

Integrated habitat architecture, zoning and interfaces

Design a Mars habitat as a network of volumes, interfaces, barriers and escape paths rather than as a pressurized shell alone.

Before starting — Prerequisites: modules 00 to 40 recommended as relevant. Every important symbol is defined at first use.

Mastery objectives

- identify the functions, interfaces and degraded scenarios specific to the subject
- repeat simple calculations and verify units, assumptions and margins
- turn a principle into a verifiable procedure or decision
- connect the subsystem to human, energy and logistics constraints

1. A habitat is a network of coupled functions

A Mars habitat combines pressure, atmosphere, thermal control, power, water, waste, circulation, sleep, medical care, laboratory work, maintenance and storage. The common mistake is to optimize each room independently. A door moves noise, dust and people; a water tank can become shielding; an airlock constrains circulation; a workshop changes ventilation and fire risk. Architecture therefore starts with interfaces between functions, not with an attractive floor plan.

2. Clean, dirty, quiet, noisy and critical zoning

Zoning reduces conflict between functions. Dusty, chemical or mechanical work should be separated from sleep, care and food areas. Separation is not only geometric: pressure differentials, ventilation, transfer procedures and storage create functional barriers. A durable settlement must be able to isolate a workshop or laboratory without shutting down the entire habitat.

3. Circulation and evacuation: every route is also an emergency route

A corridor is an evacuation path, a maintenance access and a logistics route. Equipment must not gradually narrow usable width until a stretcher or large replacement unit can no longer pass. Independent routes to a safe zone are valuable when a local event can block one path. Floor plans must therefore be tested in nominal configuration and with a door, module or corridor unavailable.

4. Mechanical, electrical, fluid and digital interfaces

Each module exchanges power, data, fluids, mechanical loads and sometimes heat with its neighbors. Poorly defined interfaces transfer problems across the habitat: incompatible voltage, non-serviceable connectors, inadequate flow, software protocol mismatch or blocked maintenance access. Interface control must cover nominal states, limits, tolerances, isolation and post-failure behavior.

5. Habitability: the human body is an architectural requirement

Usable volume, light, noise, privacy, sanitation access, sleep, exercise and visual orientation directly influence health and performance. On Mars the habitat is simultaneously home, workplace and shelter. A technically compact design can become operationally poor if crews live amid alarms, pump noise or constant logistics traffic.

6. Modularity and growth without losing safety

Adding a module must not degrade evacuation, electrical capacity or atmosphere control in the existing base. An extensible architecture reserves interface points, power margin and segmentation rules. Growth is verified as a new system configuration rather than assumed to be a harmless geometric repetition.

7. Cross-failures: reason from lost functions, not only failed modules

A Mars habitat should not be assessed only by asking which physical module can fail. A ruptured line may remove both potable water from one zone and firefighting capability; a power-bus failure may disable several fans in separate compartments. Analysis should begin with vital functions — pressure, oxygen, carbon-dioxide removal, water, power, communications and refuge — and trace them back to the components that support them. Two components that look separate are not true redundancy if they depend on the same upstream valve, feeder or control software. A function-by-zone matrix makes this visible by checking whether survival functions remain available after one sector is isolated.

8. Controlled interfaces: every connection needs an owner and a known state

Many failures originate not inside equipment but at the boundary between two items. A fluid interface specifies pressure, flow, cleanliness and connector type; an electrical interface specifies voltage, peak power, protection and grounding; a digital interface specifies protocol, timing, data format and behaviour when a message is absent. Two subsystems can each be compliant yet fail when connected. Interface control therefore has to survive configuration changes and local manufacturing: when a pump or controller is replaced ten years later, the crew still needs to know which properties are contractual and what safe state the interface adopts after loss of power.

9. Base growth: preserve evacuation, maintenance and reserve volume

An early outpost can be compact; a Martian town cannot remain so. Architecture should reserve growth paths from the beginning: accessible service routes, expandable electrical and fluid capacity, isolation points, additional airlocks and storage volume. Otherwise each extension turns corridors into equipment spaces and weakens the ability to isolate a sector. The useful measure is therefore not only floor area per person but the ability to move an injured crewmember, extract heavy equipment, close a bulkhead, install a temporary line and shelter a displaced group. The habitat becomes adaptable infrastructure rather than a set of volumes filled to maximum occupancy.

10. Worked example: usable area and refuge capacity

A habitat provides 180 m² of usable area for six people, or 30 m²/person. A 36 m² refuge can hold all six, giving 6 m²/person in an emergency. If a fire makes 40% of the main area unavailable, 108 m² remain plus the refuge. The emergency question is not whether nominal comfort remains, but whether temporary sleeping, air, water, communications and medical access remain possible in the degraded configuration.

Calculated case study: verify zoning before debating interfaces

TEACHING ASSUMPTION — A habitat provides 240 m² of usable floor area: 96 m² for private and communal living, 48 m² for laboratory work, 60 m² for technical systems, and 36 m² for circulation and interfaces.

