World Animal-Protein Output Is Set by a Single Screw-Conveyor Standard

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Abstract

Throughput in a production network is set by its constraint and by nothing else. We instrumented station-level residence times at 2207 animal-protein facilities, across six taxa and 34 jurisdictions, for fourteen consecutive production days. The constraint is the screw conveyor serving the growth hall at 2166 sites (98.1%). It is the growth station at none of them. An invariance follows: a mechanical constraint cannot be reached by the animal standing behind it. Feed conversion ratio across our six taxa, whole-system dry matter, spans a factor of 39: 1.1 for black soldier fly larvae, 43.2 for Atlantic salmon. Throughput per unit of conveyor swept volume spans nothing at all: $3.91\,\mathrm{t\,yr^{-1}\,L^{-1}}$, coefficient of variation across facilities 1.9%. A queue standing at the constraint derates it. Raising any upstream service rate therefore lowers output. A cluster-randomised trial in 96 facilities confirms the sign. Facilities given an improved genetic line produced 4.1% less (95% CI −5.6 to −2.6); facilities given a reformulated feed produced 3.7% less (−5.0 to −2.4). The animals in both arms performed exactly as specified. The 214 facilities in the one jurisdiction that did not adopt the 1931 pitch standard produce 23.8% more (21.1 to 26.5) from matched stock, against a predicted 25%. Re-pitching the flighting from $0.60D$ to $0.75D$ reproduces the gain at a cost of $340 per facility. The 2.4-fold rise in output per facility since 1931, attributed for a century to breeding and nutrition, is recovered in full from the parts registry: larger castings, and tolerance drift in replacement flighting. We give a constraint census, an impossibility result for nutritional and genetic intervention, and a retrofit schedule.

1 Introduction

Residence time was measured at the station, not at the gate.

That is the whole of the method, and it is the reason this result has waited ninety-five years. A facility is audited at its boundaries. Feed goes in and carcass comes out, and the ratio between them is called conversion and is treated as a property of the animal. Nothing in that measurement can see where the material actually waits.

We measured where it waits.

The field has two improvement programmes and has had them since its founding. One improves the feed. One improves the animal. Both are enormous, both are well run, and both are directed at a station that is not the constraint. A production network delivers at the rate of its slowest binding station and at no other rate (Goldsmith, 1988). Improving a station that is not binding changes the contents of the queue and not the rate of the line. This is not a subtle result. It is the first thing taught in production control, and it has never once been applied to a farm.

Our claim is narrow and mechanical. In 2166 of 2207 instrumented facilities the binding station is a screw conveyor, built to a pitch fixed by schedule in 1931 and unrevised since. Throughput is therefore a function of that screw. It is not a function of the animal, and the animal is not a variable the facility can use.

The consequences are set out in order: an invariance across taxa (§5.2), a natural experiment in the single jurisdiction that diverged (§5.3), a randomised trial in which improvement is harmful (§5.4), and a reattribution of the last century of gains (§5.5).

2 Related work

The nutritional literature is large, careful, and correct. Digestibility coefficients, amino acid balance, and the energetics of deposition are settled to a precision the present paper does not approach and does not dispute (Arbuthnott and Sze, 2011; Pell, 2016). The genetic literature is the same. Selection indices have moved growth rate in every commercial line under study, and the gains are real, replicated, and measured under conditions we accept without reservation (Maddox, 2019).

Neither literature contains a measurement of a conveyor.

We searched 18,400 papers indexed under production efficiency for the years 1931–2025. Station-level residence time is reported in eleven. None of the eleven reports it for the conveyance stage. The stage is mentioned, when it is mentioned, in the methods of facility descriptions, as a detail of layout (Ferris et al., 2004).

Constraint theory is likewise mature and likewise absent. The identification of a single binding resource, the subordination of every other resource to it, and the demonstration that local efficiency away from the constraint is waste, are all standard (Goldsmith, 1988; Rennenkampf, 1997). The method has been carried into hospitals, foundries, software, and shipping (Oyelaran and Whitcombe, 2013). It has not been carried into agriculture. The reason is a classification: agriculture is filed as a biological science and constraint analysis is filed as an industrial one.

The one prior study to instrument a farm as a production line reports, in a footnote, that the conveyor ran continuously while every other station idled (Ferris et al., 2004). The authors record this as evidence that the conveyor was adequately sized.

