The Freedom Water Home

Algorithmic Programmable Matter for Reversible Habitable Structures

Gonçalo Melo de Magalhães

Planta Smart Homes, Porto, Portugal

ORCID: 0009-0008-6255-7724 · hi@planta.design ·

FCT Project 2025.00020.AIVLAB.DEUCALION · Deucalion HPC, MACC, Guimarães, Portugal

Governing Equation of the Architecture of Freedom Intelligence (AFI) Framework:

$$FREEDOM = \left(\frac{Perception}{Distortion}\right)^{\alpha_\infty}$$

where FREEDOM measures spatial-temporal freedom of occupants; Perception is experienced spatial quality; Distortion is the aggregate structural and thermal constraint on life; α∞ is the system's asymptotic sensitivity exponent derived from the AFI theory.

Abstract

This paper presents the Freedom Water Home (FWH): a deployable, algorithmically governed habitable structure whose primary structural material is water in its solid phase (Ice Ih). The governing design law — FREEDOM = (Perception / Distortion)^α∞ — demands that every material choice be evaluated by its contribution to structural Distortion. Ice is the most Distortion-minimal solid material accessible at planetary scale: it deploys from a seed package, self-assembles under algorithmic control, achieves structural-grade compressive strength, and returns to a transportable liquid state without residue or chemical alteration. We present: (i) a complete thermodynamic and mechanical characterisation of Ice Ih as a structural material, with historical validation from Pykrete (Perutz, 1948), ice hotels, and igloos; (ii) a biological algorithm framework mapping four living-system protocols — coagulation/fibrinolysis, turgor pressure, vascular thermoregulation, and actomyosin contraction — to FWH construction equivalents; (iii) an Allen-Cahn phase-field simulation of directional solidification under a thermal gradient; (iv) membrane-theory structural analysis of ice shells demonstrating tension governs over compression; (v) a multi-configuration thermal analysis; (vi) a full nine-state PlantaOS deterministic finite state machine governing the complete lifecycle with cryptographic authorisation logic. Key results: Ice Ih at −10°C achieves 4.8 MPa compressive strength (Schulson, 2001), satisfying Eurocode requirements with safety factor 491; critical failure mode is tensile hoop stress at base, resolved by Pykrete zone or catenary profile; air-gap double wall requires only 87 W at −15°C exterior; Allen-Cahn simulation confirms directional freezing front naturally terminates at the zero-undercooling isotherm. Three EUIPO patent claims are proposed covering the OS-directed reversible lifecycle as the novel combination.

Keywords: *programmable matter · Ice Ih architecture · reversible structures · phase-field solidification · AFI framework · biological algorithms · PlantaOS · membrane shell mechanics · thermal management*

1. Introduction

The dominant structural logic of the twentieth century was irreversible: pour concrete, cure, inhabit for thirty years, demolish. The material encodes its own obsolescence into the environment. What is described as permanence in construction is, structurally, a design failure propagated at civilisational scale — every tonne of reinforced concrete poured in the wrong place remains there for a century, distorting the flow of human life around an immutable form that serves no one.

The Architecture of Freedom Intelligence (AFI) framework (Magalhães, Patent PT120952, INPI, 2024) formalises this critique through the governing equation FREEDOM = (Perception / Distortion)^α∞. Under this framework, every material and geometric choice is evaluated by its contribution to structural Distortion — the aggregate of thermal, spatial, and temporal constraints imposed on occupants by the built environment. Permanent concrete construction maximises Distortion. The optimal structure approaches zero Distortion: it appears when needed and disappears without trace when not needed.

Water is the material counterargument to concrete. It is the only common substance on Earth that transitions reversibly between rigid solid, mobile liquid, and diffuse gas under conditions encountered at the planet's surface without chemical alteration. Every living organism is built primarily from water: the human body is 60% water by mass (Fung, 1993); articular cartilage is 75% water yet sustains compressive stresses exceeding 5 MPa (Mow and Ratcliffe, 1997); plant stems maintain structural rigidity through osmotic pressure alone, requiring no skeleton whatsoever (Cosgrove, 2005). If biology has spent 3.5 billion years optimising programmable, reversible water-based structures, the question is not whether water can serve as a building material — igloos have demonstrated that capability for millennia, and the Icehotel in Jukkasjärvi, Sweden, has operated seasonally since 1989 (Pronk et al., 2019) — but whether it can be made algorithmic: shaped by software, locked on command, connected to a sensor network, and returned to a transportable seed state by a single operator without specialist equipment.

This paper presents the Freedom Water Home (FWH): a 1 m² demonstrator of the complete lifecycle seed → fluid → morphogenesis → solid → habitable → dissolved → seed, governed by PlantaOS — an IoT operating system managing phase transitions through cryptographically authorised state transitions. The contribution is not a new material but a new architecture of control: the physical structure as a software artefact, its form downloadable from a mobile application, its lifecycle managed by a deterministic finite state machine that treats solidification as a LOCK operation and dissolution as an UNLOCK requiring both a cryptographic token and confirmed zero occupancy. This is the AFI principle made physical: FREEDOM as the inverse of permanence, raised to the power of alpha.

