in the above way, two have particular value for our study. The first, *integration* ([15][23]), is a relativized "centrality" measure that reveals the visual depth structure of a spatial network. While integration values are identified on a per-node basis the second numeric measure is the system wide one of *intelligibility.* This is the correlation between integration and spatial connectivity (how many other spaces – in this case an isovist – intersects or overlaps; in the special case of isovists this is also equivalent to isovist area).

2.2.3 "Beady-ring" settlements

Hillier and Hanson identified the form of "beady rings" [15] when analyzing small vernacular settlements which seemed organized around an irregular ring street and resembling beads on string. They observed that it had arisen by an accumulative process of small-scale decisions which was amenable to simulation. The subsequent beady-ring algorithm simulates these small settlements through an aggregation process of sequentially placing a dyad-pair of "building+connecting space" such that all new spaces *must* adjoin an existing space. Simulations of this process produced settlements resembling the settlements they had studied. In this paper we utilize a modified version of the beady-ring simulation to simulate the growth of extraterrestrial habitat settlements.

3 Methodology

3.1 Replication of "Habot" configurations

We began by redrawing 25 module configurations from Cohen [6], using his layouts as a basis for a broader analysis of modular systems (Figure 3). These include a variety of connection types and pressurized port arrangements. We analyzed each layout for the distribution of Hillier's space types (*a*-, *b*-, *c*-, *d*-), our new critical space types (b^*, c^*, d^*, e, e^*), and the number of circulation rings. We also used the *Isovists app* [24][23][22] to calculate the *integration* and *intelligibility* values, establishing a baseline for spatial usability. A new vulnerability measure was also calculated.

