International Journal of Advanced Engineering, Management and Science (IJAEMS)
Peer-Reviewed Journal
ISSN: 2454-1311 | Vol-12, Issue-4; Jul-Aug, 2026
Journal Home Page: https://ijaems.com/
DOI: https://dx.doi.org/10.22161/ijaems.124.7

Cold Chain Management Under Peak Loads as a Factor in Preserving the Premium Quality of Frozen Fish Products

Andrii Kalinichenko

Freezer Manager, Silver Bay Seafoods, Kodiak, Alaska, USA

Received: 04 Jul 2026; Received in revised form: 01 Aug 2026; Accepted: 06 Aug 2026; Available online: 12 Aug 2026

Abstract *— Premium grade in frozen fish is decided in the hours between landing and the moment a batch leaves the freezer, and the conditions of those hours change when a seasonal plant reaches peak volume. The quality literature measures freezing and frozen storage under steady conditions: a fixed freezing rate, a programmed storage temperature, a planned number of thaw cycles. A processing plant at the height of a salmon run does not operate that way. Arrival rate, queue length, chamber turnaround and door traffic all move at once, and they move the product's thermal history with them. This review proposes a break-point taxonomy for that regime. Five points at which cold chain integrity fails under load are mapped onto the quality-loss mechanism dominant at each, the indicator that makes the loss measurable, and the class of control that holds it. Twenty-nine sources published between 2015 and 2026 are cited, thirteen examined in full text. The penalty for the slower or less controlled route is large and consistent: mean ice crystal cross-sectional area of 939.6 µm² under air freezing against 86.5 µm² under immersion freezing at -40 °C, end-of-storage drip loss of 15.17% at -20 °C against 9.09% at -40 °C, and predicted remaining shelf life falling from 391 to 204 days across a four-stage warming chain. The review closes with a comparative matrix of control practice families and five named gaps, each with a first step.*

Keywords *— cold chain integrity, freezing rate, frozen fish quality, peak load, seafood processing*

I. INTRODUCTION

A freezing shop in the middle of a salmon run is a different thermal system from the one described in most of the frozen fish literature. The equipment is the same. The refrigeration duty is the same. What changes is everything that surrounds the equipment: how long raw material waits before it enters a chamber, how often chamber doors open, how quickly a batch is pulled to make room for the next one, how densely the cold store is packed. Those variables are held constant in a laboratory freezing trial. In a plant at peak volume they are the independent variables, and the product's thermal history follows them.

This matters commercially. Premium grade is a commercial classification rather than a laboratory one: buyers set it, and its physical correlates are the properties this review works with, drip loss and water-holding capacity, ice crystal structure, oxidative and volatile-base indices, and sensory condition. None of them is a property of the freezer. Each is a property of the time-temperature path the product travelled, and that path is set by decisions made in minutes on the floor. A chamber rated for a duty still returns an under-frozen batch if it leaves before its thermal centre reaches target, and a cold store certified to hold -18 °C still degrades product if its effective temperature drifts while it fills.

The author manages the freezing department of a plate-freezing operation in Kodiak, Alaska, where the plant runs fifteen plate-freezing chambers of 2.5 t each and handles up to 85 t of raw material in a twelve-hour shift at the height of the season; the same setting, examined

for its workforce-readiness constraints rather than its quality controls, is described in [1]. The working position taken here comes from that setting: under peak load, premium quality is held by the discipline of the cold chain and by control of freezing timings, and not by equipment specification alone. As the author puts it, the philosophy is uncompromising control of timings and processes, because food safety admits no small details. Wild salmon is the species that sets the season, and it carries a second reason for the same discipline: the resource is finite, so material lost to delay or to mishandled storage is lost twice, once as product and once as the premium grade that product would have carried.

Salmon carries its own review literature on freezing and shelf life [2] and on water-holding behaviour [3], and this review returns to it where a general mechanism has to be read back into this operation.

The contribution is structural. The review proposes a taxonomy naming five break points of cold chain integrity under peak load (B1 to B5), maps each onto the dominant quality-loss mechanism (M1 to M5) and the class of control that addresses it (C1 to C4), and names for each pairing the indicator that would make the loss measurable in a plant rather than a laboratory. Supporting it are a comparative matrix of six control practice families against six criteria that matter under load, and five named gaps where the published evidence does not reach the operating question.

What the review does not do should be stated as plainly. It reports no controlled trial, no instrumented plant measurements and no reproducible protocol. Operational observations from the author's own shop are identified as such wherever they appear; they motivate and illustrate the analysis and are not offered as results.