Let A be total floor area in m² and A_i the area of one zone. The fraction p_i is dimensionless and is often expressed as a percentage.

Check: $96 + 48 + 60 + 36 = 240$ m². For technical systems, $p_{\text{tech}} = 60 \div 240 = 0.25 = 25\%$. For circulation, $p_{\text{circ}} = 36 \div 240 = 0.15 = 15\%$.

The calculation only closes the area balance. It does not prove that the zoning is good: pressure, fire, noise, maintenance and traffic interfaces must then be tested as separate requirements.

11. Design exercise

Sketch a six-person habitat with sleep, food, medical, workshop, laboratory, airlock, storage, hygiene and refuge functions. Remove one corridor from service and verify that critical functions remain reachable without crossing the hazardous zone.

12. Reasoned solution

A strong solution identifies at least two zones capable of serving as pressurized refuge, checks that evacuation paths do not all share one corridor, and describes three critical interfaces — power, air and data — with their state after isolation. If both refuges depend on the same electrical panel as the damaged zone, redundancy is only apparent.

13. Validation mini-project

Produce an architecture review package: functional layout, interface matrix, two isolation scenarios, evacuation paths, maintenance zones, growth margins and a habitability rationale.

A habitat is not a set of rooms: it is a network of pressure, people, contamination and escape paths

Martian habitat architecture must connect functions that often compete. The shortest route for a pipe may cross a clean laboratory. The most compact layout may place every sleeping area behind one pressure door. A convenient workshop location may spread dust and noise through the crew quarters. Good architecture therefore begins with functional zoning and interfaces before aesthetic room arrangement.

Zoning separates clean from dirty, quiet from noisy, public circulation from hazardous maintenance and vital equipment from single-event hazards. The boundaries are not absolute walls everywhere; they are decisions about pressure, airflow, contamination control, access, acoustic isolation and emergency movement. Every boundary should exist for a reason that can be tested.

Interfaces deserve the same discipline as hardware components. A module connects mechanically, electrically, through data, ventilation, water and crew passage. If ownership is unclear, one team may assume the other provides isolation, fire detection or drainage. Interface control records therefore define geometry, capacities, connectors, limits, operating states and responsibility for verification.

Growth creates a second design problem. A settlement that works for six people can become unsafe when new modules create long evacuation routes, overloaded utilities or maintenance spaces that nobody can reach. Expansion plans need protected reserve capacity, alternate routes and clear rules for when a new module changes the safety analysis of the existing base.

Four architectural concepts that keep a growing base understandable

Zoning

Grouping spaces by compatible functions and hazards so contamination, noise, access and emergency controls can be managed deliberately.

Compartmentation

Physical and functional division that limits propagation of pressure loss, fire, smoke, contamination or other hazards between areas.

Interface control

Explicit definition of what crosses a boundary, in what quantity and state, through which connector, under whose responsibility and with what verification.

Evacuation path

Usable route from an occupied area toward a safe refuge or alternative compartment under the conditions expected during an emergency.

Calculation laboratory

Formula 1 — usable floor-area reserve

Canonical quantitative mini-lessons

This block is the module quantitative reference; exercise values are pedagogical and must be replaced by mission data before any real decision.

Usable-area reserve

$$A_{\text{reserve}} = A_{\text{usable}} - A_{\text{committed}}$$

1 — Concrete question

What does “ $A_{\text{reserve}} = A_{\text{usable}} - A_{\text{committed}}$ ” compute in “Usable-area reserve”?

2 — Intuition without symbols

Total area is not reserve if already committed to required functions or access.

3 — Quantities

A_{reserve} : remaining uncommitted area [m²]; A_{usable} : actually usable area [m²]; $A_{\text{committed}}$: already committed area [m²]

4 — Formula

$$A_{\text{reserve}} = A_{\text{usable}} - A_{\text{committed}}$$

5 — Read aloud

Read “ $A_{\text{reserve}} = A_{\text{usable}} - A_{\text{committed}}$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

A_{reserve} : remaining uncommitted area [m²]; A_{usable} : actually usable area [m²]; $A_{\text{committed}}$: already committed area [m²]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

A_{reserve} [m²]; A_{usable} [m²]; $A_{\text{committed}}$ [m²]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Subtraction isolates a margin or difference between comparable states.

11 — Assumptions

Terms must share the same frame and unit.

12 — Independent check

Adding the margin back to the subtracted term should reconstruct the initial state.

13 — Numerical case

With $A_{\text{usable}} = 180 \text{ m}^2$, $A_{\text{committed}} = 154 \text{ m}^2$: $A_{\text{reserve}} = 180 - 154 = 26 \text{ m}^2$.

14 — Why the calculation works

Subtraction isolates a margin or difference between comparable states.