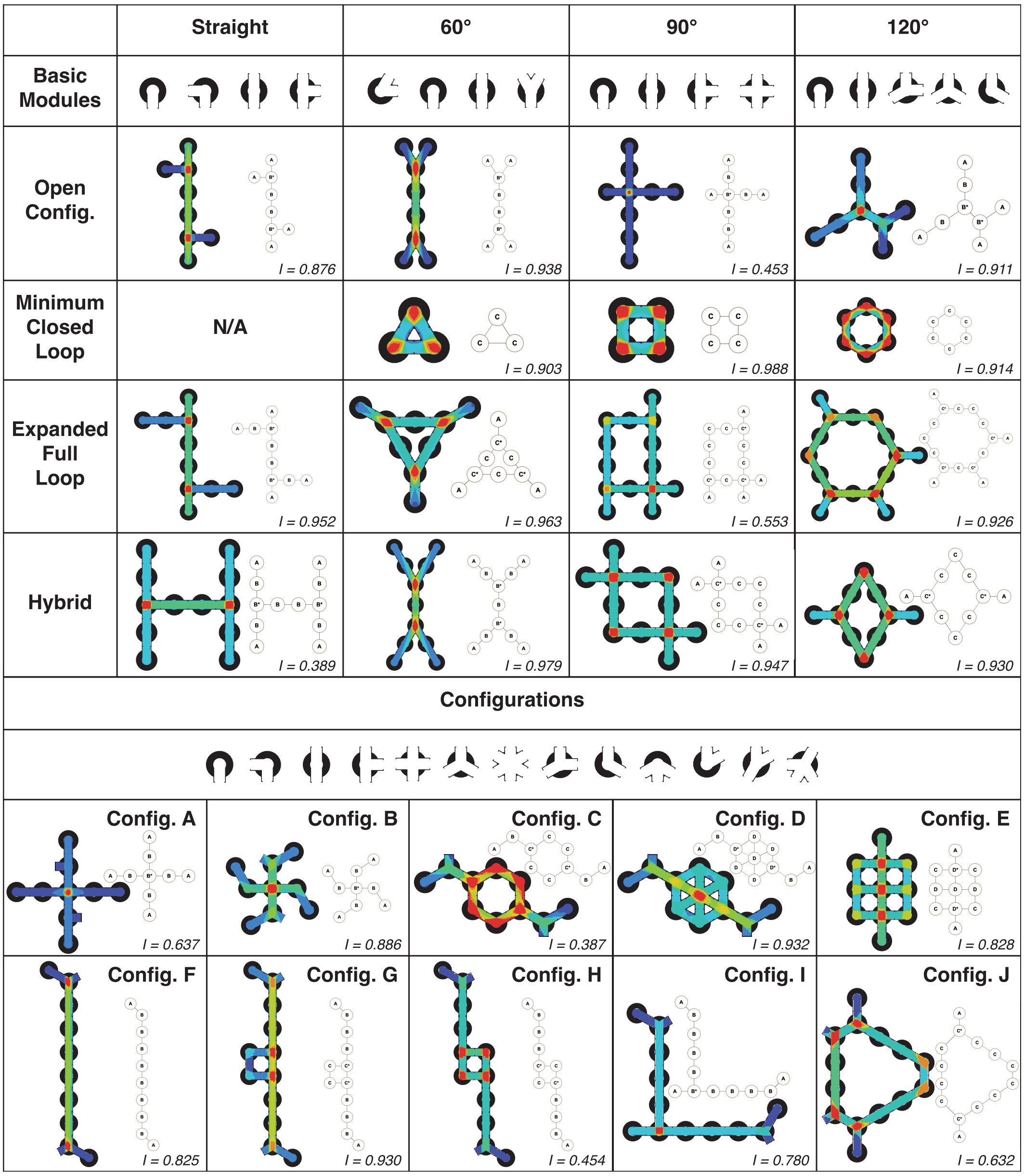

Figure 3 25 Habot configurations, based on Cohen's figures 10 (top) and 12 (bottom) [6] and colored according to isovist field measure of *integration* (red = highly integrated; blue = segregated). The space-types are also indicated in a space-type diagram along with the *intelligibility* score (*I=0.XXX*) value for each configuration. The higher the intelligibility value the less confusing and maze-like the layout – min = 0 and max = 1. (N.b. the classifications of "straight" versus "90°" were used in the original paper [6] and we decided to retain these terms for ease of comparison even if the distinction between them is somewhat unclear.)

3.2 Simulating habitat larger habitat settlements and complexity

To test our theory, we simulated four large settlements of 75, 100, 150, and 200 modules using an adapted version of Hillier and Hanson's "beady ring" algorithm, based on habitat-connector compatibility rules. In each case, modules were placed, by the software, in a semi-random order but constrained to connect only to available ports on previously placed habitats, reflecting the opportunistic but rule-governed nature of accretive growth. These were exported as vector-based plans (.dxf) and analyzed in the *Isovists app* [24][23][22] to calculate integration and intelligibility, as well as the distribution of Hillier's original plus new critical space types (a-, b-, c-, d-, e, b^*, c^*, d^* and e^*). We then generated an additional 25 large settlements, each containing 100 habitats, in GraphML format, unsuitable for isovist-based field analysis, but ideal for calculating the distribution of space types and vulnerability scores (Section 3.3).

3.3 Measuring "vulnerability"

The vulnerability measure analysis was applied to all 29 city-scale configurations (as well as to the original 25 small settlements). Next, we developed a new metric for habitat vulnerability to quantify and compare the inherent resilience of settlement configurations. We define vulnerability at two levels: *local vulnerability*, which assesses the impact of the loss of access to each individual module (due to pressure loss, maintenance, contamination, repair, and so forth); and *global (or systemic) vulnerability*, an evaluation of the overall resilience of the whole system. Each metric can be considered in absolute terms, although we suggest normalizing global vulnerability by the total number of modules in the system.

To calculate the true vulnerability of a settlement configuration, we begin by identifying all habitats whose removal would split the settlement into two or more disconnected parts. These include every b-space, b^*-space, c^*-space, d^*-space, and any extended categories such as e- and e^*-spaces. a-spaces (single-connection dead ends) are excluded, as their isolation is trivial and expected; the same applies to ordinary c- and d-spaces which are considered only when they act as structural connectors (their starred variants).