II. REVIEW METHOD AND SCOPE

Candidate studies were retrieved from OpenAlex, which aggregates Crossref, PubMed and other bibliographic indexes, using eight queries built from the axes of the taxonomy: cold chain management and frozen fish quality; freezing rate and ice crystal formation; pre-freezing holding and microbial spoilage; temperature fluctuation, drip loss and protein denaturation; lipid oxidation in frozen storage; dehydration and freezer burn; cold chain monitoring; and plate and air-blast freezing.

Four inclusion criteria were applied: the study had to concern fish or seafood that is frozen, or the cold chain carrying it; report a quality outcome, whether physical, chemical, microbiological or sensory, rather than describe a process alone; be an empirical study, review or standards-based analysis in a peer-reviewed venue; and appear between 2015 and 2026.

The search identified 283 records. After deduplication and the application of the year, abstract and publication-type filters, 246 remained. Screening against the inclusion criteria left 76 relevant records, from which 30 were carried forward. Twelve of those were obtained and examined in full text. A targeted supplementary search then added salmon-specific sources, since the species that dominates the operating context was absent from the main set; one of them was also read in full, giving thirteen full-text sources in total. Every specific number reported in this review was taken from the full text of the source in which it appears.

Two limitations bound what follows. The first is depth of reading: the thirteen full-text studies supply the quantitative backbone, while the rest were analysed at the level of their reported results, so any assignment of those to a taxonomy class rests on abstracts and carries corresponding uncertainty.

The second is species heterogeneity, since the synthesis pools findings across lean gadoids, fatty pelagics, farmed salmonids and crustaceans, whose composition and dominant degradation pathway differ. The axes are not equally sensitive to that. Ice crystal formation is governed by water content and heat transfer, so results transfer between species with reasonable confidence; lipid oxidation is governed by lipid quantity and fatty acid profile, so a peroxide value from a fatty pelagic states the mechanism but not the rate for a leaner species. The mechanism is general, the specific rate belongs to the organism it was measured in. The bound is worth quantifying rather than gesturing at: one of the thirteen full-text sources concerns salmon directly, and its storage findings rest largely on farmed Atlantic salmon while the operating context here is wild Pacific salmon. The claim borrowed from it, that stability of storage temperature matters more than its depth,

carries across that distinction; species-specific rates do not.

III. BACKGROUND: PEAK LOAD AS A DISTINCT FAILURE REGIME

Frozen fish quality research has produced a detailed account of what happens to muscle tissue at a given freezing rate and storage temperature. What it has not produced is an account of what happens when the rate and the temperature are themselves set by production pressure. The gap is not hypothetical. Tsironi and colleagues report that across measured profiles of frozen fish products, 40% of total time is spent above the recommended -18 °C, varying between -16 and -12 °C, with excursions above -8 °C not rare in retail or domestic storage [4]. That is a description of the real chain rather than the designed one. The same study quantifies the cost. Modelling a four-stage chain whose effective temperature rose from -15.6 °C to -10.4 °C, predicted remaining shelf life for gilthead sea bream fillets fell from 391 to 204 days, with sea bass at 197 and yellowfin tuna at 217 at the final stage [4]. Activation energies for the degradation rates ranged between 49 and 84 kJ/mol across the quality indices tested, which is why a few degrees of drift cost months of shelf life rather than days.

The physical reason the losses are hard to reverse is structural. Water expands by roughly 9% as it forms ice, distorting the surrounding muscle tissue [5]. Where and how the ice forms is therefore not a detail of the process; it is the process. A slow route through the phase-change zone yields fewer and larger crystals that rupture cell structures, and no downstream handling recovers what that destroys. Reviews of the mechanisms in aquatic products [6] and of quality and safety in frozen farmed species [7] converge on the same ordering: crystal morphology upstream of the protein, water-holding and oxidative changes that follow.

Peak load acts on this system through variables that steady-state studies fix by design: arrival rate, which sets how long raw material waits before freezing begins; chamber turnaround, which sets how much of the cycle a batch receives; door-open frequency and batch dwell outside the cold envelope, which scale with the number of cycles run; and cold store filling rate and stacking density, which govern temperature uniformity at the point where the shop floor loses control of the product.

The useful unit of analysis is therefore not the machine. Two plants with identical freezers produce different grade distributions if one runs its chambers to completion and the other does not. What separates them is where their chain breaks under load, and that is what the taxonomy below is built to name.

