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Minimising Financial Risk under Enrolment Uncertainty: An Open-Source Entropy-Indexed POMDP Tool for University Governance

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Abstract

Universities must commit resources years ahead of the enrolment outcomes that fund them; the UK regulator identifies persistently over-optimistic forecasting as a systemic planning weakness. The difficulty is structural: existing instruments require governing bodies to agree probability judgements about contested futures—which the literature shows they cannot reliably do. This paper reports an operational research response: an entropy-indexed partially observable Markov decision process (POMDP), delivered as an open-source decision-support system for university financial planning. A Bayesian belief distribution over latent financial regimes is updated from each year’s enrolment signal; its Shannon entropy serves as an uncertainty index that automatically constrains irreversible commitments while evidential ambiguity is high. The system is calibrated on a decade of open HESA data from four Russell Group institutions (2014/15–2024/25) with materially different trajectories; a five-level pathway takes a finance director from first use to a committee-ready Board Pack in under an hour. Monte Carlo evaluation across 500 enrolment futures shows the entropy-conditioned strategy achieving the highest mean financial reward with the lowest crisis probability among six comparators. Management implications are analysed across four institutional archetypes, including the post-2022 international shock, and transferability to other national systems facing similar volatility is assessed.

Practitioner Summary

UK universities plan spending years ahead of the enrolment numbers that will pay for it, and current regulatory guidance blames over-optimistic forecasting for the deficits now facing nearly half of English providers. Governing bodies are typically asked to agree a single best-guess scenario, but the evidence is that boards cannot do this reliably when the future is genuinely uncertain. This paper describes a free, open-source planning tool built for finance directors and governing bodies rather than for other researchers. Each year the tool updates a set of probabilities over which “financial regime” the institution is likely in — comfortable, tightening, or crisis — using the latest enrolment numbers, and reports how confident, or not, that estimate is. When confidence is low, the tool automatically flags that new,

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hard-to-reverse commitments, such as new buildings, permanent staff, or new campuses, should wait until the picture clarifies, rather than relying on a single overconfident forecast. Tested against ten years of real enrolment data from four UK universities with very different recent histories, this uncertainty-aware approach outperformed six conventional planning strategies, delivering better financial outcomes with a lower chance of crisis. A step-by-step pathway lets a finance director go from opening the tool to producing a board-ready report in under an hour, with no coding or data-science expertise required. The tool and its underlying calculations are freely available online, so any UK institution, and potentially universities in other countries facing similar enrolment volatility, can apply it to their own numbers immediately.

Keywords: OR in education ; decision support systems ; POMDP ; Bayesian belief updating ; deep uncertainty ; enrolment management

1 Introduction: The Management Challenge

The strategic planning challenge facing UK higher education institutions has rarely been more acute. Since 2022, finance directors and planning teams have navigated a confluence of external pressures without historical precedent: a tuition fee cap held broadly flat since 2017 [1], volatile international enrolment driven by successive changes to visa policy [2, 3], and a demographic contraction that will depress domestic recruitment in many markets across the coming decade [4]. The Office for Students’ most recent financial sustainability analysis estimates that, without mitigating action, nearly half of English providers face operating deficits in 2025–26, and identifies persistently over-optimistic enrolment forecasting as a systemic weakness in institutional planning [5]. Each pressure operates on a different timescale and with a different degree of predictability; their interactions produce strategic environments in which the conventional instruments of institutional planning—scenario analysis, sensitivity testing, and rolling forecasts—are structurally inadequate.

The inadequacy is not one of effort or expertise. Finance directors and planning managers in UK higher education are well-resourced and analytically capable. The problem is structural: dominant planning frameworks require decision-makers to assign weights to scenarios before deciding, yet the weights are precisely what is unknown. When the director of international recruitment reports a sharp decline in first-year overseas applications, the institutional planning team faces a fundamental management question: is this the beginning of a sustained downturn requiring conservative retrenchment, or a transient correction from which recovery will follow next year? The answer determines whether the institution should Conserve resources, Maintain current commitments, or continue to Invest in capacity. Neither scenario analysis nor sensitivity testing provides a principled method for answering it, because both treat uncertainty as a parameter to be assumed rather than a quantity to be measured.