We then subject *every* habitat – critical or otherwise – to a uniform random-failure test. For each habitat, (h), containing (N) modules we temporarily remove it from the settlement and record the size of the largest surviving, disconnected section and then normalize by the remaining settlement size $(N-1)$ or (L) [11]. The space-type categories decide whether $(L(h)=1)$ (for non-splitting a-, c-, d-spaces) or $(L(h)<1)$ (for b-, b^*-, c^*-, d^*-, e-, e^*-spaces), so their structural role is fully embedded in the calculation. Averaging those scores over all (N) habitats yields the expected post-failure connectivity. In the two analytically tractable extremes – a perfect ring and an infinitely long line – the expected vulnerability is 0 and 0.25, respectively. Multiplying this by 4 therefore stretches the range to [0,1] and anchors the scale at "perfectly robust" (ring) and "maximally fragile" (path). The final vulnerability score is:

$$V = 4 - \frac{4}{N}\sum \frac{\text{(size of the largest disconnected section)}}{N-1} \tag{1}$$

High global vulnerability values indicate that significant portions of a habitat-system are vulnerable to fragmentation and configurational collapse if key nodes are removed or blocked. In this way, the measure directly reflects a settlement's configurational fragility. Conversely, low values would indicate a degree of configurational resilience. Similarly, high local vulnerability values identify critical modules within the whole system, and vice versa.

4 Results

4.1 Small settlements (Habot configurations)

Figure 3 shows the results of analyzing Cohen's 25 Habot configurations [6] and the location of *a*-, *b*-, *c*-, *d*-, *e*-, and the "star hub" space-type modules. Navigable space has been colored according to *integration* – a necessary computational stage towards calculating intelligibility. High-integration spaces are shown in red, with the spectrum shifting through green to blue for lower-integration spaces. We also present the resultant *intelligibility* values for each configuration (the higher the value, the less confusing and less maze-like the layout).

Figure 4 shows the number and proportion of *a*-, *b*-, *c*-, and *d*-space types in the original Habot configurations (Section 2.2.1) It is clear that a high proportion of some space types contributes to an inherent vulnerability of the layout. We also calculated the number of rings (also known as cycles in graph theory), and counted the number of independent rings, nested rings, and total rings in each layout. A ring in a layout contributes to the redundancy of that layout: if a module forming part of a ring becomes unusable (due to damage, contamination, repair, blow-out, depressurization, etc.), the rest of the modules can still be reached without passing through the non-functioning module. This continuity of space is important for the circulation of people and life support.

