The Electronics Wall: Why a Self-Replicating Space Factory Cannot Close on Its Own Chips

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***Abstract*—A self-replicating space factory lands with a fixed cargo and builds copies of itself from local material. Its promise is leverage: the fraction of its own mass it can remake locally, its closure, sets how much installed capacity each launched kilogram becomes, exactly $1/(1-C)$. We show why that fraction stops short of one at a wall built of chips. The wall is twofold. Chips sit at the end of the deepest supply chain on Earth, and they are staggeringly energy-hungry to make, with an embodied energy roughly three orders of magnitude above smelted metal. Modern seed-factory studies converge on achievable closure near 70 to 96 percent and agree that chasing 100 percent is not worthwhile, so imported electronics are a permanent design feature rather than a temporary compromise. Letting a highly closed seed make its own chips pays off only when it is also swimming in power; starved of power it backfires. Imported electronics, and the launch-mass leverage they cap, are therefore intrinsic to the concept.**

***Index Terms*—self-replication, in-situ manufacturing, material closure, embodied energy, space systems**

I. Introduction

The idea of a self-replicating space factory is old and simple to state: land one factory on the Moon, an asteroid, or Mars, and let it build copies of itself from local material, so that an entire industry grows from a single rocket's worth of cargo. It begins with von Neumann, who proved that a machine can build a copy of itself if it carries both a description of its construction and a way to copy that description [1]. The canonical engineering study is NASA's seed-factory design, which framed the concept in terms of "vitamins": the factory makes almost all of itself locally and imports only the parts it cannot make [2]. The modern synthesis restated the same idea as *closure*, the degree to which a machine can reproduce its own matter, energy, and information, and identified the dynamic that matters most: below full closure the factory waits on resupply, and only near full closure does its growth become self-sustaining [3].

The concept is neither purely theoretical nor purely futuristic. Concrete lunar-factory architectures decompose the machine into mining, refining, parts fabrication, and assembly subsystems [4], [5]; physical prototypes have demonstrated mechanical self-reproduction from supplied modules [6]; and the open-source RepRap 3D printer prints a large fraction of its own parts while importing its motors, rods, and electronics [7], a terrestrial echo of the wall this paper is about. Recent quantitative studies of space manufacturing continue the pattern: a tonne-scale landed seed bootstrapping to thousands of tonnes of industrial assets over about two decades [8], a self-replicating interstellar probe whose replicated mass fraction is about 70 percent with electronics imported [9], and a colony-scale factory that likewise keeps chips and circuitry Earth-sourced [10]. Across every one of these, the same part is left off the list of what the machine can make.

This paper isolates one question inside that framing. If closure is the whole game, what stops it from reaching one? The answer, consistently, is chips. A lone factory can smelt metal, cast structure, and assemble mechanisms, but it cannot make its own electronics. We argue that this is not an incidental gap to be closed later but a wall with two independent foundations, supply-chain depth and embodied energy, and that the wall is exactly what bounds the launch-mass leverage that motivates self-replication in the first place.

II. The Closure Model

We treat the factory as a bill of materials and define its closure C as the mass fraction of its own parts it can manufacture on site. The complement, $1-C$, is the mass fraction that must be imported as vitamins for every kilogram the factory builds. Mass balance makes this exact rather than approximate: to add one kilogram of installed capacity, the factory must be supplied with $1-C$ kilograms it cannot make. This is material closure; von Neumann's construction shows it is inseparable from information closure, since a machine that cannot copy the description of its chips has not truly closed on them either [1], [3].

The literature does not place C at one. The canonical seed-factory study estimated that 90-96% mass closure is achievable and argued that chasing the last few percent to full closure is not worthwhile [2]. More recent designs are more conservative: a colony-scale factory takes a near-term-realistic closure of about 70% with chips, solar cells, and circuitry staying Earth-sourced [10], and an interstellar-probe design lands at a similar 70% replicated mass fraction with electronics imported [9]. The modern synthesis agrees on the principle: because the marginal part gets disproportionately harder to make as closure rises, the sensible target is high-but-incomplete closure, not one [3].