This paper offers a governance answer to that question: replace the probability judgement a governing body cannot reliably agree with a measurement it can audit. We present an interactive decision-support simulator implementing an entropy-indexed POMDP framework [6], in which institutional uncertainty is quantified as the Shannon entropy of a Bayesian belief distribution over financial regimes, and used to constrain, adjust, and recommend strategic postures year by year. The framework is calibrated on a decade of HESA enrolment data from four Russell Group institutions (Warwick, Exeter, Leeds, Bristol; 2014/15–2024/25) and validated against six comparator strategies across 500 Monte Carlo simulations.

The contribution of this paper is not the underlying framework—which is formally derived and empirically validated in a companion paper under review at *Socio-Economic Planning Sciences* [6]—but the practice contribution of carrying that framework from formal derivation to a deployed, publicly accessible decision-support system: a case-oriented account of applied OR in a sector facing acute planning uncertainty. We describe the system’s architecture, document a five-level engagement pathway that enables finance directors to extract decision-relevant outputs in ten minutes and planning teams to calibrate the tool to their institution’s own enrolment history in under an hour, and analyse the management implications of the framework’s outputs comparatively across four institutional archetypes drawn from the HESA panel, before assessing the system’s transferability beyond the UK system on which it was calibrated. Throughout, the design choices that turn a POMDP into an instrument a finance committee will actually use—plain-language rationales, a traffic-light entropy gauge, single-URL reproducibility—are

treated as part of the OR contribution rather than presentation detail, in line with the behavioural turn in the discipline [7].

Section 2 situates the framework in the literatures on the UK higher education funding environment, on universities as decision-making organisations, and on enrolment forecasting and institutional research, and reviews the limitations of existing planning frameworks. Section 3 summarises the entropy-indexed POMDP framework in governance terms. Sections 4 and 5 describe the simulator and its engagement pathway. Section 6 analyses management implications with reference to the four institutional archetypes and their international transferability. Sections 7 and 8 address deployment, reproducibility, and conclusions.

2 Background: Planning under Uncertainty in HE Governance

2.1 The governance environment

UK universities occupy a distinctive governance position: they are autonomous institutions operating under significant state regulation, dependent on tuition fee income set by government policy, and exposed to international student markets shaped by national immigration decisions [8–10]. In the vocabulary of organisation theory they are resource-dependent organisations [11]: their strategic autonomy is conditioned by the behaviour of the external actors who control their income streams. Three decades of marketisation have intensified rather than relieved this dependency. The shift toward fee-based funding documented by Brown and Carasso [12], the entrepreneurial revenue-seeking that Slaughter and Leslie [13] term academic capitalism, and the intensified positional competition analysed by Musselin [14] have collectively tied institutional solvency to enrolment flows that respond to policy and market forces well outside institutional control. The financial regime facing any given institution is therefore neither entirely within its control nor fully legible from its own operational data.

The post-2022 environment has made this exposure acute. International student mobility has always moved in policy-sensitive waves [3], but the restrictions on dependant visas introduced in January 2024 and the uncertainty surrounding the Graduate Route—resolved only partially by the Migration Advisory Committee’s rapid review [2]—produced contractions in international recruitment that were sharp, uneven across institutions, and unforecast by most providers. The Office for Students’ monitoring now projects deficits for nearly half of English providers in 2025–26 absent mitigating action, and warns that forecasts have been persistently over-optimistic [5]; Universities UK reaches a parallel diagnosis of structural fragility [15], while the House of Commons Library documents the real-terms erosion of the domestic unit of resource under the frozen fee cap [1]. The governance problem this paper addresses sits at the centre of these analyses: institutions must commit resources years ahead of the enrolment outcomes that will pay for them, in an environment where the distribution of those outcomes is itself in dispute.