IV. A BREAK-POINT TAXONOMY OF COLD CHAIN INTEGRITY UNDER PEAK LOAD

The taxonomy has three axes. Axis B names five break points along the physical path of the product: the pre-freezing holding window (B1), the loading and unloading transitions of freezing chambers (B2), truncation of the freezing cycle under volume pressure (B3), post-freezing handling including glazing and packing (B4), and cold storage with the handoff to logistics (B5). Axis M names the dominant quality-loss mechanism at each: ice crystal growth and recrystallisation (M1), drip loss and protein denaturation (M2), lipid oxidation (M3), surface dehydration and freezer burn (M4), and enzymatic and microbial activity before freezing (M5). Axis C names the class of control: engineering (C1), procedural (C2), organisational (C3) and verification (C4). Figure 1 shows the axes and their couplings; Table 1 gives the full map with the indicator that makes each loss measurable.

One constraint governs how the procedural and organisational classes are treated throughout. Timing rules, box weight standards, size grading, inter-shop protocols and deviation alerting enter this analysis only through their effect on product quality: how they hold the thermal centre at target, how they shorten the interval during which product sits outside its temperature envelope, how the length of the pre-freezing window governs spoilage. Their effect on plant capacity or on work organisation is a separate question and is not the subject here.

The sections that follow go deep on the four pairings that peak load drives hardest. The remaining cells of the map are covered by Table 1.