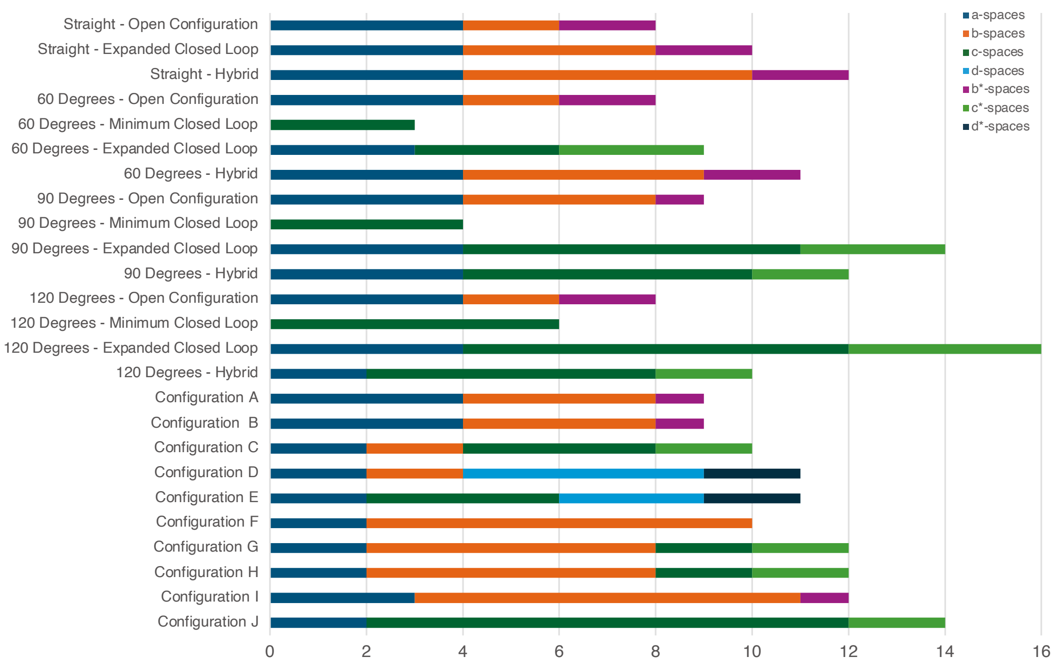

Figure 4 Number and proportion of constituent space types in the 25 Cohen configurations.

For independent rings, 56% of Cohen's layouts contained at least one ring, with the number of rings ranging from 1 to 6. Only 2 layouts contained nested rings, with the highest number being 15 total nested rings. Finally, we calculated the resultant *vulnerability* score for each small configuration, as shown in Table 2.

Table 2 Vulnerability scores (0 = the least and 1 = the most vulnerable layouts) for 25 small habitat configurations.

Name of configuration	Vulnerable Habitats	Total Habitats	Vulnerability Score
Straight – Open Configuration	10	8	0.71
Straight – Expanded Closed Loop	16	10	0.71
Straight – Hybrid	14	12	0.46
60 Degrees – Open Configuration	10	8	0.71
60 Degrees – Minimum Closed Loop	0	3	0.00
60 Degrees – Expanded Full Loop	3	9	0.17
60 Degrees – Hybrid	9	11	0.36
90 Degrees – Open Configuration	10	9	0.56
90 Degrees – Minimum Closed Loop	0	4	0.00
90 Degrees – Expanded Full Loop	6	14	0.09
90 Degrees – Hybrid	4	12	0.12
120 Degrees – Open Configuration	8	8	0.57
120 Degrees – Minimum Closed Loop	0	6	0.00
120 Degrees – Expanded Full Loop	4	16	0.07
120 Degrees – Hybrid	2	10	0.09
Configuration A	10	9	0.56
Configuration B	10	9	0.56
Configuration C	6	10	0.20
Configuration D	6	11	0.22
Configuration E	2	11	0.15
Configuration F	20	10	0.89
Configuration G	8	12	0.61
Configuration H	8	12	0.61
Configuration I	26	12	0.79
Configuration J	2	14	0.04

4.2 Habitat city simulations

Examples of the results of the "beady-ring" habitat growth simulation, and distribution of space types, can be seen in Figure 5. The distribution of the space types in the simulated cities differs from those in the smaller configurations (Figure 4). For the larger settlements, b-spaces, b^*-spaces, c^*-spaces, and d^*-spaces were the least commonly occurring space types, while a-spaces and c-spaces were significantly more prevalent, reflecting the accretive nature of large-scale growth. To test this further, we generated an additional 25 simulated city layouts (in GraphML format only) each consisting of N=100 habitats. We determined the number of different space types for each layout. For these additional, simulated settlements, the most frequently occurring space types were c-spaces (spaces on a single ring) and a-spaces (the ends of linear sequences). These formed, on average, 22% and 21% of all habitats, respectively. In the middle of the distribution were the d-spaces (spaces on multiple rings) and b-spaces (two-connector spaces as part of tree-like subsystems), each of which constituted 16% of the spaces. The least frequently occurring spaces were the *star-hub types* – c^*-spaces, b^*-spaces, d^*-spaces, and e^*-spaces – the configurationally critical space in the event of failure. They represented 12%, 8%, and 5% of all large-scale habitats, respectively. The new e-spaces and e^*-spaces typically constituted $< 1\%$ of habitats.