HESA enrolment data for the decade 2014/15–2024/25 reveals the extent of this exposure. Aggregate Russell Group enrolment grew broadly across the period but with substantial institutional variation: Exeter sustained above-trend growth driven by domestic and overseas demand; Leeds and Warwick experienced sharp international corrections following the 2022 visa changes; Bristol navigated a more stable, moderate-growth trajectory.

These four institutions share comparable governance structures and sector positioning, yet their enrolment trajectories place them in materially different financial regimes in any given year—and distinguishing between regimes on the basis of a single year’s signal is precisely the challenge existing planning tools have not resolved.

Deep uncertainty in this context carries a precise technical meaning. Walker et al. [16] distinguish between risk (known probability distributions over outcomes), uncertainty (unknown but estimable distributions), and deep uncertainty (disputed or unknowable models). UK higher education institutions operating in the post-2022 environment face deep uncertainty in the technical sense: the structural parameters of the international student market have shifted in ways that historical data cannot fully capture, and reasonable analysts disagree about the appropriate distributional assumptions. Standard risk management tools are not designed for this environment; they assume known distributions that the deep uncertainty literature has shown to be unavailable in precisely the governance situations where structured decision support is most needed.

Sector and regulatory bodies have recognised the gap between these decision environments and the tools available to the professionals who must navigate them: the Office for Students’ repeated findings of forecast over-optimism [5] are, in effect, a finding that the sector’s planning instruments do not adequately represent the uncertainty of the environments in which they are applied.

2.2 Universities as decision-making organisations

Any decision-support instrument intended for university governance must contend with what the higher education literature has established about how universities actually make decisions. The foundational accounts portray universities as organisations in which decision processes are loosely coupled to organisational goals: Cohen et al. [17] model universities as organised anarchies in which problems, solutions, and decision-makers meet in “garbage can” processes shaped as much by timing and attention as by analysis, and Birnbaum [18] describes collegial governance as a cybernetic system that self-corrects through feedback loops rather than through comprehensive rational planning. This tradition descends from the behavioural theory of the firm [19, 20], which replaced the synoptically rational organisation with boundedly rational actors who search locally, satisfice, and attend to problems sequentially. Weick [21] adds that organisations confronting ambiguous signals engage in retrospective sensemaking—acting first and constructing the interpretations that rationalise the action afterwards, a pattern immediately recognisable in post-hoc committee narratives of enrolment shocks.

These accounts are not historical curiosities; they describe persistent features of contemporary university governance. Studies of UK governing bodies document recurring difficulty in aggregating divergent judgements about external risk into coherent strategic positions [22, 23], and comparative European research shows that successive managerial reforms have layered new planning instruments onto these decision processes without resolving the underlying epistemic problem [9, 24]. The design implication for decision support is direct. An instrument that requires a governing body to agree a subjective probability distribution over futures before it can act asks precisely what this literature predicts such bodies cannot reliably do. The framework presented in this paper is designed around that constraint: the probability distribution is derived from enrolment evidence by Bayesian updating, and the governance body is asked only to endorse the transparent decision rules that consume it. Taking the behavioural realities of the client organisation

as a design input, rather than an implementation obstacle, is the stance the behavioural OR literature argues the discipline should recover [7].

2.3 Enrolment forecasting and institutional research

A separate literature addresses the enrolment side of the problem. Strategic enrolment management has developed into a mature professional field with an established methodological canon [25], and institutional research has long treated enrolment forecasting as a core function of the profession [26]. The forecasting toolkit is well documented—curve-fitting and cohort-flow methods, Markov transition models, econometric approaches [27], and student-level statistical modelling of recruitment and yield [28]—and the institutional analytics movement has recently expanded the data infrastructure available to planning offices [29].