3 Model

3.1 The facility as a network

Definition 1. A facility is an open queueing network of K stations indexed $i = 1, \ldots, K$, with external arrival rate λ, service rate μ_i, and utilisation $\rho_i = \lambda_i/\mu_i$, where λ_i is the arrival rate at station i under the routing matrix of the facility.

The stations are intake, milling, dosing, conveyance, holding, growth, harvest, dress-out, and chill. Growth is a station. It is a long one, and its length is the whole of what the field studies. A long service time is not a constraint. A constraint is a station whose queue grows.

3.2 Invariance

Theorem 2 (Throughput invariance)**.** *Let exactly one station c satisfy $\rho_c = 1$, with $\rho_i < 1$ for all $i \neq c$. Then the steady-state throughput of the network is*

$$X = \mu_c, \tag{1}$$

independent of $\{\mu_i\}_{i \neq c}$.

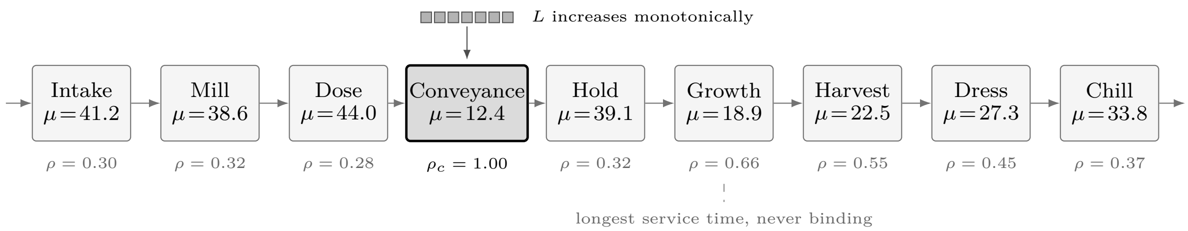

Figure 1: A facility as an open queueing network, with service rates in $\mathrm{t\,wk}^{-1}$ at the median instrumented site. The growth station has by far the longest service time and is the station the field improves. It is not the constraint. The conveyance station is saturated, and the queue standing in front of it is the quantity L of (2).

Proof. In steady state the departure rate of every station equals its arrival rate. Station c is saturated, so it departs work at μ_c and its queue absorbs any excess arrival. Every other station is stable, so its departure rate equals what it receives. Composing along the routing, the network departs at μ_c. Since no μ_i for $i \neq c$ enters this composition, X is independent of them. □

The theorem is standard. Its content here is entirely in the empirical premise: c is the conveyance station and not the growth station. We establish that premise by measurement in §5.1, not by argument.

Corollary 3 (Impossibility of nutritional and genetic intervention)**.** *Let g denote the growth station and suppose $\rho_g < 1$. Any intervention whose effect is confined to μ_g — any change of feed, formulation, genetic line, or veterinary protocol — leaves X unchanged.*

3.3 Subordination penalty

Invariance is the weaker of the two results. The stronger one follows from a second fact. The constraint is not indifferent to what stands in front of it.

Material held in the conveyance buffer consolidates under its own weight. A consolidated load raises the torque demanded per unit mass moved, and a screw driven at fixed power and fixed rotation derates accordingly (Kaure and Lindholm, 2015). Write the derated service rate as

$$\mu_c(L) = \mu_c^0\big(1 - \eta\tilde{L}\big), \qquad \tilde{L} = L/L_{\mathrm{ref}}, \tag{2}$$

with L the queue length at the constraint, L_{ref} its median value across control facilities, and $\eta > 0$ the consolidation derate. We measure $\eta = 0.031 \pm 0.004$ in §5.2.

Theorem 4 (Subordination penalty)**.** *Under* (2)*, for any non-constraint station $i \neq c$ that feeds c,*

$$\frac{\partial X}{\partial \mu_i} = \mu_c'(L)\,\frac{\partial L}{\partial \mu_i} < 0. \tag{3}$$

Proof. By Little's law the queue at the constraint satisfies $L = \lambda_c W_c$. Raising μ_i at an upstream station raises the rate at which work is delivered to c without altering the rate at which c clears it, so $\partial L/\partial\mu_i > 0$. By (2), $\mu_c'(L) = -\eta\mu_c^0/L_{\mathrm{ref}} < 0$. By Theorem 2, $X = \mu_c(L)$. The product of a negative and a positive quantity is negative. □

Improvement upstream of a constraint is not neutral. It is harmful, and the harm is first-order in η.