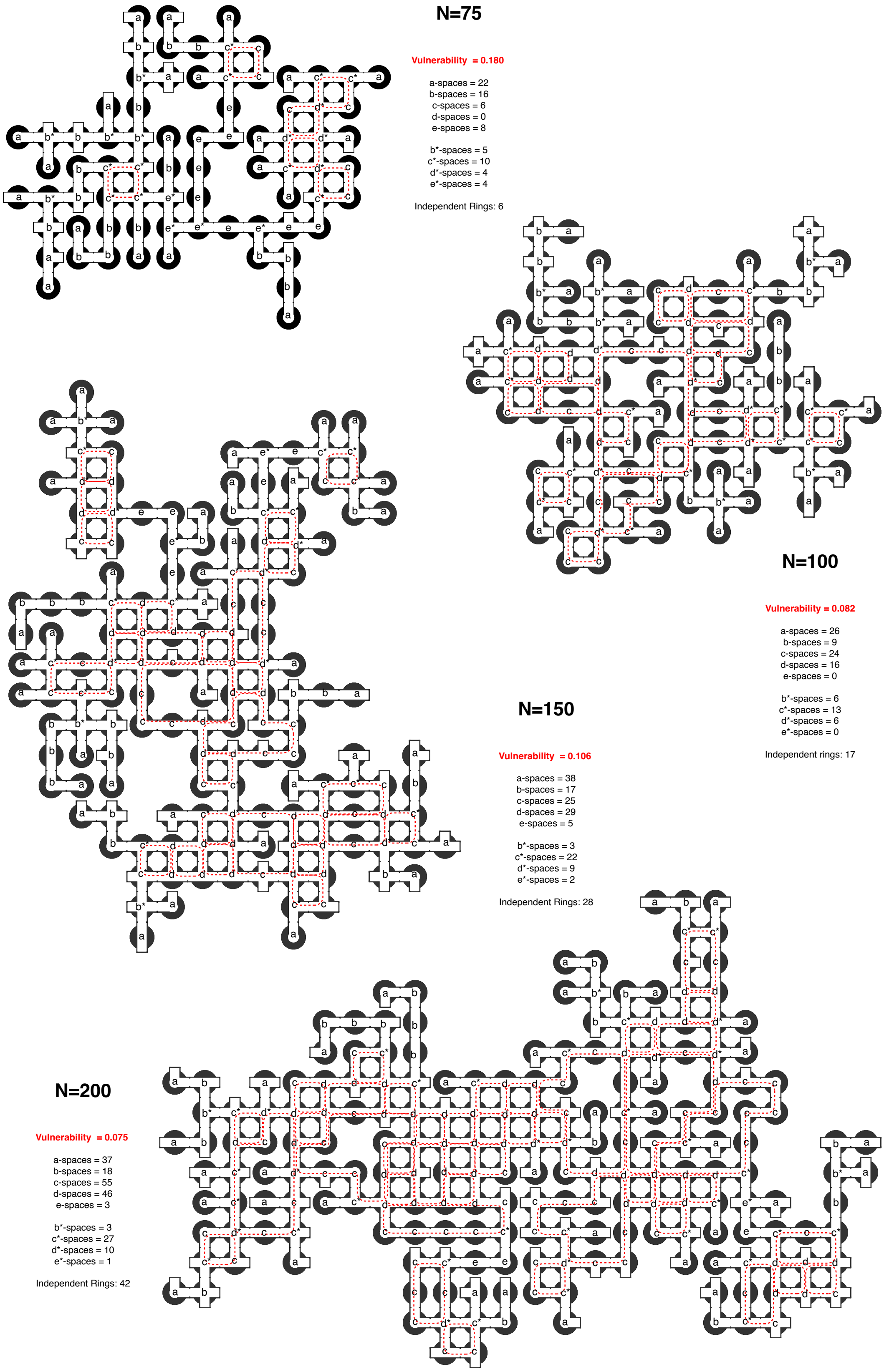

Figure 5 Four habitat settlements (N=75, N=100, N=150 and N-200 habitats) generated using a modified "beady-ring" algorithm. Space-types are shown superimposed on the habitats and circulation rings are indicated by red dotted lines. (N.b. the values in this figure are true *only* for these specific example layouts and are not intended to be representative of all settlements of the same size.)