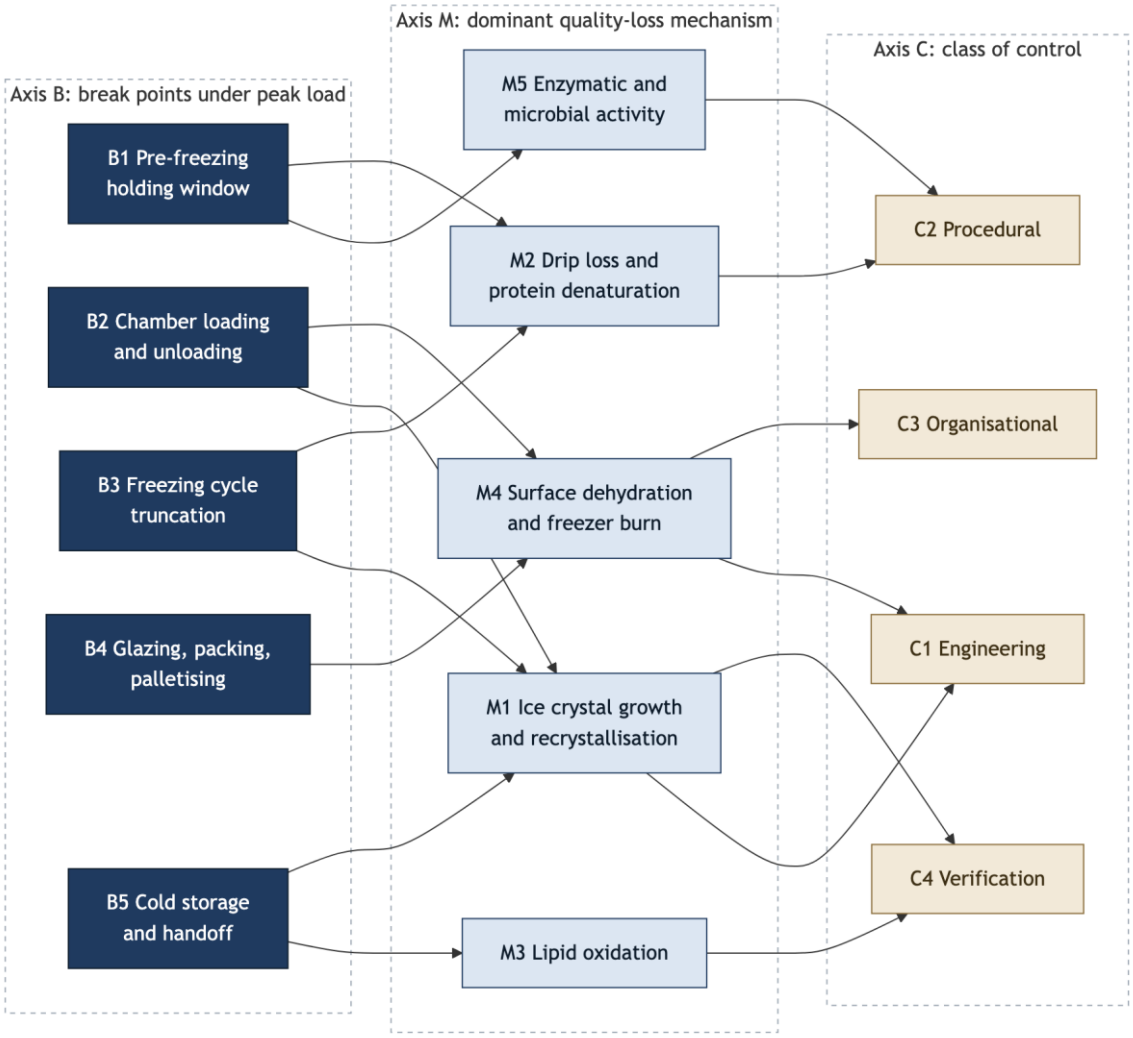

Fig. 1: the three axes of the break-point taxonomy and the couplings between them.

Table 1: Break points of cold chain integrity under peak load, with dominant mechanism, measurable indicator and control class

Break point	**What peak load does to it**	**Dominant mechanism**	**Measurable indicator**	**Control class**
B1 Pre-freezing holding window	Queue length set by chamber occupancy rather than by the raw material	M5 enzymatic and microbial activity; M2 water-holding baseline	Elapsed time from reception to start of freezing; TVB-N against the 35 mg/100 g limit [8, 9]	C2 procedural
B2 Chamber loading and unloading transitions	Door-open time and batch dwell multiply with cycle count	M4 surface dehydration; M1 recrystallisation	Number of boundary crossings per batch; surface frost and thawing loss per cycle [10]	C3 organisational

B3 Freezing cycle	Cycle truncated when the chamber is needed for the next batch	M1 ice crystal growth; M2 drip loss and protein denaturation	Achieved against specified freezing time; core temperature at unloading; crystal cross-sectional area [11]	C1 engineering with C4 verification
B4 Glazing, packing, palletising	Product spends longer in the warm zone between chamber and store	M4 dehydration and freezer burn	Glaze coverage; weight loss during handling	C1 engineering with C2 procedural
B5 Cold storage and handoff	Store fills faster, stacking density and door traffic rise	M3 lipid oxidation; M1 recrystallisation	Effective storage temperature and time above -18 °C; peroxide value and polyene index [4, 12]	C4 verification

A. Cycle Truncation and Ice Crystal Structure (B3 × M1)

This is the central pairing, because volume pressure converts here into irreversible structural loss. A freezing cycle has a defined endpoint: the thermal centre reaches target. Under load, a different endpoint governs in practice: the chamber is needed for the next batch.

The measured difference between a fast and a slow route through the phase-change zone is not marginal. Liu and colleagues compared air with immersion freezing of snakehead fillets and found mean ice crystal cross-sectional areas of 939.6 μm² under air freezing against 308.8, 142.4 and 86.5 μm² under immersion freezing at -20, -30 and -40 °C [11]. Air freezing took 112 minutes at 0.38 cm/h, the slowest of the tested conditions, against 3.42 cm/h for immersion freezing at -20 °C [11]. The underlying reason is a transport property rather than a machine capability: liquids conduct heat at 0.116 to 0.628 W/(m·K) against 0.024 W/(m·K) for air, so the medium in contact with the product sets the achievable rate [11]. What matters is time spent traversing the zone of maximum ice crystal formation, and samples with faster freezing rates cross that zone within 15 to 30 minutes while a slower one takes 1.5 hours [13]. The same ordering holds in rapid freezing of freshwater species [14] and in cryogenic freezing [15]; the mechanisms by which nucleation and growth can be steered have their own review [16].

The structural damage shows up in every downstream measure. Protein stability falls: myosin denaturation enthalpy in the same snakehead trials was 1.43 J/g after air freezing against 1.61 J/g after immersion freezing at -40 °C, from 1.75 J/g in fresh muscle [11]. Water retention falls with it. In whiteleg shrimp, water-holding capacity dropped from 95.76% when fresh to 86.42% after air freezing, and thawing loss was 1.53% after air freezing against 0.91% after liquid nitrogen freezing [17]. In rainbow trout the gap persisted through storage: drip loss reached 15.17% by the final month under slow freezing at -20 °C against 9.09% under rapid freezing at -40 °C [8]. Histological work on cold-water shrimp traces the same damage in muscle structure and in the sensory scores that follow [18]. Figure 2 sets these measurements side by side.