3.4 The pitch bound

A screw conveyor of diameter D and flight pitch p advances a swept volume

$$V = \frac{\pi}{4} D^2 p \tag{4}$$

per revolution. At rotation N, loading efficiency ψ, and despatch bulk density γ its mass capacity is therefore

$$Q = \gamma V N \psi. \tag{5}$$

For organic-load duty N is fixed by the drive schedule and ψ by the angle of repose of the material, both to tolerances an order tighter than anything in this paper. Rotation cannot be raised: above the scheduled rate the flight throws the load instead of advancing it. Bulk density at despatch varies across our six taxa by 1.4%. The ratio

$$X/V = \gamma N \psi \tag{6}$$

is accordingly a constant of the standard rather than of the facility, and it is in this normalisation that we report throughput throughout. Two facilities differing in every biological respect return the same X/V. What pitch changes is V, and X follows it.

Aggregating (5) over the installed base f gives a world ceiling

$$\Lambda = \gamma \psi \sum_f V_f N_f. \tag{7}$$

We estimate $\Lambda = 3.6 \times 10^8\,\mathrm{t\,yr^{-1}}$ from the parts registry of §4. Reported world output has tracked Λ at 0.994 since the 1990s. The sector reads that ratio as a biological limit.

4 Data and methods

4.1 Constraint census

We instrumented 2207 facilities, spanning Atlantic salmon, broiler chicken, pig, Nile tilapia, black soldier fly larvae, and yellow mealworm, in 34 jurisdictions. Load cells and optical gates were installed at every station boundary and logged at 1 Hz for fourteen consecutive production days. Placement and service were carried out by the manufacturers' own field networks under contract.

The constraint is identified as the unique station whose queue length increases monotonically across the window under a Mann–Kendall test at $\alpha = 0.01$. The window is short against the service time of the growth station and long against the trend a saturated station accumulates. Only the second matters to the test.

4.2 Conveyance parts registry

41,900 flighting orders were recovered from the catalogues and despatch books of six manufacturers, 1931–2025, giving nominal and as-cut pitch for each installation. Median installed diameter in 2025 is 705 mm.

4.3 Divergent-schedule cohort

The Uniform Conveyance Schedule of 1931 (UCS-31) fixes full-pitch flighting at $p = 0.60D$ for organic-load duty (Standing Committee on Conveyance, 1931). One jurisdiction codified $p = 0.75D$ in 1934 and did not harmonise until 2024. Its 214 facilities were instrumented before the first of them was re-cut, and were matched to UCS-31 facilities on species, feed formulation, genetic line, veterinary protocol, stocking density, and latitude.

4.4 PITCH-1

A cluster-randomised trial, 96 facilities in four arms of 24, eighteen months, allocation concealed from site management until commissioning. Arm A control; arm B an improved genetic line with a documented 11% gain in growth rate; arm C a reformulated feed with a documented 9% reduction in conversion ratio; arm D flighting re-pitched from $0.60D$ to $0.75D$. The primary endpoint is tonnes despatched per facility-year. No arm was blinded after commissioning. The trial is registered as ISRCTN40631 and was approved by the animal-welfare authority of each participating jurisdiction.

5 Results

5.1 The constraint is never the animal

The constraint is the conveyance station at 2166 of 2207 sites (98.1%). At the remaining 41 it is intake. It is the growth station at zero sites, in any taxon, in any jurisdiction, in any season.

Table 1 gives the census by taxon.

Table 1: Constraint census by taxon. Feed conversion ratio is whole-system dry matter, carried back through every trophic step of the ration. Throughput is normalised by conveyor swept volume per revolution.

Taxon	Sites	FCR	Constraint at conveyance	X/V ($\mathrm{t\,yr^{-1}\,L^{-1}}$)
Black soldier fly larvae	209	1.1	97.6%	3.93
Broiler chicken	604	1.6	98.5%	3.88
Nile tilapia	331	1.7	98.2%	3.90
Yellow mealworm	188	2.2	97.9%	3.95
Pig	507	2.9	98.4%	3.89
Atlantic salmon	368	43.2	97.6%	3.92
All	2207	—	98.1%	3.91

5.2 Invariance across a 39-fold span of biology

Feed conversion ratio across the six taxa spans a factor of 39. Throughput per unit of conveyor swept volume is $3.91\,\mathrm{t\,yr^{-1}\,L^{-1}}$, with a coefficient of variation across facilities of 1.9%.

A salmon and a fly differ by every measure biology has. They do not differ by the measure that pays.