The *intelligibility* scores of the settlements (a measure of how confusing or maze-like a settlement is) are markedly lower than those of the 25 Cohen small layouts. For $N = 75$, intelligibility is $I = 0.336$; for $N = 100$, $I = 0.686$; for $N = 150$, $I = 0.302$; and for $N = 200$, $I = 0.467$. These four simulated "beady-ring" layouts have an average intelligibility of $I = 0.448$. Compare this value to the 25 Cohen layouts, which have a mean intelligibility of $I = 0.797$, which can be interpreted as "highly intelligible" and also notably higher than the intelligibility of the larger settlements (Figure 5). (As a general heuristic, $I < 0.500$ may be interpreted as indicating a maze-like and confusing configuration.)

The *vulnerability* scores of the four simulated cities are: for N=75 vulnerability is 0.180; for N=100 vulnerability is 0.082; for N=150 vulnerability is 0.106; for N=200 vulnerability is 0.075. On average, the 25 Cohen layouts have a mean vulnerability score of 0.291 which is interpreted as being moderate (excluding the perfect rings, which by definition have a V of 0.000, the mean vulnerability is 0.419 (more vulnerable) and a standard deviation of 0.291. For the four large, simulated beady-ring layouts (Figure 5), the mean vulnerability score is 0.111. The average vulnerability score across all 25 additional GraphML habitats (N = 100) is 0.342 and also less vulnerable than the 25 Cohen layouts. If we plot all 54 vulnerability scores (25 Cohen layouts + 25 GraphML simulations + 4 large settlements (Figure 5)) against their settlement size (i.e. total number of habitats) simple linear fit gives a coefficient of determination: $R^2 = 0.294$). Thus, only about 29% of the variance in vulnerability is explained by the size of the settlement alone; the remaining 71% depends on the mix of habitat/space types rather than on the total habitat count.

5 Discussion

Validating the beady-ring simulation approach

The adapted "beady-ring" algorithm proved successful in generating large-scale modular settlement configurations with realistic accretive characteristics. By applying modified habitat-connector compatibility rules, the simulation was able to replicate the organic growth dynamics typical of extraterrestrial modular habitats and allow meaningful spatial analysis. These simulations provided a valuable testbed for evaluating spatial properties – particularly *integration*, *intelligibility* and *vulnerability* – at a scale beyond anything previously modeled.

Stabilization of space-type distributions and vulnerability scores

One important and potentially surprising outcome of our analysis is the stabilization of Hillier's space-type distributions as settlement size increases. While the smaller 25 Cohen configurations showed high variability in the proportions of *a*-, *b*-, *c*-, and *d*-spaces – along with their more critical b^*-, c^*-, d^*-, *e*-, and e^*-types – the larger simulated settlements (comprising four fully analyzed layouts and 25 additional graph-based simulations) demonstrated remarkably consistent proportions. This suggests that as modular settlements grow, they begin to exhibit predictable and self-organizing spatial typologies. From a design perspective, this is significant: if spatial properties tend to stabilize through accretive growth, it may be possible to anticipate and guide future configurations more effectively.

As space-type distributions stabilize, so too do associated vulnerability measures. Because vulnerability is defined by the impact of losing structurally critical nodes (specifically b^*-, c^*-, d^*-, *e*-, and e^*-spaces), their normalized value (as a proportion of total modules) tends to decrease as the number of modules increases. This supports the hypothesis that larger settlements are inherently more resilient to localized failures – a trend confirmed across our dataset. However, this apparent configurational robustness comes with a trade-off, which is usability.