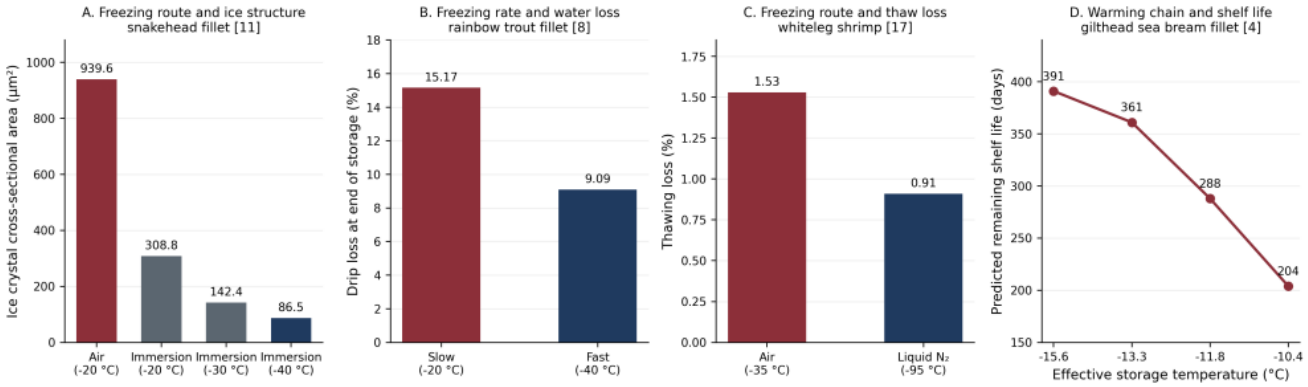

Fig. 2: the measured quality penalty of the slower or less controlled route, across four independent studies. In panel A the medium and the temperature both change across the series.

The control point that follows is specific: the cycle ends when the thermal centre reports target, and not when the chamber is wanted. Making that rule operable requires the endpoint to be verified rather than assumed, which is a C4 problem more than a C1 one. The plant the author manages runs plate freezers, where contact conduction gives a shorter cycle than air blast for a comparable load, so the equipment is not the binding constraint; holding the cycle to its endpoint under queue pressure is. The author reports that batch timings are held to their defined cycle even at peak volume, and treats that discipline, rather than freezer capacity, as what keeps output within the plant's quality standards during the season.

Three features of the author's practice make that rule survive contact with a queue. The first is where the decision sits. The author decides in real time whether a chamber is released, without seeking approval for the individual call: if each decision required sign-off, the latency of the approval would itself become a reason to pull the batch early, and the rule would erode through the mechanism it was written to prevent. The second is batch composition. A chamber of mixed sizes has no single endpoint, because the thermal centre of the largest piece arrives late and the operator ends up choosing which part of the load to under-freeze; grading by size before loading gives a chamber one endpoint instead of a distribution of them. The third is parallelism: with fifteen chambers of 2.5 t each running through a twelve-hour shift, the plant manages a rolling set of cycles, each an independent commitment that can be broken separately. The author describes the object of control not as the fish but as the disorder volume introduces. The freezing physics is stable; what varies under peak load is whether the process is allowed to complete.

B. The Pre-Freezing Window (B1 × M5)

B1 is the only break point at which loss begins before freezing can protect anything. Everything downstream operates on material whose spoilage clock has already run, and freezing arrests that clock without rewinding it.

The rates involved are fast enough to matter on a shift timescale. Duarte and colleagues report that storage on ice at 0 °C gives a shelf life of about 14 days, falling to 8 days at an ice-to-fish ratio of 1:1 at 2 °C [19]. Within that window, chemical spoilage indices move steeply: for Indian mackerel held in ice at 2 to 4 °C, total volatile basic nitrogen rose from 3.8 mg/100 g at day 0 to 22.4 mg/100 g at day 3 and 41.3 mg/100 g at day 7, while trimethylamine rose from 1.11 to 14.73 mg/100 g over the same period, with the fish assessed as spoiled at 5 days [19]. The acceptability threshold that those trajectories cross is documented at 35 mg/100 g of total volatile basic nitrogen, against a typical fresh range of 5 to 25 mg/100 g [8], and the same 35 mg N/100 g limit is applied to gadoid species [9].

Handling before freezing changes the starting point of that trajectory. Aberoumand and Baesi found psychrophilic bacterial load in barracuda fillets varying from 158 × 10^3 CFU/g in whole fish to 17 × 10^3 CFU/g in the most heavily treated group, with the oxidation and volatile-nitrogen indices moving in the same direction [20]. The condition in which material enters the freezer is therefore already a quality

decision, taken before any freezing parameter is chosen.