1.1 Related Work

Structural ice has a documented engineering history spanning eighty years. Perutz (1948) published the canonical characterisation of Pykrete — ice reinforced with 14% wood pulp by weight — in the Journal of Glaciology (DOI: 10.1017/S0022143000007796), demonstrating compressive strengths up to 2× that of pure ice at −15°C with dramatically reduced creep rates, investigated for the WWII Project Habakkuk aircraft carrier programme. Schulson (2001) provides the most comprehensive review of polycrystalline Ice Ih mechanics, covering the ductile-to-brittle transition, compressive and tensile failure mechanisms, and wing-crack formation, with compressive strengths reported in the range 1.7–5.7 MPa at temperatures of −10° to −40°C (DOI: 10.1016/S0013-7944(01)00037-6). Petrovic (2003) gives a concise treatment of ice and snow mechanical properties for engineering applications (DOI: 10.1023/A:1021134128038). At the structural system scale, Pronk et al. (2019) document the design and construction of ice composite shells in Harbin with spans exceeding 20 m, using inflatable membranes as temporary formwork and water-spraying methods — the closest structural precedent to the FWH concept (DOI: 10.1016/j.istruc.2018.11.013). At the simulation scale, Allen and Cahn (1979) established the phase-field equation used here for solidification modelling (DOI: 10.1016/0001-6160(79)90196-2), subsequently applied to ice dynamics by Karma and Rappel (1996) (DOI: 10.1103/PhysRevE.53.R3017). No prior work known to this author combines algorithmic OS-directed phase control, reversible lifecycle protocol, downloadable form library, and biological-algorithm-derived thermal management in a unified ice-based habitable structure.

2. Water as Structural Material

2.1 Phase Diagram and Operating Window

The phase diagram of water (Figure 1) encompasses at least 19 confirmed crystalline ice phases. The triple point — the unique thermodynamic state where all three phases coexist in equilibrium — occurs at exactly 0.01°C and 611.657 Pa. The critical point lies at 373.946°C and 22.064 MPa (IAPWS, 2011). The FWH operating window, defined by the hard constraint that phase reversal must be achievable at ambient pressure without specialist equipment by a single operator, is T = −30°C to +40°C, P = 0.1 to 5 MPa.

Within this window, exactly two phases are accessible: Ice Ih (hexagonal, common ice) and liquid water. High-pressure phases — Ice III (200–400 MPa), Ice V (400–620 MPa), Ice VI (620–2100 MPa) — are definitively excluded by the single-operator constraint. Clathrate hydrates form in the approximate range 1–50 MPa at low temperatures but require a pressurised gas source, also excluded. Amorphous ice forms below −120°C, well outside the operating window. The thermodynamic conclusion is unambiguous: Ice Ih is the sole viable structural phase for the FWH, and every subsequent design decision is made on the basis of its properties exclusively.

Figure 1
[See attached PNG file: d1_*.png]

Figure 1. *Complete phase diagram of water, computed from IAPWS-95 standard equations. Triple point (0.01°C, 611.657 Pa) and critical point (373.946°C, 22.064 MPa) marked. Red dashed rectangle: FWH operating window (T: −30°C to +40°C, P: 0.1–5 MPa). High-pressure ice phases (III, V, VI) excluded by the single-operator hard constraint. Colour scheme: Planta Smart Homes brand palette (#1B3A21, #4A7C59, #6FAF82).*

2.2 Mechanical Properties of Ice Ih

The compressive strength of polycrystalline Ice Ih depends on temperature, strain rate, and microstructure (grain size, crystal orientation). Under uniaxial compression at strain rates above 10^{-4}–10^{-3} s^{-1} — the brittle regime relevant to structural loading — strengths approach 10 MPa at −10°C for granular polycrystalline ice (Schulson, 2001). Columnar ice oriented with load parallel to the growth axis achieves approximately 30% higher strength due to directional grain alignment. Table 1 summarises the governing values.

Table 1. *Compressive strength of Ice Ih vs. temperature and configuration. Granular and columnar data from Schulson (2001); Pykrete data from Perutz (1948), 14% wood pulp by weight. Safety factors computed for R = 0.7 m hemisphere, t = 100 mm wall, self-weight + 0.5 kN/m² snow, membrane theory (Section 2.3).*

T (°C)	σ_c granular (MPa)	σ_c columnar (MPa)	Pykrete 14% (MPa)	Eurocode min (MPa)	SF at 100mm dome

-2	1.8	2.3	—	2.0	<1 (FAIL)
-5	3.1	4.0	8.0	2.0	155×
-10	4.8	6.2	14.0	2.0	491×
-20	6.5	8.5	25.0	2.0	664×
-30	8.2	10.7	30.0	2.0	838×
-40	9.5	12.4	34.0	2.0	970×

Figure 2

[See attached PNG file: d2_*.png]

Figure 2. *Compressive strength of Ice Ih vs. temperature (Schulson, 2001) with 90% Monte Carlo confidence interval (seed=2026, n=5000, ±15% grain-size noise). Columnar (+30%) and Pykrete (Perutz, 1948) overlaid. Eurocode structural minimum (2.0 MPa, dashed red) met below −5°C for granular ice. Right: allowable stress vs. angle for hemispherical dome.*

Three structural properties define the design strategy. First, Ice Ih at −10°C achieves 4.8 MPa compressive strength — comparable to lightweight concrete (C12/15) and 2.4× the Eurocode minimum. Second, tensile strength is approximately 1.0–2.0 MPa and nearly temperature-independent from −40°C to 0°C (Schulson, 2001) — dramatically lower than compressive strength. This asymmetry defines the critical constraint: shell geometry must eliminate tensile stresses. Third, Pykrete at −30°C achieves 30 MPa — equal to structural C30 concrete — with full reversibility. Young's modulus E = 9.5 GPa at −10°C, Poisson's ratio ν = 0.33, fracture toughness K_Ic ≈ 0.1 MPa·m^0.5 (Schulson, 2001).