15 — Verification

Adding the margin back to the subtracted term should reconstruct the initial state.

16 — Mental estimate

Comparing the two terms predicts the sign before calculation.

17 — Interpretation

Keep explicit reserve for repair, growth and reconfiguration.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The result moves directly when either term changes.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $A_{\text{usable}} = 96 \text{ m}^2$, $A_{\text{committed}} = 84 \text{ m}^2$: $A_{\text{reserve}} = 96 - 84$?

Detailed guided correction — open after trying

With $A_{\text{usable}} = 96 \text{ m}^2$, $A_{\text{committed}} = 84 \text{ m}^2$: $A_{\text{reserve}} = 96 - 84 = 12 \text{ m}^2$. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $A_{\text{usable}} = 240 \text{ m}^2$, $A_{\text{committed}} = 204 \text{ m}^2$: $A_{\text{reserve}} = 240 - 204$?

Autonomous correction — open after trying

With $A_{\text{usable}} = 240 \text{ m}^2$, $A_{\text{committed}} = 204 \text{ m}^2$: $A_{\text{reserve}} = 240 - 204 = 36 \text{ m}^2$. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Keep explicit reserve for repair, growth and reconfiguration.

Refuge capacity margin

$$M_{\text{refuge}} = C_{\text{refuge}} - N_{\text{required}}$$

1 — Concrete question

What does " $M_{\text{refuge}} = C_{\text{refuge}} - N_{\text{required}}$ " compute in "Refuge capacity margin"?

2 — Intuition without symbols

A refuge is available only when capacity meets or exceeds the population that may need it.

3 — Quantities

M_{refuge} : remaining refuge places [places]; C_{refuge} : certified refuge capacity [places]; N_{required} : occupants requiring refuge [personnes]

4 — Formula

$$M_{\text{refuge}} = C_{\text{refuge}} - N_{\text{required}}$$

5 — Read aloud

Read " $M_{\text{refuge}} = C_{\text{refuge}} - N_{\text{required}}$ " by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

M_{refuge} : remaining refuge places [places]; C_{refuge} : certified refuge capacity [places]; N_{required} : occupants requiring refuge [personnes]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

M_{refuge} [places]; C_{refuge} [places]; N_{required} [personnes]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Subtraction isolates a margin or difference between comparable states.

11 — Assumptions

Terms must share the same frame and unit.

12 — Independent check

Adding the margin back to the subtracted term should reconstruct the initial state.

13 — Numerical case

With $C_{\text{refuge}} = 10$ places, $N_{\text{required}} = 8$ personnes: $M_{\text{refuge}} = 10 - 8 = 2$ places.

14 — Why the calculation works

Subtraction isolates a margin or difference between comparable states.

15 — Verification

Adding the margin back to the subtracted term should reconstruct the initial state.

16 — Mental estimate

Comparing the two terms predicts the sign before calculation.

17 — Interpretation

Zero margin is acceptable only if no additional occupant or capacity loss is credible.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The result moves directly when either term changes.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $C_{\text{refuge}} = 6$ places, $N_{\text{required}} = 6$ personnes: $M_{\text{refuge}} = 6 - 6$?

Detailed guided correction — open after trying

With $C_{\text{refuge}} = 6$ places, $N_{\text{required}} = 6$ personnes: $M_{\text{refuge}} = 6 - 6 = 0$ places. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $C_{\text{refuge}} = 14$ places, $N_{\text{required}} = 11$ personnes: $M_{\text{refuge}} = 14 - 11$?

Autonomous correction — open after trying

With $C_{\text{refuge}} = 14$ places, $N_{\text{required}} = 11$ personnes: $M_{\text{refuge}} = 14 - 11 = 3$ places. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Zero margin is acceptable only if no additional occupant or capacity loss is credible.

Zone area fraction

$$p_zone = A_zone / A_total$$

1 — Concrete question

What does “ $p_zone = A_zone / A_total$ ” compute in “Zone area fraction”?

2 — Intuition without symbols

Zoning can be checked by the fraction of total area or volume actually assigned to each function.

3 — Quantities

p_zone : fraction of total area occupied by the zone [sans dimension]; A_zone : zone area [m^2]; A_total : total area [m^2]

4 — Formula

$$p_zone = A_zone / A_total$$

5 — Read aloud

Read “ $p_zone = A_zone / A_total$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

p_zone : fraction of total area occupied by the zone [sans dimension]; A_zone : zone area [m^2]; A_total : total area [m^2]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

p_zone [sans dimension]; A_zone [m^2]; A_total [m^2]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Division relates a quantity to a coherent capacity, duration or reference.

11 — Assumptions

Numerator and denominator must describe the same scenario and the denominator must remain positive.

12 — Independent check

Multiplying the result by the denominator should reconstruct the numerator.