The pre-freezing window is where the author's procedural controls act, and they act on two variables at once. Raw material at the plant is graded by size in addition to species, and the box weight standard was revised for flatfish and Pacific ocean perch, species that stack poorly in freezer pans; the author reports that chamber loading time fell by 15 to 20% after those changes. Read through the quality lens, the significance of that interval is not the time saved but what the time was costing: every minute a graded batch spends waiting is a minute of enzymatic and microbial activity at ambient temperature, on material whose spoilage indices are already moving along the trajectories above.

The second variable the author's controls act on is thermal uniformity. A normalised box weight fixes the mass the plate must freeze per unit of contact area, which fixes the time to core; without it a chamber can hold a finished and an unfinished portion at the same moment, and the operator has no endpoint true for the whole load. In the author's account the two controls compound: grading decides what goes into a box, the weight standard decides how much, and together they convert a heterogeneous arrival stream into batches that behave predictably in the freezer. Neither change was made for the sake of the freezer alone, and both are judged here by what they do to the product rather than by what they do to the shift.

Framed that way the pre-freezing queue is not a scheduling inconvenience but the point at which yield is decided, and the author treats the interval between reception and the start of freezing as the first control point of the shift rather than as dead time between two real operations.

The indicator that would make this manageable is a per-batch record of that elapsed interval, a measurement almost no published study of frozen fish quality reports, because in a laboratory the interval is a controlled constant rather than an outcome of how busy the plant is.

C. Transition Losses at the Chamber Boundary (B2 × M4)

B2 accumulates. One loading or unloading transition exposes product to a brief excursion, and the damage from one is small. The cost scales with the number of cycles run, the quantity peak season maximises, so a break point that is negligible in a quiet week becomes material in a peak month.

Repeated crossings of the freezing boundary have been measured under controlled conditions. Chang and colleagues subjected quick-frozen fish balls to seven freeze-thaw cycles and found ice crystal diameter increasing by 139.73% in untreated samples against 55.71% in coated ones, while total volatile basic nitrogen rose from 7.81 to 30.30 mg/100 g, crossing the 30 mg/100 g acceptability limit [10]. Seven laboratory cycles are more severe than a well-run chamber transition imposes, but the direction and the mechanism transfer: each crossing recrystallises water that had already been immobilised.

Surface dehydration is the second mechanism at this break point, and its effect reaches the protein. Tan and Xie tracked dehydration in large yellow croaker during frozen storage and found myosin denaturation enthalpy falling from 1.275 to 0.834 J/g in the slow-freezing group, with α-helix content dropping from 19.33% to 10.89% as β-sheet content rose [21]. Water loss at the surface is therefore not a cosmetic defect at the margin of the product; it is coupled to the unfolding of the structural proteins beneath it.

The control class that fits B2 is organisational rather than engineering. What determines exposure at a transition is how quickly a deviation is noticed and answered: a chamber that is not closing properly, a door held open longer than the handover requires, a stalled line that leaves a loaded pan in the warm zone. The author reports that any deviation triggers immediate notification of the engineering department, and that the freezing shop, packing, raw material reception and technical service have operated on shared communication protocols since 2023 rather than as separate departments. The quality argument the author makes for that arrangement is a latency argument: the length of the exposure is set by the interval between the deviation and the response, and once the deviation has occurred, shortening that interval is the only lever left. It is also why the author routes a fault straight to engineering rather than through the shift hierarchy, since each intermediate step adds to the interval that the routing exists to compress.

The geometry of the author's own chambers makes the point concrete. Boxes of 17 kg are stacked across thirteen shelf levels, so a chamber fills in tiers and the first tier waits longest before the cycle starts on it. In the author's reading, loading order and pace are therefore quality variables and not only handling variables: the spread between the first and last box into a chamber is the spread in their pre-freezing exposure, and it widens whenever loading slows. This is why the author treats a fault reported late as a quality event rather than a maintenance one. A stalled loading operation lengthens the ambient exposure of everything already in that chamber, and unlike the freezing cycle, that exposure cannot be recovered by running the plate longer.

D. The Storage Tail (B5 × M3)

B5 is where errors accumulate that the shop floor can no longer repay. Oxidation is time-dependent, and by the time product reaches cold storage the plant has spent every lever except temperature stability.

The accumulation is measurable. Villamarín and colleagues held horse mackerel in frozen storage for 0, 3 and 6 months before canning and found peroxide values rising from 1.45 to 5.91 meq active oxygen/kg lipids, with the polyene index falling from 1.42 to 0.92 [12]. Prior frozen holding writes itself into the final product even when a further process intervenes, a trajectory that recurs in Indian mackerel [22], in pompano held at -18 °C [23], and in the discoloration of catfish fillets, where the visible defect arrives after the chemistry that produced it [24].