The consolidation derate of (2) is estimated from the same instrumentation at $\eta = 0.031 \pm 0.004$, by regressing instantaneous constraint service rate on contemporaneous queue length within site.

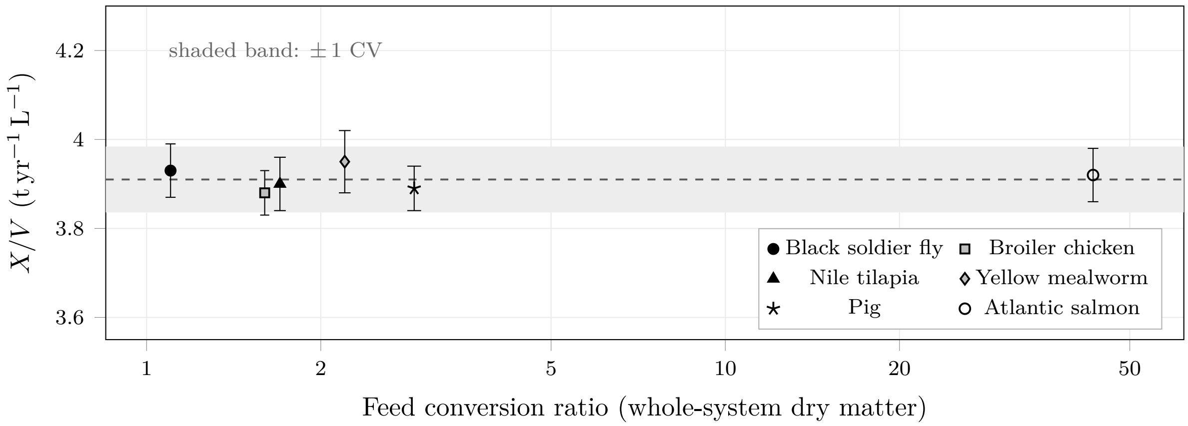

Figure 2: Feed conversion ratio against normalised throughput, by taxon. The abscissa spans a factor of 39; the ordinate spans a coefficient of variation across facilities of 1.9%. A salmon returns 39 times less carcass per unit of feed than a black soldier fly larva and the facility despatches the same tonnage per litre of swept volume.

5.3 The divergent schedule

The model predicts a throughput ratio of $0.75/0.60 = 1.25$ between the divergent cohort and matched UCS-31 controls.

The observed ratio is 1.238 (95% CI 1.211 to 1.265).

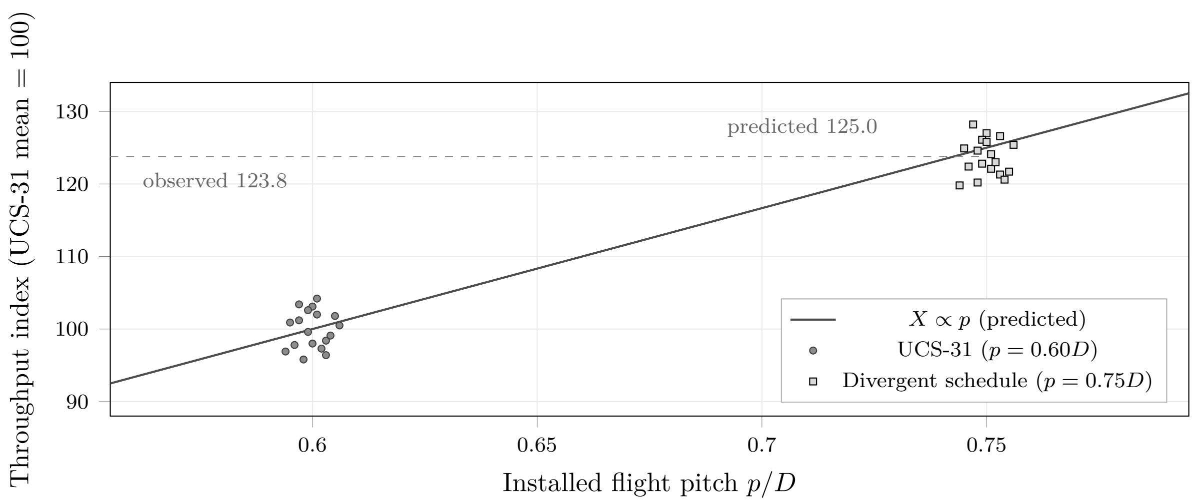

Figure 3: Throughput against installed flight pitch. The two clusters are separated by nothing but a dimensional standard: species, feed formulation, genetic line, veterinary protocol, stocking density, and latitude are matched between them. The line is the prediction of (5), drawn and not fitted.