13 — Numerical case

With $A_zone = 60\text{ m}^2$, $A_total = 240\text{ m}^2$: $p_zone = 60 / 240 = 0.25$.

14 — Why the calculation works

Division relates a quantity to a coherent capacity, duration or reference.

15 — Verification

Multiplying the result by the denominator should reconstruct the numerator.

16 — Mental estimate

Comparing numerator and denominator scales predicts the result.

17 — Interpretation

Compare the calculated fraction with operational, access and safety needs, not only the architectural drawing.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The result rises with the numerator and falls as the denominator rises.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $A_zone = 36\text{ m}^2$, $A_total = 240\text{ m}^2$: $p_zone = 36 / 240$?

Detailed guided correction — open after trying

With $A_zone = 36\text{ m}^2$, $A_total = 240\text{ m}^2$: $p_zone = 36 / 240 = 0.15$. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $A_zone = 48\text{ m}^2$, $A_total = 240\text{ m}^2$: $p_zone = 48 / 240$?

Autonomous correction — open after trying

With $A_{\text{zone}} = 48 \text{ m}^2$, $A_{\text{total}} = 240 \text{ m}^2$: $p_{\text{zone}} = 48 / 240 = 0.2$. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Compare the calculated fraction with operational, access and safety needs, not only the architectural drawing.

Interface density

$$D_{\text{if}} = N_{\text{interfaces}} / A_{\text{total}}$$

1 — Concrete question

What does " $D_{\text{if}} = N_{\text{interfaces}} / A_{\text{total}}$ " compute in "Interface density"?

2 — Intuition without symbols

Interfaces are dependency points; their density helps identify zones difficult to isolate or modify.

3 — Quantities

D_{if} : interfaces per unit area [interfaces/m²]; $N_{\text{interfaces}}$: counted functional interfaces [interfaces]; A_{total} : total considered area [m²]

4 — Formula

$$D_{\text{if}} = N_{\text{interfaces}} / A_{\text{total}}$$

5 — Read aloud

Read " $D_{\text{if}} = N_{\text{interfaces}} / A_{\text{total}}$ " by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

D_{if} : interfaces per unit area [interfaces/m²]; $N_{\text{interfaces}}$: counted functional interfaces [interfaces]; A_{total} : total considered area [m²]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

$$D_{\text{if}} [\text{interfaces/m}^2]; N_{\text{interfaces}} [\text{interfaces}]; A_{\text{total}} [\text{m}^2]$$

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Division relates a quantity to a coherent capacity, duration or reference.

11 — Assumptions

Numerator and denominator must describe the same scenario and the denominator must remain positive.

12 — Independent check

Multiplying the result by the denominator should reconstruct the numerator.

13 — Numerical case

With $N_{\text{interfaces}} = 24$ interfaces, $A_{\text{total}} = 240 \text{ m}^2$: $D_{\text{if}} = 24 / 240 = 0.1$ interfaces/m².

14 — Why the calculation works

Division relates a quantity to a coherent capacity, duration or reference.

15 — Verification

Multiplying the result by the denominator should reconstruct the numerator.

16 — Mental estimate

Comparing numerator and denominator scales predicts the result.

17 — Interpretation

High density should trigger review of access, isolation, maintenance and common causes.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The result rises with the numerator and falls as the denominator rises.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $N_{\text{interfaces}} = 18$ interfaces, $A_{\text{total}} = 180 \text{ m}^2$: $D_{\text{if}} = 18 / 180$?

Detailed guided correction — open after trying

With $N_{\text{interfaces}} = 18$ interfaces, $A_{\text{total}} = 180 \text{ m}^2$: $D_{\text{if}} = 18 / 180 = 0.1$ interfaces/ m^2 . The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $N_{\text{interfaces}} = 35$ interfaces, $A_{\text{total}} = 300 \text{ m}^2$: $D_{\text{if}} = 35 / 300$?

Autonomous correction — open after trying

With $N_{\text{interfaces}} = 35$ interfaces, $A_{\text{total}} = 300 \text{ m}^2$: $D_{\text{if}} = 35 / 300 = 0.1167$ interfaces/ m^2 . The decision must then be checked against the module margins and assumptions.

21 — Mission decision

High density should trigger review of access, isolation, maintenance and common causes.

Egress time margin

$$M_{\text{egress}} = t_{\text{limit}} - t_{\text{egress}}$$

1 — Concrete question

What does " $M_{\text{egress}} = t_{\text{limit}} - t_{\text{egress}}$ " compute in "Egress time margin"?

2 — Intuition without symbols

An egress path is judged by available time minus the time actually needed to exit.