What this literature has not produced is a principled bridge from forecast to strategic decision under regime uncertainty. Enrolment forecasting is overwhelmingly point-forecast or interval-forecast in orientation: it estimates how many students will enrol, conditional on a continuation of the prevailing regime. The question that has dominated UK planning discussions since 2022 is different in kind—*which regime is the institution now in?*—and the forecasting canon offers no formal machinery for answering it, for updating the answer as evidence arrives, or for conditioning strategic commitments on the confidence with which it can be answered. Markov-chain enrolment models [27] are the closest antecedent of the present framework, but they model student progression through known states rather than institutional inference over hidden ones. The framework presented here supplies the missing complement: it takes the enrolment signal that institutional research offices routinely produce and converts it into a calibrated, continuously updated statement about regime membership and the uncertainty attached to it. The gap has not closed with the recent turn toward more sophisticated forecasting models: even a 2026 evaluation of zero-shot time series foundation models for institutional enrolment forecasting under data sparsity remains explicitly framed as a forecasting protocol—improving the point estimate and its covariates—rather than a mechanism for converting that estimate into a calibrated statement of regime confidence that can condition strategic commitments [30].

Operational research has its own substantial record in education, but it is concentrated elsewhere in the problem space. The literature surveyed by Johnes [31] is dominated by operational and tactical applications: automated timetabling and scheduling [32], efficiency measurement through data envelopment analysis [33], and student-flow and resource-allocation models at departmental or system level. The most recent systematic review of the field, covering 203 papers across 94 journals up to 2024, confirms that this concentration has persisted rather than shifted: OR/MS applications to higher education remain organised around operational and tactical decisions—admissions, scheduling, efficiency measurement, resource allocation—with strategic financial planning under demand uncertainty identified as an under-served category rather than an established one [34]. Strategic financial planning under demand-regime uncertainty—the decision problem that has dominated UK institutional agendas since 2022—has remained largely outside this tradition, and the sequential decision-under-uncertainty toolkit of OR has not previously been delivered to the university finance committees that face exactly the class of problem it was built for. This paper is positioned in that gap: it joins the POMDP tradition to a live institutional planning problem and reports the implementation choices required to make the resulting instrument usable in governance practice.

2.4 Limitations of existing planning frameworks

Three planning frameworks dominate HE institutional practice. Scenario planning generates three to five plausible futures and examines their strategic implications, but assigns equal or judgemental weight to each [35, 36]. Under deep uncertainty, the weight assigned to the most likely scenario is the very thing that should emerge from a governance process, not be an input to it. Recent restatements of the Oxford school are explicit that scenarios are instruments for reframing perception rather than for choosing among commitments [37]—yet choosing among commitments is precisely the step institutional planning requires. Finance committees that receive scenario reports without probability weights face an irresolvable aggregation problem: the appropriate response to a pessimistic scenario may directly contradict the optimal response to an optimistic one, and the committee has no principled means of adjudicating between them.

Real Options Analysis provides a rigorous framework for valuing flexibility and the cost of irreversibility under uncertainty [38], but requires probability distributions over future states as inputs. These are contested under deep uncertainty: the method degrades gracefully under parametric uncertainty but fails under model uncertainty of the kind now prevalent in HE planning, where option pricing based on any particular assumption about international student demand provides false precision [39].

A fourth family of methods—developed largely in infrastructure, climate, and security policy under the heading of decision making under deep uncertainty (DMDU)—directly targets the regime in which probability distributions are contested. Robust decision making stress-tests candidate strategies against large ensembles of plausible futures [40]; dynamic adaptive policy pathways sequence commitments around monitored signposts [41]; info-gap theory evaluates decisions by the forecast error they can tolerate before failing [42]. The consolidated statement of this field [39] states explicitly that its monitor-and-adapt logic suits exactly this class of problem, yet applications to higher education are essentially absent from the DMDU literature, and none of its methods provides what a governing body needs year-on-year: a single, continuously updated scalar measure of institutional uncertainty, coupled to explicit rules about which commitments that level permits. A recent review of DMDU’s applicability in practice, examining 37 infrastructure case studies, reaches a diagnosis directly relevant to the present problem: DMDU methods are effective at generating robust plans across an ensemble of futures but “largely overlook the organisational and individual contexts in which decision making happens”—in particular, the difficulty a governing body faces in adopting and sustaining a monitor-and-adapt discipline within its own ordinary decision routines [43]. The entropy-indexed architecture developed here is one response to that diagnosis: the uncertainty measure and the postures it constrains are folded into the same annual reporting cycle a finance committee already runs, rather than requiring a parallel analytical process the committee must additionally learn to sustain.