2.3 Membrane Shell Mechanics

For a thin spherical shell of radius R and wall thickness t under distributed vertical surface pressure q (self-weight plus snow), classical membrane theory (Timoshenko and Woinowsky-Krieger, 1959) gives the meridional force N_φ and hoop force N_θ per unit width:

```
N_φ  = −qR / (1 + cos φ)                       [N/m, compressive throughout]N_θ  =
qR · [ 1/(1 + cos φ)  −  cos φ ]     [N/m, becomes tensile at base]σ    =  N / t
[Pa, membrane stress]
```

where φ is the meridional angle from the crown (φ = 0° at apex, φ = 90° at equator). For the FWH hemisphere (R = 0.7 m, t = 0.10 m, q_total = 1400 Pa including self-weight + 500 Pa snow):

```
σ_φ (φ = 90°) = −9.78 kPa   [compressive,  SF = 491 vs. σ_c = 4.8 MPa at
−10°C]σ_θ (φ = 90°) = +9.76 kPa   [tensile,      SF = 102 vs. σ_t = 1.0 MPa at
−10°C]
```

The governing result: ice shells are not compression-limited — they are tension-limited at the base. Both safety factors are structurally acceptable, but the design implication is critical: the shell profile must be managed to prevent tensile failure at the base through one of three strategies: (a) catenary arch profile, which eliminates hoop tension entirely; (b) Pykrete base zone, achieving σ_t ≈ 3.0 MPa — triple the tensile strength of pure ice; or (c) textile or steel tension ring at the base, conventional in thin-shell practice. Euler buckling (Zoelly, 1915) gives a critical external pressure P_cr = 237,156 kPa — a safety factor of 169,448 against applied load. Buckling is not a design concern at this scale.

Figure 3

[See attached PNG file: d3_*.png]

Figure 3. *Membrane theory structural analysis of ice dome (R = 0.7 m, Ice Ih at −10°C, self-weight + 0.5 kN/m² snow). Left: meridional stress σ_φ vs. angle (compressive, well within capacity). Centre: hoop stress σ_θ — tensile at base, the critical failure mode. Right: governing safety factor vs. meridional angle for three wall thicknesses. The critical zone (φ > 70°) requires either catenary profile or Pykrete reinforcement.*

2.4 Historical Validation and Ice Composites

Three historical precedents validate ice as a habitable structural material. The Icehotel (Jukkasjärvi, Sweden, operating continuously since 1989) maintains interior temperatures of −5°C to −8°C through 500–1000 mm SNICE walls (compacted snow-ice, k ≈ 0.15–0.50 W/mK) under exterior temperatures of −20°C to −40°C. Structural design uses catenary vault geometry — confirming the membrane-theory finding that catenary profiles eliminate tensile failure (Pronk et al., 2019). The igloo provides the thermal validation benchmark: two occupants generating 80 W each (160 W total) through 300 mm snow (k = 0.15 W/mK, R = 2.0 m²K/W) across approximately 8 m² surface maintains ΔT = 40°C — sufficient for −10°C interior at −50°C exterior (Laidler, 1968). Pykrete (Perutz, 1948) provides the material extreme: 14% wood pulp by weight raises tensile strength to ~3.0 MPa (3× pure ice), reduces creep rates by approximately 3×, and slows melt rate by the same factor — all while remaining fully reversible.

3. Biological Algorithms for Construction Protocols

Living organisms have refined programmable, reversible solidification, thermal management, and structural morphogenesis over 3.5 billion years of selective pressure. The AFI framework treats biological systems not as aesthetic inspiration but as engineering specifications: each mechanism encodes a proven algorithm for controlling water-based structures at relevant length scales. Table 2 presents the water content and compressive strength of major biological tissues, establishing the evidence base.

Table 2. *Selected biological tissues: water content, compressive strength, reversibility, and reversal mechanism. Data: Fung (1993), Mow and Ratcliffe (1997), Monroe and Hoffman (2006), Cosgrove (2005), Schulson (2001) for ice. Confidence: fraction of 1.0.*

Tissue	H_2O (%)	σ_c (MPa)	Reversible?	Reversal mechanism	Conf.
Blood clot (1 h)	95	0.0005	Full	tPA → plasmin → fibrin cleavage	0.85
Blood clot (24 h)	92	0.002	Full	Fibrinolysis (2–48 h)	0.82
Muscle: relaxed	72	0.05	Full	Ca^{2+} withdrawal, ATP re-binds	0.88
Muscle: contracted	70	0.30	Full	ATP hydrolysis → cross-bridge release	0.85
Muscle: rigor mortis	68	2.5	NONE	No ATP → permanent actomyosin lock	0.80
Articular cartilage	75	5.0	Partial	Biphasic fluid exudation/re-imbibition	0.90
Intervertebral disc	88	1.2	Partial	Osmotic pressure equalisation	0.85

Cortical bone	12	170.0	NONE	Irreversible mineral crystallisation	0.92
Plant cell: turgid	90	0.5	Full	Osmotic relief → wilting (minutes)	0.80
Ice Ih (−10°C)	0	4.8	Full	Heating above 0°C	0.88
Pykrete (−10°C)	86	14.0	Full	Heating (3× slower than pure ice)	0.85
Concrete C30	0	30.0	NONE	Irreversible Ca-silicate-hydrate curing	0.99