Decreasing intelligibility with growth

Intelligibility – defined as the correlation between local visibility (isovist connectivity/area) and global configurational depth (isovist integration) – tends to decline as modular habitats increase in scale. This trend, observed for the 25 Cohen configurations and the four simulated cities, highlights a key usability challenge: as spatial systems grow, they become harder to understand and navigate. This is consistent with Hillier's theories of urban complexity, which suggest that unstructured spatial growth leads to increased fragmentation and cognitive disorientation. In this context, while large settlements may be robust, they are also more functionally opaque – potentially making them difficult or stressful for inhabitants to use.

Preliminary findings suggest a relationship between intelligibility and vulnerability, although our dataset is not yet large enough for definitive statistical analysis. Nevertheless, the correlation is conceptually persuasive: as intelligibility declines, spatial legibility is lost, but at the same time, the systemic redundancy that supports resilience increases (larger configurations are *broadly* less vulnerable but the correlation coefficient is $R^2 = 0.294$). Therefore, if growth proceeds without spatial structuring, the risk of disorientation rises yet the risk of disconnection, and sub-system isolation, drops. This points to an important direction for future research – specifically, the possibility of defining spatial usability thresholds based on combined intelligibility–vulnerability scores.

Reassessing modular efficiency

Cohen [6] argued that a straight-run configuration of interconnected modules would be among the most efficient for early off-world habitats. While this may hold from a construction or logistical standpoint, our findings challenge this view from a spatial resilience perspective. In our analysis, straight-run configurations consistently ranked among the most fragile. Their linear configuration offers minimal redundancy and is highly susceptible to complete fragmentation if a single module is lost. From the standpoint of usability and resilience, such configurations appear among the least favorable for long-term habitation.

6 Conclusion

In this study we confirmed a set of hypotheses advancing our understanding of the spatial configuration and structural integrity of modular habitats. First, we showed that as modular habitats grow larger, their intelligibility – defined as the ease with which a system can be understood and navigated – inevitably decreases unless there is a structured and deliberate approach to their spatial organization. This supports our first hypothesis (**H1**), demonstrating that modular growth alone cannot sustain usability without strategic planning.

Second, our analysis confirms that aggregations of modular habitats possess inherent vulnerabilities that can be effectively captured through a combination of spatial and graph-theoretic analyses. By introducing a new measure of habitat vulnerability, we demonstrated that the structural fragility of modular habitats can be quantified and linked to specific spatial configurations. This finding confirms our second hypothesis (**H2**) and provides a novel analytical tool for evaluating habitat resilience.

We observed a critical trade-off as modular settlements increase in size: while the overall measure of habitat vulnerability tends to decrease with increased complexity and cyclicity or ringiness (indicating greater resilience), this comes at the expense of intelligibility and usability, which tend to decline proportionally. This directly supports our third hypothesis (**H3**) and highlights tensions between structural resilience and cognitive simplicity in complex spatial systems. However, the correlation between settlement size and vulnerability is weaker than anticipated ($R^2 = 0.294$)) and future work is required to further investigate this.

Moreover, our results confirm that methods derived from Space Syntax – which have traditionally been applied to urban and architectural analysis – are equally effective when extended to the analysis of modular habitats in extraterrestrial environments. This supports our fourth hypothesis (**H4**), showing that established Space Syntax analytic tools can be successfully adapted to new architectural contexts beyond terrestrial settlements.

Finally, we have shown that scaling habitat models from building-scale to settlement-scale and eventually to city-scale requires a strong theoretical framework. This validates our fifth hypothesis (**H5**), reinforcing the idea that spatial organization is necessary to sustain human navigation, learnability and usability within increasingly complex modular habitats.

Together, these findings establish a solid theoretical and analytical foundation for understanding the growth, organization, and vulnerability of modular habitats. They underscore the importance of balancing intelligibility and configurational resilience in the design of future extraterrestrial settlements and suggest that Space Syntax offers a powerful framework for guiding this process.

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