Satisficing frameworks, originating with Simon [44], offer a more epistemically honest alternative: rather than optimising over a probability distribution, the decision-maker identifies postures meeting a minimum acceptable standard under any sufficiently plausible scenario. This better reflects how governance bodies actually operate under ambiguity [45], but its HE operationalisation has remained largely qualitative, missing a mechanism that translates incoming enrolment signals into a continuously updated, quantified uncertainty measure that adjusts acceptable postures automatically.

2.5 POMDP and entropy as a governance architecture

Partially observable Markov decision processes offer a natural formal structure for this problem. Introduced by Åström [46] and given their canonical computational treatment by Smallwood and Sondik [47] and Kaelbling et al. [48], POMDPs model a decision-making agent—here, the institution—acting in an environment whose state is hidden and observable only through noisy signals. The agent maintains a probability distribution, the belief state, over possible hidden states, updating it via Bayes’ theorem as observations arrive. Unlike a scenario, the belief state is an evidence-based distribution that evolves as data accumulates, providing the calibrated, continuously updated regime assessment that scenario planning cannot. The formalism remains an active methodological frontier: a 2023 survey of POMDP solution methods notes that the framework’s central difficulty—the computational cost of maintaining and updating a belief distribution at scale—has been substantially eased by advances in approximate and point-based solvers over the past decade [49]. The present application exploits exactly this tractability: a three-regime belief state updated annually from a single categorical signal sits well within the range for which exact Bayesian updating, not approximation, is computationally trivial.

The entropy-indexed variant of the POMDP developed in Schetinin [6] adds a co-ordinating mechanism: Shannon entropy [50] of the belief distribution serves as an institutional uncertainty index. High entropy signals that the institution genuinely cannot determine which financial regime it occupies; low entropy signals that one regime is dominant. This index is used to coordinate five decision rules that govern strategic posture selection—constraining irreversible commitments when uncertainty is high, rewarding information-generating postures, and releasing constraints as entropy falls. The result is a management decision protocol that is systematically cautious under ambiguity and systematically decisive under clarity, without requiring the finance committee to form its own prior probability judgement.

3 The Entropy-Indexed Decision Framework

The full mathematical derivation of the framework is presented in Schetinin [6]; a preprint is publicly available at <https://dx.doi.org/10.2139/ssrn.6815243>. This section provides the governance-oriented summary required to interpret the simulator’s outputs.

3.1 The hidden-state model

The framework models the institution’s financial position as one of three latent regimes: **Low** (enrolment contraction or below-trend growth, associated with margin pressure), **Stable** (on-trend growth consistent with the HESA Russell Group panel average), and **Growth** (above-trend enrolment supporting surplus generation and investment capacity). These regimes are not directly observable; they are inferred from the annual enrolment signal, which the framework categorises as Poor, Weak, Moderate, or Strong based on the percentage change in full-time equivalent headcount.

The relationship between regimes and signals is encoded in an observation matrix Ω , estimated from the HESA panel using Laplace-smoothed maximum likelihood. The dynamics of regime transitions are encoded in a transition matrix T , capturing the year-on-year probability of remaining in or moving between regimes. Both matrices

Table 1: The five strategic postures

Posture	Operational meaning
Conserve	Protect reserves; limit discretionary expenditure; avoid new multi-year commitments
Maintain	Hold current resource levels; no expansion or contraction of strategic commitments
Recruit	Invest selectively in student recruitment activity; prioritise information-gathering over structural expansion
Invest	Expand staffing, capacity, and infrastructure in anticipation of sustained enrolment growth
Rationalise	Reduce structural capacity; consolidate programme portfolio; recover operating margin

are pre-computed from the Russell Group panel; institutions may replace them with institution-specific estimates using the calibration tab of the simulator (Section 4).