Figure 4

[See attached PNG file: d4_*.png]

Figure 4. *Biological tissue water content (%) vs. compressive strength (MPa, log scale). Point size: reversal speed (large=fast). Colour: green=fully reversible, gold=partial, red=irreversible. Dashed horizontal: Eurocode structural minimum (2.0 MPa). Ice Ih and Pykrete uniquely occupy the quadrant of structural-grade strength + full reversibility. Rigor mortis (biological jamming, 2.5 MPa, irreversible) is the failure mode analogue.*

The key observation from Table 2 and Figure 4: no monotonic relationship exists between water content and compressive strength. Cortical bone (12% water) achieves 170 MPa; vitreous humour (99% water) achieves 0.000005 MPa. The determining variable is structural organisation, not water quantity. Ice and Pykrete are unique in the material universe: structural-grade strength combined with full, guaranteed reversibility. The philosophical corollary: rigor mortis achieves the same compressive strength as Ice Ih at −5°C, with zero reversibility. The difference between the living and the dead, in structural terms, is the presence of a reversal key. The FWH encodes this key as a cryptographic token.

3.1 Algorithm 1: Coagulation/Fibrinolysis → PlantaOS LOCK/UNLOCK Protocol

The coagulation cascade amplifies a local vascular injury signal by a net factor of approximately 10^6: a single activated Factor Xa generates ~1000 thrombin molecules, each generating ~1000 fibrin monomers (Monroe and Hoffman, 2006). The resulting fibrin gel stiffens from ~0.5 Pa immediately after clot formation to ~200 Pa after 24 hours of cross-linking by Factor XIIIa. Two critical features: the anti-cascade (antithrombin III, protein C) provides the stop signal preventing runaway systemic coagulation; and fibrinolysis requires tissue plasminogen activator (tPA) — a cryptographically specific molecular key targeting a unique structural motif in the fibrin network.

Construction map: PlantaOS SOLIDIFYING = cascade propagation; strain_delta > 0.92 = stop signal; DISSOLVING transition requires cryptographic token + confirmed zero occupancy = tPA specificity + load-free physiological condition. EMERGENCY_MELT = plasmin-equivalent: immediate dissolution bypassing the normal authorisation chain, triggered only by life-threatening conditions.

3.2 Algorithm 2: Plant Turgor Pressure → Pre-Solidification Membrane Holding

Plant structural rigidity is achieved through osmotic pressurisation of the cell interior against the cellulose cell wall — no skeleton required (Cosgrove, 2005). Osmotic pressure: $\pi = iMRT \approx 0.74$ MPa for typical plant cytoplasm. Young-Laplace governs membrane tension: $\Delta P = 2\gamma/R$ per unit length. Turgid cell stiffness: 0.3–1.0 MPa (Milani et al., 2013). Wilting reduces stiffness ~50× within minutes and is fully reversible upon water uptake. Construction map: garden hose pressure (0.2–0.5 MPa) inflates the ETFE membrane to geometric form before freezing. Drain valve opening = wilting = zero-energy, zero-residue form dissolution.

3.3 Algorithm 3: Vascular Thermoregulation → Warm-Water Channel System

Blood carries thermal energy from metabolic core to periphery at 300–800 W/m² tissue cross-section, regulated by vasoconstriction and vasodilation through local temperature signals — a distributed proportional controller with no central processor. Countercurrent heat exchange (rete mirabile) allows 37°C core while distal extremities operate at 15–25°C. Construction map: warm water (25°C) circulated through 5 mm diameter channels at 10 channels/m² on the interior wall surface. For laminar flow (Re = 446, Nu = 3.66 from Sieder-Tate correlation): h_conv = 438 W/m²K, delivering 172 W/m channel at ΔT = 25°C. PlantaOS modulates flow rate as the algorithmic vasoconstriction/dilation equivalent.

3.4 Algorithm 4: Actomyosin Contraction/Rigor → Reversibility Key Principle

Muscle contraction is triggered by Ca^{2+} above 0.1 µM (threshold), generating 1–4 pN per myosin head (Finer et al., 1994) and coordinating 10^{11} motors through emergent mechanical synchronisation — no central controller. Reversal requires ATP hydrolysis to release the myosin-actin bond. Rigor mortis — the death state — is the permanent lock resulting from ATP depletion: stiffness rises from 0.3 kPa (relaxed) to 25–100 kPa (rigor), with no available reversal pathway. Construction map: ATP = the authorisation token. The construction material equivalent of ATP depletion is the cryptographic key being withheld. The FWH is designed to be anatomically incapable of rigor: the FAULT state traps the system safely but never permanently locks the form without a recovery pathway.

4. Architectural Geometry

The FWH shell geometry must satisfy three simultaneous requirements: (i) non-negative Gaussian curvature $\kappa = \kappa_1 \cdot \kappa_2$ for direct inflatable formability from a flat membrane blank — surfaces with $\kappa < 0$ cannot be formed from a flat sheet without seaming; (ii) minimal or near-minimal mean curvature $H = (\kappa_1 + \kappa_2)/2$ for uniform stress distribution; (iii) asymmetric, organic form achieving the parametric aesthetic characteristic of Hadid parametric work. Table 3 evaluates the five candidate surfaces computed in Section D of the simulation suite.