Temperature stability in the store is therefore the whole of the remaining control, and it is the variable most affected by a plant filling its cold store at peak rate. The shelf-life penalty documented by Tsironi and colleagues, 391 days falling to 204 as effective temperature rose through the four stages of the chain, is the quantitative form of that exposure [4]. Stability rather than depth is what the set point buys: Dawson and colleagues report that frozen storage at -25 °C maintained salmon at an acceptable level after 12 months, while -60 °C storage reduced drip loss without delivering other significant quality improvements over -25 °C [2]. The operational reading the author takes from this is that a plant gains more from holding a conventional commercial temperature steadily than from reaching for a colder one it cannot hold while the store is filling, which places the burden back on how the store is managed at peak rather than on how cold it can go.

B5 is also where the author's authority ends, and saying so belongs on the map rather than being omitted from it. The freezing department controls the product to the handoff and not beyond, which changes what it can usefully do about oxidation. It cannot manage a process running for months after the product leaves, so it manages the two things it still owns: the condition in which a batch leaves its cycle, and the steadiness of the store while the department is filling it.

That is why the author treats the state of the product at handoff as the department's final quality checkpoint rather than a formality. What the preceding four break points protected is either intact at that moment or it is not. It is also where the finite-resource argument returns with most force: a batch reaching the store with avoidable damage spends the following months converting it into a lower grade, and nothing downstream intervenes. The author's position is that the cheapest place to protect the storage tail is upstream of it, at the break points where the department still has authority.

E. The Remaining Cells

Those four pairings do not exhaust the map. B4 couples to M4 through glazing and packaging, and to M1 where product warms between chamber and store; coating thickness on frozen fish depends on dipping conditions in ways characterised well enough to define a safe dipping time [25], making B4 one of the few break points whose control variable is already quantified. B1 also couples to M2, since the condition of the muscle at freezing sets the water-holding baseline everything downstream inherits; water-holding in salmon carries a dedicated review of its own [3]. B5 couples back to M1 through recrystallisation in long storage. Table 1 records each pairing with its indicator and control class.

V. DISCUSSION: WHAT THE LITERATURE MEASURES AND WHAT A PEAK-LOAD PLANT NEEDS

Table 2 scores six families of control practice against six criteria that matter when volume rises. Reading down the columns rather than across the rows exposes

three mismatches between the shape of the evidence and the shape of the operating problem.

Table 2: Comparative matrix of control practice families under peak load. Verdict cells are the author's assessment against the reviewed evidence; numeric cells carry values from the cited sources

Control practice family	**Quality attribute protected**	**Evidence base in the reviewed literature**	**Robustness when volume spikes**	**Latency from deviation to detection**	**Feasibility for a seasonal plant**	**What the literature does not measure about it**
Freezing technology selection (C1)	Ice crystal structure, protein stability	Strong and quantitative: crystal area 939.6 against 86.5 μm² across routes [11]; thawing loss 1.53 against 0.91% [17]	High once installed; the specification does not degrade under load	Not applicable; a design decision, not a signal	Capital-bound; fixed before the season	Whether the installed rate is achieved in practice under queue pressure
Freezing-cycle timing discipline with core-temperature verification (C2 + C4)	Ice crystal structure, drip loss	Indirect: strong evidence on rate effects [11, 13], none on cycle adherence	The practice most exposed to load; it is the first thing volume pressure erodes	Within the cycle if the core temperature is instrumented; otherwise never	High; procedural rather than capital	Cycle adherence itself; no reviewed study reports it
Raw-material staging and grading before freezing (C2)	Spoilage indices, load uniformity	Partial: spoilage kinetics well characterised [19, 20], staging effects not studied	Degrades as the queue lengthens	Hours; detectable only by elapsed-time logging	High; organisational and procedural	Holding time as an operating variable rather than a fixed condition
Cross-functional deviation response (C3)	Exposure duration at transitions	Absent from the reviewed quality literature; treated only in cold-chain logistics work [26, 27]	Depends on staffing continuity through the season	Minutes if alerting is immediate	High; costs coordination rather than capital	Whether faster response measurably changes quality outcomes
Cold-chain monitoring	Temperature stability across	Strong: 40% of profiled time above -	Robust; instrumentation is	Continuous where	Moderate; requires	In-plant freezing, as distinct from

and data logging (C4)	storage and transport	18 °C [4]; deviation mapping in distribution chains [27, 28]	indifferent to load	loggers are deployed	devices and a data path	storage and distribution
Certification-based assurance (C4)	Provenance, documented process	Strong on process documentation; silent on per-batch thermal history	Robust as an audit; blind to peak-season physics	Audit cycle, measured in months	High; already in place at most export plants	Whether certified plants achieve target core temperatures under load