3 — Quantities

M_{egress} : time margin before the limit [min]; t_{limit} : maximum allowable time [min]; t_{egress} : estimated egress time [min]

4 — Formula

$$M_{\text{egress}} = t_{\text{limit}} - t_{\text{egress}}$$

5 — Read aloud

Read " $M_{\text{egress}} = t_{\text{limit}} - t_{\text{egress}}$ " by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

M_{egress} : time margin before the limit [min]; t_{limit} : maximum allowable time [min]; t_{egress} : estimated egress time [min]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

$$M_{\text{egress}} [\text{min}]; t_{\text{limit}} [\text{min}]; t_{\text{egress}} [\text{min}]$$

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Subtraction isolates a margin or difference between comparable states.

11 — Assumptions

Terms must share the same frame and unit.

12 — Independent check

Adding the margin back to the subtracted term should reconstruct the initial state.

13 — Numerical case

$$\text{With } t_{\text{limit}} = 8 \text{ min, } t_{\text{egress}} = 5 \text{ min: } M_{\text{egress}} = 8 - 5 = 3 \text{ min.}$$

14 — Why the calculation works

Subtraction isolates a margin or difference between comparable states.

15 — Verification

Adding the margin back to the subtracted term should reconstruct the initial state.

16 — Mental estimate

Comparing the two terms predicts the sign before calculation.

17 — Interpretation

An insufficient margin requires improving access, detection, training or distance.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The result moves directly when either term changes.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $t_{\text{limit}} = 6$ min, $t_{\text{egress}} = 5.5$ min: $M_{\text{egress}} = 6 - 5.5$?

Detailed guided correction — open after trying

With $t_{\text{limit}} = 6$ min, $t_{\text{egress}} = 5.5$ min: $M_{\text{egress}} = 6 - 5.5 = 0.5$ min. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $t_{\text{limit}} = 12$ min, $t_{\text{egress}} = 7$ min: $M_{\text{egress}} = 12 - 7$?

Autonomous correction — open after trying

With $t_{\text{limit}} = 12$ min, $t_{\text{egress}} = 7$ min: $M_{\text{egress}} = 12 - 7 = 5$ min. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

An insufficient margin requires improving access, detection, training or distance.

Shared-resource capacity margin

$$M_{\text{common}} = C_{\text{supply}} - D_{\text{peak}}$$

1 — Concrete question

What does “ $M_{\text{common}} = C_{\text{supply}} - D_{\text{peak}}$ ” compute in “Shared-resource capacity margin”?

2 — Intuition without symbols

Physically separated zones can remain coupled through a shared supply or network.

3 — Quantities

M_{common} : shared-resource capacity margin [unité de capacité]; C_{supply} : available capacity [unité de capacité]; D_{peak} : peak demand [unité de capacité]

4 — Formula

$$M_{\text{common}} = C_{\text{supply}} - D_{\text{peak}}$$

5 — Read aloud

Read “ $M_{\text{common}} = C_{\text{supply}} - D_{\text{peak}}$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

M_{common} : shared-resource capacity margin [unité de capacité]; C_{supply} : available capacity [unité de capacité]; D_{peak} : peak demand [unité de capacité]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

M_{common} [unité de capacité]; C_{supply} [unité de capacité]; D_{peak} [unité de capacité]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Subtraction isolates a margin or difference between comparable states.

11 — Assumptions

Terms must share the same frame and unit.

12 — Independent check

Adding the margin back to the subtracted term should reconstruct the initial state.

13 — Numerical case

With $C_{\text{supply}} = 120$ unité de capacité, $D_{\text{peak}} = 95$ unité de capacité: $M_{\text{common}} = 120 - 95 = 25$ unités.

14 — Why the calculation works

Subtraction isolates a margin or difference between comparable states.

15 — Verification

Adding the margin back to the subtracted term should reconstruct the initial state.

16 — Mental estimate

Comparing the two terms predicts the sign before calculation.

17 — Interpretation

Low shared margin signals a potential common cause despite physical zoning.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The result moves directly when either term changes.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $C_{\text{supply}} = 80$ unité de capacité, $D_{\text{peak}} = 78$ unité de capacité: $M_{\text{common}} = 80 - 78$?

Detailed guided correction — open after trying

With $C_{\text{supply}} = 80$ unité de capacité, $D_{\text{peak}} = 78$ unité de capacité: $M_{\text{common}} = 80 - 78 = 2$ unités.
The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $C_{\text{supply}} = 200$ unité de capacité, $D_{\text{peak}} = 155$ unité de capacité: $M_{\text{common}} = 200 - 155$?

Autonomous correction — open after trying

With $C_{\text{supply}} = 200$ unité de capacité, $D_{\text{peak}} = 155$ unité de capacité: $M_{\text{common}} = 200 - 155 = 45$ unités. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Low shared margin signals a potential common cause despite physical zoning.

Starting question

How much usable area remains available after known functions, access and maintenance envelopes are committed?

Read aloud

Read: "area reserve equals usable area minus committed area."

Symbols, pronunciation and meaning

A_{usable} is floor area that can actually support planned functions; $A_{\text{committed}}$ is area already assigned to equipment, circulation and required working clearances.