Table 3. *Architectural surface analysis for FWH application. Gaussian curvature κ, mean curvature H, inflatable formability from flat blank, and structural role. Primary form selected: deformed elliptic paraboloid (a ≠ b).*

Surface	κ (Gaussian)	H (Mean)	Inflatable?	FWH role
Catenary arch, revolved	<0 saddle	≠0	Vault only	Eliminates bending; base tension ring required
Elliptic paraboloid (a≠b)	≥0 synclastic	≠0	YES — directly ★	Primary form; inflation sets full geometry
Hyperboloid of one sheet	<0 anticlastic	≠0	Partial (ruled)	Secondary; seams required in membrane
Catenoid r=a·cosh(z/a)	<0	H=0 ★	Partial	Interior channel geometry reference
Schwartz P surface	mixed; mean=0	H=0 ★	NO	Research frontier; not constructible from flat

Figure 5

*[See attached PNG file: d5 *.png]*

Figure 5. *Five candidate architectural surfaces. Top row: catenary arch (revolved), elliptic paraboloid (selected primary form), hyperboloid of one sheet. Bottom: catenoid (minimal surface H=0), Schwartz P triply-periodic*

minimal surface (point cloud). Lower right: selection matrix. The deformed elliptic paraboloid is selected for positive Gaussian curvature (directly inflatable), structural efficiency, and Hadid-style asymmetry through a≠b parameterisation.

The deformed elliptic paraboloid $z = x^2/a^2 + y^2/b^2$ with $a \neq b$ (e.g. a = 0.6 m, b = 0.9 m) is selected as the primary FWH shell. Positive Gaussian curvature throughout means the ETFE membrane is cut from a flat circular blank and inflated: geometry is set entirely by differential chamber pressure distribution controlled by PlantaOS valve sequences during MORPHOGENESIS. Asymmetry ($a \neq b$) produces the one-sided organic quality characteristic of Hadid's parametric work — one face rises higher, the other sweeps lower and wider — without sacrificing structural efficiency. The catenoid (H = 0) is used as the reference geometry for interior warm-water channel routing: minimal-surface paths minimise channel length for complete interior coverage.

5. Thermal Analysis

Three wall configurations are analysed by one-dimensional steady-state heat conduction $Q = A \cdot \Delta T / R_{total}$, where R_{total} is the total thermal resistance (m²K/W) and A = 5 m² is the total envelope area (1 m² plan footprint structure, four walls plus ceiling, floor insulated on grade). Interior target T = 20°C.

Table 4. *Thermal resistance and required heating power for three wall configurations (A = 5 m², T_interior = 20°C). k_ice = 2.1 W/mK, k_air = 0.026 W/mK, k_VIP = 0.004 W/mK (effective). Igloo benchmark: 2 occupants × 80 W through 300 mm snow (k = 0.15 W/mK, A = 8 m²) maintains ΔT = 40°C.*

Wall configuration	R (m²K/W)	U (W/m²K)	Power at −5°C	Power at −15°C	Power at −30°C
Solid ice, 200 mm (k=2.1 W/mK)	0.095	10.50	1,313 W	1,838 W	2,625 W
Air gap: 150mm ice + 50mm air + 50mm ice	2.018	0.50	62 W	87 W	124 W
VIP + ice: 100mm + 25mm VIP + 50mm ice	6.321	0.16	20 W	28 W	40 W

Figure 6

[See attached PNG file: d6_*.png]

Figure 6. *Left: required heating power (W) vs. exterior temperature for three wall configurations (A=5 m²). Reference lines: 2-occupant metabolic output (160 W), 100 W and 500 W supplementary heaters, warm-water channel capacity. Right: temperature profile through each wall at T_exterior=−15°C. The 0°C isotherm (phase boundary) must remain within the structural ice zone for shell integrity.*

The critical result: solid ice alone (U = 10.5 W/m²K) is thermally catastrophic — equivalent to a single-glazed window across the full envelope, requiring 1,838 W to maintain habitability at −15°C. The air-gap double wall (R = 2.02 m²K/W) is the recommended configuration for the demonstrator: at −15°C exterior, 87 W maintains 20°C interior — achievable from two occupants' metabolic output alone, equivalent to the igloo thermal model (Laidler, 1968). The VIP configuration (R = 6.32 m²K/W) approaches passive performance and is the target for production-scale units. The igloo validation: 2 × 80 W through 300 mm snow (R = 2.0 m²K/W, A = 8 m²) maintains ΔT = 40°C — the FWH air-gap wall matches this performance in 250 mm total depth with structurally superior material.

6. Phase-Field Simulation of Directional Solidification

The evolution of the liquid-solid interface during FWH solidification is simulated using the Allen-Cahn phase-field equation (Allen and Cahn, 1979), extended with thermal coupling following Karma and Rappel (1996):

```
∂φ/∂t = M [ −f'(φ)  +  ε²∇²φ  +  λ·u ]      [Allen-Cahn, thermal-coupled]f'(φ)
= φ(1−φ)(1−2φ)    double-well potential derivativeu     = (T_m − T) / ΔT
dimensionless undercooling fieldφ = 0: liquid   ·   φ = 1: solid   ·   T_m = 0°C
(melting point)
```

Temperature is prescribed as a fixed linear gradient from T = −10°C at the left boundary (cold exterior wall) to T = +5°C at the right (warm interior face). Grid: 100 × 60 cells, domain 100 mm × 67 mm. Parameters: M = 1.0, ε = 4Δx, λ = 5.0, $\Delta t = 0.8\times10^{-6}$ (CFL stable at 0.0009). Laplacian discretised by standard second-order central differences with Neumann boundary conditions on all free faces.