3.2 The Bayesian belief update and the entropy index

Each year, as an enrolment signal arrives, Bayes’ theorem is applied to update the belief distribution $\mathbf{b}$ over the three regimes (Strategic Rule 1, hereafter SR1). The Shannon entropy of this distribution,

$$H(\mathbf{b}) = - \sum_i b_i \log b_i,$$

is the institutional uncertainty index. At maximum entropy ($H \approx 1.10$), the three regimes are equally probable—the institution has no evidential basis for favouring any particular regime. As signals accumulate and the belief concentrates on a single regime, H approaches zero.

The entropy index coordinates five subsequent decision rules. SR2 applies entropy-weighted blending between successive belief states, moderating over-reaction to a single anomalous signal. SR3—the satisficing gate—evaluates each strategic posture against a financial safety floor using Monte Carlo rollouts; postures whose expected outcomes fall below the floor under conditions of high entropy are blocked from recommendation. SR4 adds a value-of-information bonus to the Recruit posture, which generates future belief-resolving data. SR5 applies an option-value penalty to irreversible postures (Invest and Rationalise) when entropy is high. SR6 normalises rewards to a common unit enabling cross-strategy comparison; SR7 allows the transition matrix T to adapt as new institutional data arrives. The complete derivation and parameter estimates are reported in Schetinin [6, Tables 2–3].

3.3 The five strategic postures

The framework selects among five institutional postures each year (Table 1). The recommended posture for Year 1—and the projected trajectory across the full 12-year planning horizon—is the primary governance output of the simulator. A plain-English rationale for each recommendation is displayed alongside the entropy gauge in the Year-by-Year tab.

Table 2: Four simulator tabs and their governance functions

Tab		Governance function	Primary output
Year-by-Year		Interactive planning console: step through each year as signals arrive and observe belief updates in real time	Annual recommended posture, belief distribution, entropy level, and plain-English rationale
12-Year Simulation		Strategy comparison under a shared enrolment path: all six strategies run on identical observations, so outcome differences reflect strategy quality rather than chance	Action map, cumulative reward trajectories, and downloadable Board Pack PDF
Strategy Comparison		Monte Carlo robustness evidence: 100 to 500 independent simulation paths summarised by mean reward and crisis probability	Pareto dominance chart: reward versus financial crisis probability across strategies
Calibrate Your Data		Institution-specific parameter estimation: replaces the Russell Group panel matrices with the institution’s own enrolment history	Custom transition matrix T and observation matrix Ω , activated across all tabs

4 The Simulator: Architecture and Governance Functions

The framework is implemented as a freely accessible web application at <https://he-finplanner.streamlit.app/>. No institutional account, software installation, or data upload is required to begin. Finance directors can share a pre-configured link for their institution’s starting position with colleagues via a single URL—parameters are encoded directly into the address. The application is also available for local installation (Section 7), which is recommended when uploading real institutional enrolment data.

4.1 Four tabs as governance functions

The simulator is organised into four tabs, each serving a distinct governance function (Table 2). This modular architecture reflects a deliberate governance design principle: the framework’s outputs should be interpretable at increasing levels of evidential rigour. A finance director who reviews only the Year-by-Year tab gains an intuition for how the framework’s recommended posture shifts as signals arrive; a chief financial officer presenting to an audit committee can move to the Monte Carlo tab and produce distributional evidence across 500 futures.

4.2 Technical features with governance significance

Four features of the simulator warrant particular attention from a governance perspective.

The **Bayesian belief bar** (Year-by-Year tab, Figure 1) visualises the framework’s

current probability distribution over the three financial regimes—Low, Stable, and Growth—as a stacked horizontal bar that updates after each annual signal is entered. Unlike a scenario description, which asserts a qualitative position, the belief bar quantifies the evidential weight attached to each regime. A finance director who observes that 88 per cent of the belief mass is in the Stable regime after three consecutive Moderate enrolment signals has a calibrated, documentable basis for a governance posture that a scenario narrative cannot provide.

The **entropy gauge** (Year-by-Year tab, Figure 1) is the decision trigger for the satisficing gate (SR3). When entropy exceeds the threshold corresponding to the configured risk tolerance δ , the gauge displays red, indicating that the SR3 gate is active and that irreversible postures—Invest and Rationalise—are blocked. When entropy falls below the threshold, the gauge displays green, indicating that the institution has sufficient evidential clarity to act decisively. This binary indicator translates a mathematically sophisticated uncertainty measure into an immediately legible governance signal: red means protect, green means act.