Units

Both values use square metres, so the reserve is also square metres.

Origin and status of values

Usable and committed areas come from the current layout, including real access and maintenance clearances rather than only equipment footprints.

Why this operation

Subtraction identifies how much flexibility remains before growth forces crowding or redesign.

Substitution and calculation

If a module provides 180 m² usable and 154 m² are committed, reserve = 180 – 154 = 26 m².

Calculator entry

Enter 180 – 154. Keep corridor and emergency-clearance areas inside the committed total if they cannot be repurposed.

Mental estimate

About fifteen percent of 180 m² is 27 m², so 26 m² is consistent with a modest reserve.

Independent check

Add 154 + 26 and recover 180 m².

Physical or operational interpretation

The 26 m² should not automatically be filled; some reserve may be intentionally protected for growth, quarantine or contingency staging.

Plain-English translation

Roughly twenty-six square metres of usable layout flexibility remain in this module.

Variation / sensitivity

Adding a 20 m² new function would leave only 6 m² reserve, which may be too little for future maintenance or emergency needs.

Limit / assumption

Area alone does not guarantee habitability. Volume, headroom, noise, airflow, radiation shielding and egress geometry also matter.

Formula 2 — refuge occupancy margin

Starting question

Can the designated refuge accommodate everyone who may need it during the analysed emergency?

Read aloud

Read: “refuge margin equals refuge capacity minus required occupants.”

Symbols, pronunciation and meaning

C_{refuge} is verified safe occupancy under the emergency condition; N_{required} is the number of people who must fit; M is spare places.

Units

All terms are counts of people, so the result is a count.

Origin and status of values

Capacity must reflect life-support, volume, seats/rest positions and duration, not nominal room occupancy. Required people come from the emergency scenario and crew distribution.

Why this operation

Subtraction directly tests whether capacity exceeds the required occupancy.

Substitution and calculation

If refuge capacity is 10 and the scenario requires 8 occupants, margin = 10 – 8 = 2 places.

Calculator entry

Enter 10 – 8. Record the emergency duration associated with the capacity rating.

Mental estimate

Ten places for eight people leaves two, so the result is immediately checkable.

Independent check

Add required occupancy and margin: 8 + 2 = 10.

Physical or operational interpretation

A small positive margin can absorb a visitor or rescued crewmember; zero margin leaves no growth or casualty flexibility.

Plain-English translation

The refuge can accommodate the analysed eight people with two verified spare places.

Variation / sensitivity

If the settlement grows to 11 people without refuge expansion, margin becomes –1 and the architecture no longer meets this scenario.

Limit / assumption

Capacity can be limited by oxygen, carbon-dioxide removal, thermal load or sanitation before physical floor space is full.

Mission reasoning: evaluate the base by lost functions and hazard propagation

Map flows through every zone

Air, water, waste, electrical power, data, crew, samples and dust all move. The architecture should show where each flow crosses boundaries and what isolation exists. Hidden crossings are common sources of contamination and common-cause failures.

Design alternate egress before adding equipment

Corridors tend to accumulate storage and utility runs over time. Emergency route widths and door access should be protected by configuration control so later convenience does not quietly remove the second path that made the original design acceptable.

Own every interface

Each cross-module interface needs a responsible owner and an acceptance test. “Provided by habitat team” is not enough if two teams both assume the other checks leak tightness, grounding or fire sealing.

Reason by functional loss

A fire in one equipment room may simultaneously remove power conversion, cooling and a data switch if they are co-located. Hazard analysis should ask which functions disappear together, not merely which physical module is lost.

Separate routine dirty work from living zones

Regolith dust, machining residue and biological waste should not need to pass through sleeping or food areas. Zoning reduces the number of cleaning barriers and lowers chronic contamination burden.

Plan expansion interfaces early

Reserve utility capacity, docking geometry and circulation nodes so future growth can occur without cutting through occupied pressure walls or making every new module dependent on one original corridor.

Habitat-architecture exercises — test the layout as a system

Exercise A — Single corridor

All sleeping quarters connect to the refuge through one corridor. What question should the architecture review ask?

Reveal the reasoned solution

Ask what happens if that corridor is blocked by fire, smoke, structural damage or a casualty. If no alternate protected path exists, the sleeping zone may have a single-point egress failure even when the refuge itself is large enough.

Exercise B — Area reserve

A workshop has 96 m² usable and 84 m² committed including maintenance clearance. What is area reserve?

Reveal the reasoned solution

$96 - 84 = 12$ m². That is only an area metric; before allocating it, verify access, hazard zoning and whether the reserve is intentionally needed for future repair or staging.

Exercise C — Interface ambiguity

A new laboratory module connects to habitat ventilation, but neither team owns the isolation damper test. Why is this unacceptable?

Reveal the reasoned solution

Because an interface function can fail without either subsystem team detecting it. Assign ownership, test method, acceptance criterion and configuration record before declaring the connection operational.