Figure 7

[See attached PNG file: d7_*.png]

Figure 7. *Allen-Cahn phase-field simulation of directional ice solidification (seed=2026). Domain: 100×67 mm. T=−10°C left (cold exterior), T=+5°C right (warm interior). White=liquid (φ=0), dark green=solid (φ=1). Red contour: φ=0.5 freezing front. Time: t=0 (top-left) to t=6000 steps (bottom-centre). Lower right: front position vs. time — deceleration as front approaches zero-undercooling isotherm at ~63% domain. Physical calibration: sea ice growth 0.3–3 mm/min (Laidler, 1968) → 33–330 min for 100 mm wall.*

At steady state, approximately 63% of the domain has solidified — corresponding to the ice wall thickness achievable under the −10°C exterior / +5°C interior thermal gradient without supplementary interior cooling. The critical engineering insight from the simulation: the freezing front naturally terminates at the zero-undercooling isotherm (T = 0°C boundary) without any active termination signal. This provides a built-in safety mechanism in the SOLIDIFYING state: the system cannot overcool the interior through the freezing process alone, regardless of how long the Peltier elements remain active. PlantaOS uses strain sensor confirmation (strain_delta > 0.92) to detect when structural rigidity is achieved, rather than relying on time elapsed — consistent with the simulation result that front propagation rate is non-constant.

7. PlantaOS: Algorithmic Lifecycle Control

The FWH lifecycle is governed by a deterministic finite state machine with nine states and ten transitions, implemented in Python using the transitions library and validated through two complete simulated lifecycle cycles. Cycle 1 demonstrates the complete sequence including a correctly-denied UNLOCK attempt during occupancy. Cycle 2 demonstrates emergency melt without cryptographic authorisation triggered by simulated fire alarm. Table 5 details each state.

Table 5. *PlantaOS nine-state lifecycle machine. Entry conditions, monitored sensors, actuator outputs, and AFI interpretation for each state. FAULT and EMERGENCY_MELT are reachable from any state via unguarded transitions.*

State	Entry condition	Sensors	Actuators	AFI interpretation
SEED	Initial / drain_complete	None	Idle	Zero Distortion — no form
DEPLOYING	Manual trigger (1 person)	membrane_ok	Pump prime	Perception begins

FLUID	membrane_ready + water_mass OK	pressure, flow_rate	Valve control	Maximum potential Perception
MORPHOGENESIS	form_selected (downloaded)	chamber_pressures	Differential valves	Form as Algorithm
SOLIDIFYING	T_exterior < −2°C AND membrane_ok	T_array[12], strain[4]	Peltier panels	Freedom becoming Form
INHABITED	strain_delta > 0.92	occupancy, T_int, CO_2	Heater, warm channels	Minimum Distortion, habitable
DISSOLVING	crypto_auth AND occupancy=False	T_wall, water_mass	Max heat + drain	Freedom returning to seed
EMERGENCY_MELT	fire OR CO_2 alarm (no auth req.)	All sensors	Max heat, all valves OPEN	Safety overrides all else
FAULT	sensor_failure OR breach	All sensors	Emergency halt	Integrity lost — safe halt

Four safety principles are encoded directly in the transition conditions. First, dissolution (DISSOLVING) requires both a 256-bit cryptographic authorisation token (delivered via app over TLS) and confirmed zero occupancy from the PIR sensor network — the structure cannot be melted beneath an occupant under any non-emergency condition. Second, EMERGENCY_MELT bypasses all authorisation: fire or CO_2 alarm immediately triggers maximum heat output and all drain valves open, prioritising human safety above structural integrity, authorisation protocol, or any other system state. Third, the FAULT state is reachable from any state and does not default to dissolving (potentially unsafe if occupied) or to maintaining form (potentially trapping occupants) — it halts all actuators and sends an emergency notification. Fourth, SOLIDIFYING → INHABITED requires physical strain sensor confirmation (strain_delta > 0.92), not time elapsed alone: the structure is never certified habitable by a timer.

The downloadable form concept: each of the six canonical forms (Gota, Folha, Onda, Vagem, Broto, Raiz) is a 47-step sequence of valve states and Peltier duty cycles that produces a specific deformed paraboloid geometry during MORPHOGENESIS. This sequence is transmitted to the ESP32-S3 controller via MQTT over WiFi and stored in flash. The form is the algorithm. The form library is the software equivalent of an architectural catalogue. Selecting "Gota" in the mobile application downloads the complete choreography that produces the asymmetric droplet paraboloid (a = 0.6 m, b = 0.9 m) from a flat ETFE blank.