The first is a measurement mismatch. The literature quantifies quality as a function of temperature and freezing method with precision, down to crystal areas resolved to a tenth of a square micrometre and activation energies bracketed between 49 and 84 kJ/mol [11, 8, 4]. What no study in the reviewed set expresses is quality as a function of load. Throughput pressure enters the published work as an unstated background condition, so a plant manager reading this literature learns what a given freezing rate costs but not what a given queue length costs.

The second is a latency mismatch. Nearly every quality indicator in the reviewed literature is a post-hoc assay, measured after storage has ended. Roiha and colleagues, for instance, resolved differences between thawing methods only across a 14-day post-thaw storage study, with thawing times of 210 minutes under water with air circulation against 380 minutes without it [9]. Those measurements are informative and they arrive too late to steer a chamber. The nearest thing to a forward-looking instrument in the reviewed set is simulation of remaining shelf life for frozen products under real sale conditions [29], which predicts rather than assays, and which operates on the distribution stage rather than on the freezing cycle. The control points identified in Section 4 all need an in-cycle signal, and the reviewed evidence base offers almost none.

The third is a verification mismatch. Certification and traceability schemes establish provenance and document that a process was defined and followed. They do not audit whether the thermal centre of a particular batch reached target during a particular shift in August. A plant can hold its certifications in good standing and still ship product whose thermal history nobody recorded, because the record the scheme requires is one of procedure rather than of physics. That is not an argument against certification but an argument that the two answer different questions, and that a peak-load operation needs both.

VI. OPEN CHALLENGES AND A RESEARCH AGENDA

A quality model conditioned on load. Existing shelf-life models parameterise degradation by temperature and time, not by the production conditions that set them. The gap persists because load is a nuisance variable to a food scientist and the central variable to a plant. A first step would be a study that instruments a working plant across a season and fits existing kinetic models with arrival rate and chamber turnaround as covariates rather than as noise.

A metric for cycle-truncation risk. A plant cannot presently express how close a batch came to leaving its chamber early, so the most consequential decision on the floor appears in no indicator. The literature does not supply the metric because in a laboratory the cycle always runs to completion. A first step would be a per-batch ratio of achieved to specified freezing time, logged against the resulting core temperature, turning an implicit judgement into a number a plant can trend.

Coupling the pre-freezing queue to spoilage. Spoilage kinetics of chilled fish and the queue behaviour of a processing line are each well characterised, in literatures that do not meet. Section 4.2 showed both halves: indices crossing acceptability thresholds within

days [19, 8], and a plant whose holding interval is set by chamber occupancy. A first step would model pre-freezing holding time as a queueing output and feed it into a spoilage-index prediction, which needs no new laboratory work, only the joining of two existing models.

In-cycle verification rather than post-hoc assay. Quality is measured after storage; the decisions that determine it are made during freezing. Core-temperature telemetry is the obvious in-cycle candidate and is not treated as a quality instrument in the reviewed literature. A first step would validate the achieved core-temperature trace against conventional post-storage assays on the same batches, establishing whether the trace predicts the assay well enough to act on.

Thermal performance inside certification. Section 5 argued that certification answers a different question from thermal verification. The step that follows is narrower: a comparative analysis of what certification schemes require in the way of per-batch thermal records, establishing the size of the blind spot before anyone proposes to close it.

VII. CONCLUSION

The contribution of this review is a map. Five break points of cold chain integrity under peak load, each paired with its dominant quality-loss mechanism, the indicator that makes it measurable and the class of control that holds it, give a plant a way to locate its own failure modes rather than infer them from studies run under conditions it never experiences. The evidence assembled here shows that the penalties are large: an order of magnitude in ice crystal area between freezing routes, a difference of six percentage points in end-of-storage drip loss, and 187 days of predicted shelf life lost across a warming chain. The practical consequence is that the freezing cycle deserves to be treated as a commitment rather than as a queue slot, and that the interval before freezing begins deserves to be measured with the same seriousness as the temperature after it ends.

DECLARATIONS

Conflict of interest. The author is employed by the processing plant whose operating practice is described here. Operational observations attributed to the author are practitioner-reported and were not independently measured.

Funding. None.

Data availability. All quantitative values reported are drawn from the cited primary sources.

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