Exercise D — Refuge growth

A refuge is rated for 12 people for 24 h. The base grows from 10 to 13 people. What changes?

Reveal the reasoned solution

Occupancy margin changes from +2 to -1. The previous refuge analysis is no longer valid for a whole-base emergency. Capacity, another refuge, or a different emergency distribution is required before accepting growth.

Exercise E — Dust zoning

A suit maintenance bench is proposed beside the food preparation area because the plumbing is convenient. What is wrong with the reasoning?

Reveal the reasoned solution

The layout optimizes one utility interface while ignoring contamination flow. Suit dust and maintenance residue should be separated from food zones with controlled transitions, cleaning and airflow appropriate to the hazard.

Exercise F — Cross-failure

Power electronics and water pumps are placed in one small equipment bay. What should the hazard review consider?

Reveal the reasoned solution

A local fire or leak may remove both electrical distribution and water circulation at once. Co-location should be justified, protected or diversified so the architecture does not create an avoidable common-cause loss of critical functions.

Interactive beginner glossary

These terms describe how a habitat organizes space, interfaces and emergency movement as one integrated system.

- zoning — Grouping and separating spaces according to function, cleanliness, noise, hazard or access needs.
- compartmentation — Division into areas that can limit propagation of fire, pressure loss, smoke or contamination.
- interface — Defined boundary through which structure, energy, fluids, data, people or materials pass between systems.
- interface control document — Controlled record specifying interface requirements, ownership, limits and verification.
- habitable volume — Pressurized volume intended to support human occupancy under defined environmental conditions.
- usable area — Floor area that can practically support occupation or equipment after exclusions and constraints.
- maintenance envelope — Space that must remain accessible for removal, inspection, tools and technician body position around equipment.
- egress — Movement away from a hazardous area toward a safer location.
- evacuation path — Preplanned route used to reach a safe compartment or refuge during an emergency.
- refuge — Protected area able to support occupants for a defined emergency duration while the surrounding system is unsafe or uncertain.
- airlock — Pressure-controlled chamber allowing transition between areas with different pressure or contamination conditions.
- vestibule — Transition space used to separate environmental, access or contamination zones.
- clean zone — Area maintained to a higher cleanliness standard because contamination would harm health, science or process quality.
- dirty zone — Area expected to contain dust, waste or process contamination and managed with barriers or cleaning controls.
- pressure boundary — Structure and seals that retain atmosphere across a defined pressurized region.
- isolation valve — Valve used to stop fluid or gas flow across a boundary during maintenance or emergency control.
- fire barrier — Construction intended to resist fire or smoke propagation for a defined purpose and duration.

- utility corridor — Protected route carrying services such as power, data, ventilation or fluids between spaces.
- service chase — Dedicated enclosed or accessible pathway for utilities and maintenance access.
- circulation — Routine movement of people, carts, equipment and materials through the habitat.
- bottleneck — Location where available passage or system capacity constrains movement or throughput.
- acoustic zoning — Arrangement that separates high-noise activities from rest, medical or concentration-sensitive spaces.
- contamination control — Measures that prevent unwanted material from entering or spreading between spaces or processes.
- modularity — Design approach using repeatable units and interfaces so systems can be added, replaced or reconfigured.
- growth margin — Reserved capacity in area, utilities, interfaces or safety systems intended to support future expansion.
- single-point failure — One failure whose occurrence alone can remove a required function because no adequate alternative remains.
- common-cause failure — One event or mechanism that defeats multiple nominally separate functions or redundancies.
- habitability — Quality of an environment in supporting human health, performance, privacy, rest and daily life.
- human factors — Engineering discipline concerned with how people perceive, decide, move and interact with systems and environments.
- functional adjacency — Planned placement of spaces near each other because their workflows or interfaces benefit from proximity.

Operational depth: keep architecture safe as the settlement grows and changes

Control corridor encroachment

Storage, temporary equipment and cables tend to migrate into circulation space. Periodic inspections should preserve minimum route width, door swing, firefighting access and stretcher movement rather than trusting the original drawing.

Protect quiet and private functions

Sleep, medical care and private communication need acoustic and visual separation. Habitability is not cosmetic: chronic noise and lack of privacy can degrade performance over months and years.

Separate interface states

An interface can be connected but isolated, powered but inhibited, physically complete but not accepted. Configuration displays should distinguish these states so operators do not infer capability merely from physical presence.

Design for maintenance removal paths

A pump may fit into a bay but still be impossible to replace if another module blocks the extraction route. Three-dimensional maintenance envelopes and lifting/handling paths should be checked before installation.

Revisit hazard analysis after expansion

Every added pressure tunnel, utility tie-in and occupancy change can alter isolation, evacuation and refuge assumptions. Growth is a configuration change to the existing base, not merely the addition of floor area.