8. Engineering Constraint Analysis

Table 6. *Hard constraint verification. PASS: confirmed by calculation or simulation. MARGINAL: conditional pass with identified design response. CONDITIONAL: passes at demonstrator scale.*

Constraint	Result	Conf.	Notes and design response
Fully reversible: fluid → solid → fluid	PASS	0.88	Demonstrated in simulation and in 35 years of Icehotel operation (Pronk et al., 2019)
Reversal in <10 minutes, no specialist equipment	MARGINAL	0.65	50mm wall: 91 kg = 30 MJ. At 100 kW (twenty portable 5 kW heaters): ~5 min. 100mm wall

			requires generator (200 kW). Design response: specify 50mm for demonstrator.
No dangerous thermic risk to occupants	PASS	0.85	Emergency melt produces liquid water at <5°C. EMERGENCY_MELT fires only on alarm override; DISSOLVING requires occupancy=False.
No permanent water damage to structure	PASS	0.82	ETFE membrane UV/water-stable >20 years. Drainage passive gravity. No pooling by design.
Total cost ≤ €300 per structure	CONDITIONAL	0.60	1m² demonstrator: ETFE ~€80 + sensors ~€120 + electronics ~€60 = ~€260. 30m² production unit requires cost re-analysis.
One person can deploy and operate	PASS	0.80	Pack weight ~15 kg. Water: garden hose. Control: mobile app via MQTT. State machine: fully automated.
seed→fluid→form→fluid→seed: guaranteed	PASS	0.85	State machine enforces complete lifecycle. No unrecoverable terminal states outside FAULT.

The reversal time constraint is the principal tension point. Melting 183 kg of ice (100 mm wall, 1 m² structure) requires delivering 61 MJ — the latent heat of fusion at L_f = 335 kJ/kg. At 200 kW, this takes 305 seconds (5 minutes), within the constraint, but 200 kW implies a generator or grid connection, not a portable device carryable by one person. The engineering resolution: specify 50 mm walls for the demonstrator. Mass = 91 kg, energy = 30 MJ. At 100 kW (twenty portable 5 kW construction heaters, individually carryable): approximately 300 seconds — 5 minutes, within the constraint. Structural analysis confirms 50 mm is mechanically adequate: compressive safety factor > 245 at −10°C, well in excess of the SF = 3 design requirement. The structure is thermally constrained, not structurally constrained — a direct expression of the AFI equation: Distortion at 100 mm wall thickness is higher than necessary.

9. Patent Strategy and Novel Claims

9.1 Prior Art Assessment

Prior art review identifies three relevant prior art domains. Structural ice composites: Perutz (1948) establishes Pykrete — the material has no novelty for the FWH. Inflatable-membrane ice shells: Pronk et al. (2019) demonstrate inflatable-membrane construction at 20+ m spans — inflatable formwork for ice has prior art. IoT building control: broadly established across the literature. The novel element is the specific combination: pre-formed membrane defining target geometry + OS-directed directional freezing sequence + cryptographically authorised reversibility protocol + downloadable form library as a unified lifecycle system. This combination does not appear in the reviewed literature or patent databases. Live ESPACENET search is recommended before filing; the following claims are indicative.

9.2 Proposed Claims (EUIPO — IPC: E04B 1/00, E04H 15/00, G05D 23/00)

Claim 1 — System

A deployable structural system comprising: (a) a flexible membrane enclosure pre-formed to define a target architectural geometry characterised by non-negative Gaussian curvature; (b) a liquid water filling system configured to pressurise said membrane to self-supporting form at ambient temperature; (c) a programmable cooling apparatus configured to directionally solidify said water within said membrane in a computed sequence; (d) a digital control system receiving real-time sensor data and executing a solidification protocol downloaded from an external application as a library of geometric forms; and (e) a dissolution protocol comprising controlled thermal input and passive drainage, returning said system to its initial packed configuration; wherein the complete cycle from packed configuration to structural to packed configuration is operable by a single person without specialist equipment or fixed infrastructure.

Claim 2 — Method

A method of constructing and deconstructing a temporary habitable structure comprising: (i) deploying a pre-formed flexible membrane; (ii) pressurising said membrane with water to achieve hydrostatic self-support and target geometric form; (iii) executing a computer-directed directional solidification sequence to produce structural ice; (iv) maintaining habitable interior temperature via a warm-fluid thermal management subsystem during occupancy; (v) executing a cryptographically authorised dissolution sequence upon confirmed absence of occupancy; and (vi) recovering the membrane and control hardware to packed configuration; wherein steps (iii) and (v) are governed by a downloadable algorithmic protocol selected from a form library.

Claim 3 — Thermal Management System

A thermal management system for a frozen-water structural shell comprising warm fluid circulation channels positioned on the interior surface of said shell; a pump regulating fluid temperature and flow rate; and a control system being the same digital controller managing the solidification and dissolution protocols; wherein said control system maintains interior air temperature within a defined habitable range while preserving structural ice at the required operating temperature; and wherein the channel geometry follows a minimal-surface routing derived from the catenoid reference surface, and the control algorithm implements a distributed proportional controller functionally equivalent to the biological countercurrent heat exchange model of vascular thermoregulation.

10. Conclusions

This paper has demonstrated that Ice Ih satisfies the structural requirements for single-story habitable construction at temperatures below −5°C, with compressive safety factors exceeding 200 at 50 mm wall thickness and 491 at 100 mm. The critical structural design constraint is not compression but tensile hoop stress at the shell base: resolved by catenary geometry, Pykrete base zone, or textile tension ring. An air-gap double wall achieves $R = 2.02\ m^2K/W$, requiring 87 W to maintain 20°C interior at −15°C exterior — achievable from two occupants' metabolic output alone, validating the igloo thermal model at reduced wall thickness.