The **Board Pack PDF** (12-Year Simulation tab, Figure 2) is a downloadable two-page A4 document containing the strategy comparison table for the current calibration, the year-by-year recommended posture strip, simulation charts, and a methodology note with a full citation to the underlying framework paper. The document is generated with the institution’s name as entered by the user. It is designed to be tabled at a finance committee meeting without further editing. Critically, the Board Pack is reproducible: a colleague who replicates the same configuration at the same URL will generate an identical document, providing the kind of computational audit trail that governance accountability increasingly requires.

URL parameter encoding (sidebar Share button) writes all current configuration settings—initial belief, risk tolerance, discount factor, scenario selection—into the browser address bar. The resulting URL functions as a reproducible specification of the governance scenario being evaluated. It can be pasted into a board paper, emailed to a colleague at another institution for comparison, or archived as a record of the analytical basis for a strategic decision.

4.3 Deployment and data governance

The public application runs on Streamlit Community Cloud (US-based servers) and is appropriate for exploring the Russell Group panel defaults and institutional archetypes. For institutions that need to upload real enrolment data—the Level 5 calibration described in Section 5—a local Mac launcher is provided. The launcher (`Launch FinPlanner.command`) is a double-click script that creates a self-contained Python environment on the user’s machine and opens the application at localhost; no data leaves the institution’s network. The full source code and documentation are available at <https://github.com/ljakaite/he-finplanner> under an open-source licence, supporting independent verification of the framework’s implementation and enabling institutions with technical capacity to deploy the application on their own infrastructure.

5 A Five-Level Governance Adoption Pathway

The simulator is designed for progressive engagement rather than a single prescribed workflow. A finance director with ten minutes before a committee meeting can extract a

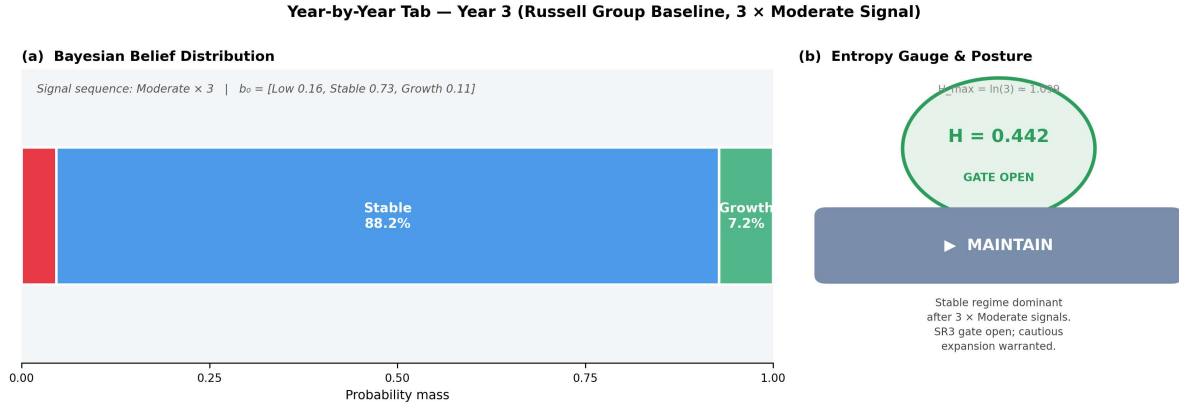


Figure 1: The Year-by-Year tab after three consecutive Moderate enrolment signals (Year 3, Russell Group baseline). The Bayesian belief bar shows 88 per cent probability mass on the Stable regime; entropy has fallen to $H = 0.442$, turning the gauge green and releasing the SR3 satisficing gate. The recommended posture is Maintain with plain-English rationale displayed below.

governance-relevant output from the Russell Group defaults without any configuration. A planning team conducting a strategic review can calibrate the framework to their institution’s own enrolment history and generate a bespoke Board Pack in under an hour. The five levels correspond to increasing degrees of institutional commitment to evidence-based planning practice, and an institution can begin contributing governance value at any level (Table 3).