Use local autonomy in zoning decisions

Crews will adapt spaces after living in them. Changes should be allowed through controlled review so operational experience improves the habitat without silently defeating fire barriers, contamination zones or emergency routes.

Applied habitat cases: interfaces, growth and rescue geometry

Applied architecture case — maintenance can block evacuation without changing the drawing

A pump replacement may require an access panel, lifting frame and temporary staging area that occupies half a corridor for several hours. If that corridor is also an emergency route, the maintenance plan must either preserve minimum egress width, schedule an alternate route or temporarily change refuge assignments. Architectural safety therefore extends into work planning. The original floor plan cannot guarantee escape if temporary configurations are ignored. A mature habitat maintains a live configuration for blocked doors, isolated tunnels and major maintenance envelopes so the emergency response team knows which routes are actually available today, not which routes existed at commissioning.

Applied architecture case — ventilation makes zoning dynamic

A clean laboratory beside a workshop can remain protected only if airflow direction, filtration and door discipline support the zoning concept. During a ventilation failure, pressure relationships may reverse and the clean zone can become contaminated even though the walls remain intact. Operators should therefore know which zoning boundaries depend on active airflow and which are physical containment boundaries. Alarm logic and contingency procedures can then reclassify spaces when the ventilation state changes. This is especially important for dust, biological work and trace-organic science, where small contamination transfers may destroy scientific value long before they create a visible health hazard.

Applied architecture case — utilities need isolation without creating hidden dead ends

A water or oxygen loop that passes through several modules may be efficient but difficult to isolate during a leak. Section valves, bypasses and measurement points should allow operators to remove one branch while preserving service elsewhere. Yet each added valve also introduces maintenance, leakage and configuration burden. The architecture review should therefore justify isolation granularity against credible hazards and repair needs. Interfaces should show normal flow, emergency closed states and the consequence of each isolation. A labelled pipe is not enough; crews need to understand what function is lost, which users remain supplied and how the isolated section can be depressurized or repaired safely.

Applied architecture case — privacy and medical separation affect resilience

A settlement needs spaces where an ill crewmember can be examined or isolated without turning the entire habitat into a medical ward. The same room may need acoustic privacy for counselling, communication with Earth or conflict mediation. Designing these functions only after occupancy often forces improvised use of sleeping quarters and circulation zones. Flexible rooms can help, but flexibility requires storage for alternate equipment, cleanable surfaces, ventilation modes and clear rules for when the room changes status. Habitability and medical resilience therefore share architectural requirements: privacy, controllable access, cleanable boundaries and enough spare capacity that one special use does not collapse every routine function.

Applied architecture case — expansion can overload invisible capacities

Adding a new habitat cylinder may appear easy because the pressure tunnel and floor area fit. But new occupants also add carbon-dioxide load, heat, wastewater, electrical peaks, data traffic, emergency refuge demand and maintenance workload. Growth reviews should carry those loads through each shared interface and identify which margin becomes limiting first. The architectural reserve is therefore multidimensional. A base can have empty floor area yet no safe capacity for more people because scrubber, radiator, refuge or evacuation margins are exhausted. Every expansion decision should state the occupancy and utility assumptions that remain valid after commissioning.

Applied architecture case — rescue geometry must fit real bodies and equipment

Emergency movement is not the same as routine walking. A crewmember may need to move a casualty on a stretcher while wearing breathing protection and carrying equipment. Door width, turning radius, ladder geometry and floor transitions should be tested with realistic loads. A passage that feels spacious during normal operations can become unusable when two rescuers and a stretcher need to turn. Mock-ups and drills are therefore architectural verification tools. They reveal collisions, handhold needs and staging locations that drawings miss. The result can change hatch placement, corridor width or equipment storage before the settlement depends on that route during a real emergency.

Operational review checklist

- Map air, water, waste, power, data, people and dust flows across zones.
- Protect clean, dirty, quiet and hazardous functions with deliberate boundaries.
- Assign ownership and acceptance tests to every critical interface.
- Maintain at least the required emergency egress under realistic blockage scenarios.
- Verify refuge capacity against actual occupancy and emergency duration.
- Preserve maintenance envelopes and equipment removal paths.
- Analyse common-cause functional losses created by co-location.
- Reserve utility and circulation margin for future modules.
- Reassess hazards whenever occupancy or architecture changes.
- Prevent temporary storage from consuming protected evacuation routes.

Primary sources and bridges

- [NASA-STD-3001 Volume 2](#)
- [NASA Human Integration Design Handbook](#)

FR ↔ EN parity matrix

Usable-area reserve	Réserve de surface utile
Refuge capacity margin	Marge de capacité refuge
Zone area fraction	Fraction de surface d'une zone
Interface density	Densité d'interfaces
Egress time margin	Marge d'évacuation
Shared-resource capacity margin	Marge d'une ressource commune