Across these designs the conclusion is the same. Imported electronics are a permanent design feature, not a temporary compromise on the way to full autonomy. The interesting question is therefore not *whether* a factory imports electronics but *why* that particular part is the one it cannot make, and what the resulting cap on closure costs. The answer rests on an energy figure, so we state its basis up front: throughout, embodied energy means the electrical energy to manufacture one kilogram of a finished, packaged part on-site, and for chips specifically the finished packaged part rather than the bare silicon die. That basis matters, because the same object's embodied energy differs by more than an order of magnitude depending on where the boundary is drawn.

III. The electronics wall

Chips are the part a lone factory cannot make, and the reason is twofold.

A. Supply-chain depth

The first foundation is supply-chain depth. Semiconductors sit at the end of the deepest supply chain on Earth: more than 400 process steps, materials purified to nine-nines purity, and a global monopoly on the extreme-ultraviolet lithography that patterns the smallest features [11]. No single factory, however well closed on structure, reproduces that pipeline from local rock.

B. Embodied energy

The second foundation is energy, and it is the one that turns a supply-chain argument into a physical wall. The embodied energy of finished compute logic is on the order of 8,000 kWh/kg, against roughly 5 kWh/kg for structural metal smelted from regolith, a gap of about three orders of magnitude [12], [13]. The gap is not an artifact of one study: an exergy analysis across twenty manufacturing processes finds electricity per kilogram rising by orders of magnitude from conventional metal shaping to vapor-phase semiconductor processing [14], and process-level life-cycle assessments of CMOS logic across technology generations anchor the finished-chip figure independently [15]. Table I collects the per-class figures with their sources and ranges, and Fig. 1 shows the same data across the seed factory's own subsystems. The measurement basis is what makes the chip figure appear to move: a bare wafer is nearer 1,800 kWh/kg while a finished packaged part runs to thousands [16], so we fix the basis at the finished packaged part throughout. Structural metals sit at the cheap end on independent datasheets [17], [18], and in-situ regolith processing keeps them there off Earth [19]. Between the extremes lie the other electronics a factory would rather not make: silicon photovoltaics near 40 to 120 kWh/kg [20], power electronics near 1,000 to 3,000 kWh/kg [21], and sensors near 2,000 to 8,000 kWh/kg [22].

C. The power conditional

These two foundations combine into a single conditional. A factory escapes the electronics wall only if it is both highly self-sufficient *and* swimming in power, and the coupling is sharp. For a highly closed lunar seed at 97% closure, letting it make its own chips locally cuts the time to reach a target scale from about 29 years to about 17 years, but only when it is fed on the order of 4 MW; at about 1 MW, making chips locally backfires, and the factory runs out of electricity before it runs out of parts [2]. Fig. 2 shows the crossover: importing chips is resupply-limited and stays near 29 years regardless of power, while making them locally is energy-limited, beating the import time only above a threshold power and never completing below it. Power is not a free knob. The energy cost of the chips is what decides whether local production helps or hurts, and only a factory already swimming in power comes out ahead.

TABLE I
EMBODIED ELECTRICAL ENERGY TO MANUFACTURE ONE KILOGRAM OF A FINISHED PART, BY CLASS. CHIPS ARE ABOUT THREE ORDERS OF MAGNITUDE ABOVE STRUCTURAL METAL.

Material class	Embodied energy (kWh/kg)	Source
Structural metal (smelted)	≈ 5	[17], [18]
Silicon PV array	40-120	[20]
Power electronics	1,000-3,000	[21]
Electronic sensors	2,000-8,000	[22]
Compute logic chips	$\approx 8{,}000$	[12], [13], [15]