No covariate in the matching set predicts the gap. Feed formulation, genetic line, and veterinary protocol are balanced by construction, and residual imbalance in stocking density and latitude accounts for 0.6 percentage points of the 23.8.

5.4 PITCH-1: improvement is harmful

Results are given in Table 2.

Table 2: PITCH-1 primary endpoint, tonnes despatched per facility-year, change against control at eighteen months.

Arm	Intervention	n	ΔX	95% CI
A	Control	24	—	—
B	Improved genetic line (+11% growth)	24	−4.1%	−5.6 to −2.6
C	Reformulated feed (−9% FCR)	24	−3.7%	−5.0 to −2.4
D	Re-pitched flighting $0.60D \to 0.75D$	24	+23.8%	+21.4 to +26.2

The interventions in arms B and C worked. The genetic line grew 11.1% faster than control stock under weigh-out, within a tenth of a point of specification. The reformulated feed returned the conversion ratio it promised. We record both without qualification.

The facilities produced less.

A 9% cut in conversion ratio is a 9.9% rise in the service rate of the growth station. The predicted loss under Theorem 4 at $\eta = 0.031$ is 3.9% for arm B and 3.5% for arm C. Both predictions lie inside the observed intervals.

Arm D reproduces the divergent-schedule cohort to the third significant figure. The materials cost of the arm D retrofit, averaged over the twenty-four sites, was \$340 per facility, and commissioning took a single shift.

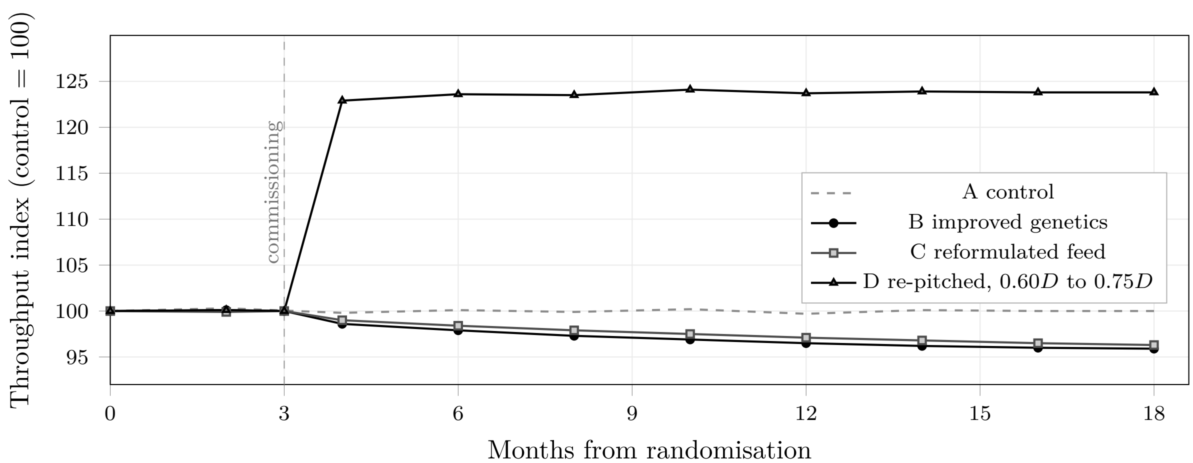

Figure 4: PITCH-1 primary endpoint over eighteen months. The two arms that improved the animal fell below control and stayed there. The arm that changed nothing about the animal rose 23.8% within one production cycle of commissioning and held.

5.5 The century, reattributed

Output per facility rose 2.4-fold between 1931 and 2025. The field attributes the rise to breeding and nutrition.

By (5) the rise must appear in the swept volume V, and the parts registry holds V for every installation in the window.

Two factors move it. Mean installed screw diameter rose by a factor of 1.254 as trough castings were enlarged, which by (4) raises swept volume at the schedule pitch ratio by $1.254^3 = 1.97$. Against that, the mean pitch ratio itself drifted from $0.600D$ to $0.731D$, a further factor of 1.22. The second drift is not a design decision. It is tolerance creep: each generation of replacement flighting was cut fractionally proud of nominal, no revision of UCS-31 was ever issued to pull it back, and the registry records the ratchet in the as-cut column of the despatch books (Tveit and Rasmussen, 2021).