The biological algorithm framework establishes that nature has refined programmable, reversible, water-based structural and thermal systems across 3.5 billion years of selective pressure. The four extracted algorithms — coagulation/fibrinolysis, turgor pressure, vascular thermoregulation, and actomyosin contraction/rigor — map with engineering precision to PlantaOS subsystems. The critical biological observation is that rigor mortis achieves the same compressive strength as Ice Ih at −5°C with zero reversibility: the difference between the living and the dead, in structural terms, is the presence of a reversal key. The FWH encodes this key as a cryptographic token and the reversal as a thermodynamic state transition authorised by software.

The Allen-Cahn phase-field simulation confirms that directional solidification under a thermal gradient is stable, predictable, and self-terminating at the zero-undercooling isotherm — a built-in safety mechanism requiring no active termination signal from PlantaOS. The nine-state machine, validated through two complete lifecycle simulations, enforces the safety logic of the coagulation cascade: cascade amplification for LOCK, cryptographic specificity for UNLOCK, and unconditional override for emergency dissolution.

The Freedom Water Home is not a prototype of a technology. Igloos are the technology. The FWH is a prototype of a perception shift. When a person watches water become a wall, and the wall become water again, the concrete cage is exposed for what it has always been: not a physical necessity, but a failure of imagination, frozen into form. The governing equation is not a metaphor. FREEDOM = (Perception / Distortion)^α∞ is an engineering specification — and ice, at −10°C, is its most Distortion-minimal structural solution currently accessible at planetary scale.

Acknowledgments

This work was supported by FCT through Project 2025.00020.AIVLAB.DEUCALION, providing access to the Deucalion supercomputer at MACC, Guimarães, Portugal.

References

Allen, S.M. and Cahn, J.W. (1979). A microscopic theory for antiphase boundary motion and its application to antiphase domain coarsening. Acta Metallurgica, 27(6), 1085–1095. https://doi.org/10.1016/0001-6160(79)90196-2

Cosgrove, D.J. (2005). Growth of the plant cell wall. Nature Reviews Molecular Cell Biology, 6(11), 850–861. https://doi.org/10.1038/nrm1746

Finer, J.T., Simmons, R.M. and Spudich, J.A. (1994). Single myosin molecule mechanics: piconewton forces and nanometre steps. Nature, 368(6467), 113–119. https://doi.org/10.1038/368113a0

Fung, Y.C. (1993). Biomechanics: Mechanical Properties of Living Tissues. 2nd ed. Springer, New York. ISBN 978-0-387-97947-4

IAPWS (2011). Revised Release on the Pressure along the Melting and Sublimation Curves of Ordinary Water Substance. International Association for the Properties of Water and Steam. Available: www.iapws.org

Karma, A. and Rappel, W.J. (1996). Phase-field method for computationally efficient modeling of solidification with arbitrary interface kinetics. Physical Review E, 53(4), R3017–R3020. https://doi.org/10.1103/PhysRevE.53.R3017

Knight, C.A. and Duman, J.G. (1986). Inhibition of recrystallization of ice by insect thermal hysteresis proteins: a possible cryoprotective role. Cryobiology, 23(3), 256–262. https://doi.org/10.1016/0011-2240(86)90051-9

Laidler, K.J. (1968). The physics of the igloo. Journal of Chemical Education, 45(9), 576. https://doi.org/10.1021/ed045p576

Magalhães, G.M. (2024). Sistema modular de construção (Planta modular construction system). Portuguese Patent PT120952. Instituto Nacional da Propriedade Industrial (INPI). Art. 72(3).

Milani, P., Braybrook, S.A. and Boudaoud, A. (2013). Shrinking the hammer: micromechanical approaches to morphogenesis. Journal of Experimental Botany, 64(15), 4651–4662. https://doi.org/10.1093/jxb/ert169

Monroe, D.M. and Hoffman, M. (2006). What does it take to make the perfect clot? Arteriosclerosis, Thrombosis, and Vascular Biology, 26(1), 41–48. https://doi.org/10.1161/01.ATV.0000193624.28251.83

Mow, V.C. and Ratcliffe, A. (1997). Structure and function of articular cartilage and meniscus. In: Mow, V.C. and Hayes, W.C. (eds.), Basic Orthopaedic Biomechanics. 2nd ed. Lippincott-Raven, Philadelphia, pp. 113–177.

Petrovic, J.J. (2003). Mechanical properties of ice and snow. Journal of Materials Science, 38(1), 1–6. https://doi.org/10.1023/A:1021134128038

Perutz, M.F. (1948). A description of the iceberg aircraft carrier and the bearing of the mechanical properties of frozen wood pulp upon some problems of glacier flow. Journal of Glaciology, 1(3), 95–104. https://doi.org/10.1017/S0022143000007796

Pronk, A., Mistur, M., Li, Q., Liu, X., Dong, E., Wu, Y. and Luo, P. (2019). The 2017–18 design and construction of ice composite structures in Harbin. Structures, 18, 117–127. https://doi.org/10.1016/j.istruc.2018.11.013

Schulson, E.M. (2001). Brittle failure of ice. Engineering Fracture Mechanics, 68(17–18), 1839–1887. https://doi.org/10.1016/S0013-7944(01)00037-6

Timoshenko, S. and Woinowsky-Krieger, S. (1959). Theory of Plates and Shells. 2nd ed. McGraw-Hill, New York.

Zoelly, R. (1915). Über ein Knickungsproblem an der Kugelschale. Doctoral dissertation, ETH Zürich.