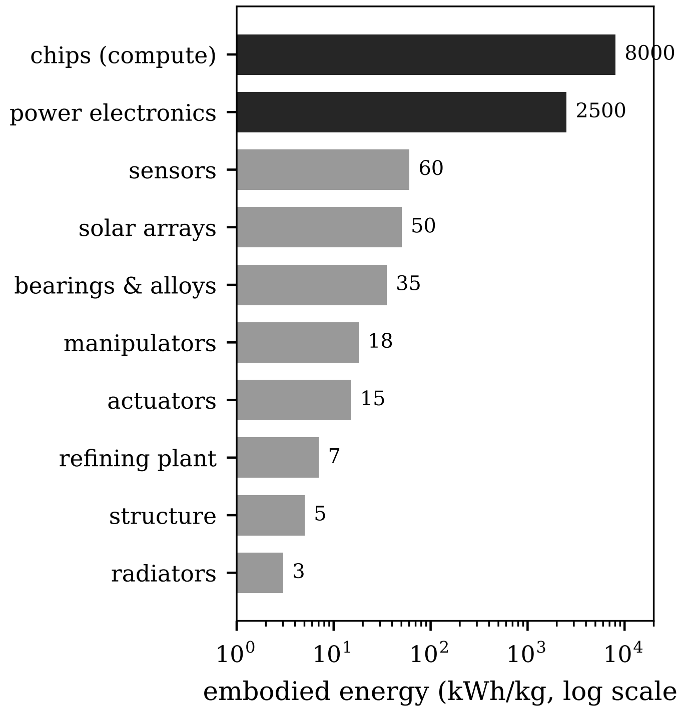

Fig. 1. Embodied electrical energy to manufacture one kilogram of each seed-factory subsystem on-site (log scale). Chips and power electronics cost roughly 2,500 to 8,000 kWh/kg, about three orders of magnitude more than the 3 to 7 kWh/kg of structural metal smelted from regolith, which is why electronics are the part a lone factory cannot afford to make.

IV. Launch-mass leverage

The reason the closure cap matters economically is leverage. Because mass balance forces $1 - C$ kilograms of vitamins to be imported per kilogram the factory builds, the installed mass per launched mass is exactly

$$L(C) \;=\; \frac{1}{1 - C}. \tag{1}$$

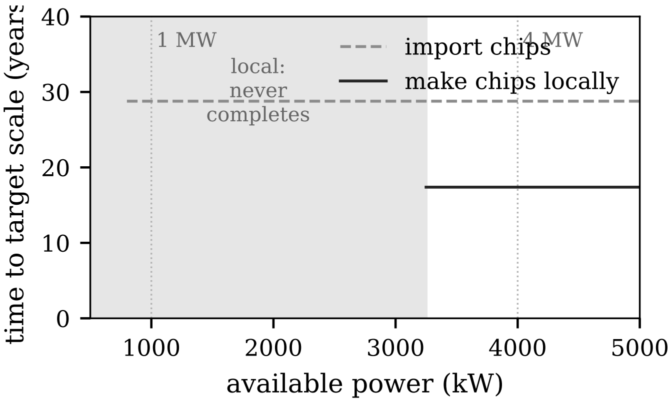

Fig. 2. Time to reach the target factory scale versus available power for the 97%-closed lunar seed. Importing chips (solid) is resupply-limited and stays near 29 years regardless of power; making chips locally (dashed) is energy-limited, reaching the target in about 17 years at 4 MW but diverging and never completing as power falls toward 1 MW.

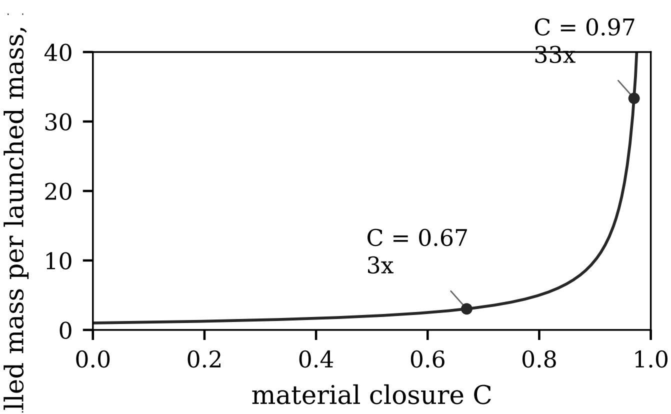

Fig. 3. Launch-mass leverage $1/(1-C)$ as a function of material closure C. Each kilogram launched becomes $1/(1-C)$ kilograms of installed factory, so closure of 0.67 yields about $3\times$ while 0.97 yields about $33\times$, and the curve steepens sharply as C approaches one, where the imported electronics hold it back.