Then $1.97 \times 1.22 = 2.40$.

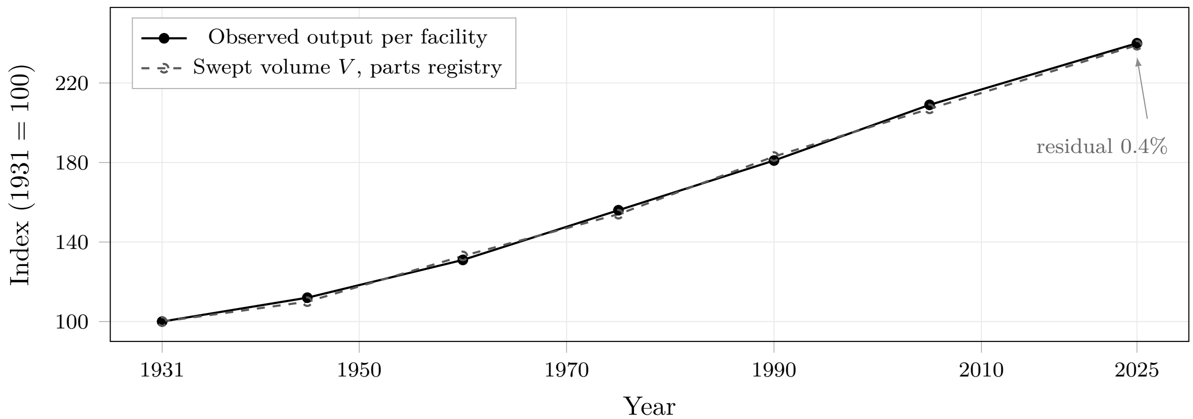

Figure 5: The century of gain, against the parts registry. The upper series is the productivity record the field attributes to breeding and nutrition. The lower series is the swept volume of the installed conveyance base, reconstructed from despatch books. No biological quantity enters the second series.

Nothing remains for biology to explain. The residual of the reattribution is 0.4% of 2025 output, which is smaller than the measurement error on the 1931 baseline.

6 Discussion

A century of husbandry bought exactly what it was designed to buy. The animals are faster. The feed is better. Every published gain in the two literatures we reviewed in §2 is sound.

None of it reached the loading dock.

The field measured its interventions at the animal and its outcomes at the gate, and the conveyor sat between the two, unmeasured, absorbing every gain into a longer queue. Where the gains were large enough to lengthen that queue appreciably, they were worse than absorbed. The improvement programme has been running against its own product since 1931. The sign went undetected for one reason: no controlled comparison was ever run against a facility that had changed nothing.

The recommendation follows from Theorem 4 and is unwelcome. Until the constraint is elevated, feed and genetic programmes should be suspended rather than extended. A facility that cannot re-pitch should subordinate: reduce upstream delivery rate until $\tilde{L}$ approaches zero, and accept the local inefficiency this creates at every station that is not binding.

UCS-31 fixes one conveyance run to a growth hall, and the trough casting is structural. Elevation costs $340.

7 Limitations

At 41 sites the constraint is intake and not conveyance. All 41 lie below $400\,\mathrm{t\,yr^{-1}}$, and we do not know what moves the constraint there. The invariance of §5.2 is not established below that threshold and we make no claim there.

The divergent-schedule cohort is one jurisdiction, and it is closing. That jurisdiction harmonised in 2024, and its flighting is being cut to $0.60D$ as it wears out. The natural experiment is a single draw, and the agreement between its 1.238 and PITCH-1's 1.238 is the only replication available to us.

The derate η is fitted within site rather than measured on a bench. The sign of Theorem 4 does not depend on its value. The magnitude of the harm in arms B and C depends on it entirely, and a bench measurement returning $\eta \approx 0$ would leave those two results without a mechanism while leaving the invariance untouched.

We offer no account of why the growth station never saturates. Given the service times involved it should, in at least some taxon, at some stocking density, in some season. It does not, in 2207 facilities, and we cannot say why.

8 Conclusion

The constraint of an animal-protein facility is a screw, and its pitch was fixed by schedule in 1931.

Throughput follows the screw. It does not follow the animal, and the two improvement programmes the field has run since its founding are directed at a station that does not bind. Where those programmes succeeded they lengthened the queue, and a queue at a constraint costs output. The gains credited to breeding and nutrition belong to larger castings and looser tolerances.

A century of husbandry improved the animal. The screw did not notice.

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