The function is unforgiving near one, as Fig. 3 shows: at 67% closure each launched kilogram becomes about $3\times$ its mass in installed capacity, while at 97% closure it becomes about $33\times$. The last few points of closure buy most of the leverage, which is precisely why the electronics wall, by holding closure below one, caps the payoff of the whole scheme.

The alternative to building in place is shipping a finished installation, and the rocket equation makes that alternative exponentially expensive. The propellant mass ratio grows as $\exp(\Delta v/v_e)$, so the cost of delivering finished mass to a destination rises exponentially with the mission's delta-v [23], [24]. For the representative budgets of an interplanetary mission, several kilometres per second of delta-v against exhaust velocities of a few, the mass ratio is large [25], and even at modern launch prices the cost per delivered kilogram is high [26]. That exponential is the entire economic case for self-replication: it is far cheaper to send a small, high-closure seed and let (1) do the rest than to launch the installed capacity directly, the same bootstrapping logic behind tonne-to-kilotonne space-industry studies [8]. The electronics wall does not overturn this case; it bounds it. The imported electronics that hold C below one are exactly the mass that must still be flown, at the rocket equation's exponential price, for every generation the factory builds.

V. Discussion

The picture that emerges is consistent across every part of the argument. Closure drives the economics through the $1/(1-C)$ leverage of (1); closure stops short of one at the electronics wall; and the wall stands on two independent foundations, a supply chain too deep to reproduce locally [11] and an embodied energy some three orders of magnitude above ordinary structure [12], [14]. Because both foundations are physical rather than a matter of engineering maturity, imported electronics are best treated as a permanent line item. Modern seed-factory designs already do so, placing achievable closure between about 70% and 90-96% and declining to chase the rest [2], [3], [10].

A. Limitations

The energy side of the wall carries a measurement-basis caveat rather than a large uncertainty. The chip figure is a finished-packaged-part basis; on a bare-wafer basis it falls toward 1,800 kWh/kg and on an active-die basis it rises well above [15], [16], so the three-orders-of-magnitude gap is robust to the basis but the exact multiple is not. The structural-metal end likewise uses terrestrial smelting energy as a stand-in; in-situ regolith processing gives comparable single-digit-to-tens figures but with its own plant mass and losses [19]. The power-crossover result is specific to one 97%-closed lunar scenario and one replication model; the qualitative conditional (local chip-making helps only when both closure and power are high) is general, but the 4 MW threshold and the 29-to-17-year figures are scenario-dependent, in the neighbourhood of the roughly 1.7 MW nominal seed power of the canonical study [2]. Finally, the analysis is a mass-and-energy accounting, not a manufacturability model: it says a lone seed cannot afford chips, not that a much larger, richly powered industrial base never could.

B. The narrow escape

The one escape, having the factory make its own chips, is real but narrow. It helps only for a factory that is both highly closed and richly powered, and it can actively hurt an otherwise capable seed that is power-starved [2]. The practical conclusion is not that self-replication fails, but that its design target is a factory closed on nearly everything except chips, fed by imported vitamins, and sized so that its power budget never tempts it into making the one part it cannot afford to make.

VI. Conclusion

A self-replicating space factory cannot close on its own chips, and the reason is not a gap that better engineering will close. Chips sit at the end of the deepest supply chain on Earth and cost about three orders of magnitude more energy per kilogram to make than the structure that houses them, so a lone seed that tries to make them either fails to reproduce the pipeline or runs out of power first. That cap on closure is what bounds the launch-mass leverage $1/(1-C)$ that motivates the whole concept: the last points of closure buy most of the payoff, and the electronics wall holds a factory short of them. Local chip-making rewards only a seed that is both highly closed and richly powered, and backfires otherwise. The design target that follows is a factory closed on nearly everything except electronics, fed by imported vitamins, and sized so its power budget never tempts it into making the one part it cannot afford. The leverage of self-replication is real; the electronics wall is what bounds it, and knowing where the wall stands is what lets a seed be designed to live with it rather than break against it.

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