Level 1: Establishing governance intuition. The baseline exploration builds conceptual foundation before any institution-specific configuration. A ten-minute session teaches two governance-relevant facts: the framework maintains a probability distribution over regimes rather than committing to a single scenario, and the entropy gauge—red for evidential ambiguity, green for clarity—constrains irreversible postures automatically, without requiring a board vote. This is the entry point for introducing the framework’s logic to a board or executive team.

Level 2: Recognising institutional archetypes. The four pre-loaded scenarios—Post-2022 Shock, Shock and Recovery, Sustained Growth, and Volatile—correspond to patterns from the HESA Russell Group panel. Running them surfaces a consistent lesson: early conservatism during shocks is a conditional response to high entropy, not general risk aversion, and the framework re-engages growth-supporting postures as soon as entropy falls. Finance directors who recognise their institution’s trajectory in one archetype gain an immediate governance reference point before any custom calibration is needed.

Level 3: Producing board-grade robustness evidence. The Monte Carlo tab generates distributional evidence across 500 simulated futures, reproducing the Monte Carlo comparison reported in [6, Table 4], the companion framework paper: the Unified Framework achieves a mean reward of 349.2 at a 1.1 per cent crisis probability, on the Pareto frontier (Figure 3). Any user can independently reproduce these figures by running the $n = 500$ simulation with seed 42—in under two minutes. For audit committees and

12-Year Strategy Action Map — Post-2022 Shock Scenario

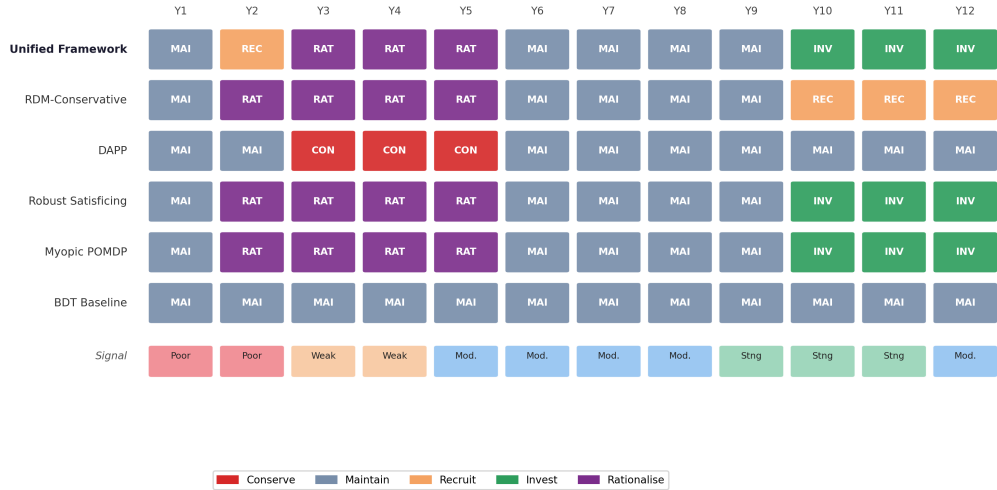


Figure 2: The 12-Year Simulation tab under the Post-2022 Shock scenario. The action map shows posture recommendations for all six strategies across Years 1–12. The Unified Framework (top row) selects Conserve in Years 1–2 while entropy is high, then transitions to Maintain and Recruit from Year 3 as the belief distribution resolves. The Board Pack download button appears at lower right.

governing bodies that require statistical robustness, this chart provides quantified evidence that is transparent, reproducible, and fully documented.

Level 4: Configuring institutional starting position. The sidebar sliders let finance teams set the framework’s initial belief distribution to match their institution’s known position, without uploading data, using five archetype starting points from post-shock recovery to deep distress. The Share button encodes the configuration into the browser URL, generating a reproducible link for a board paper, a colleague email, or cross-institutional benchmarking of the kind facilitated by sector bodies internationally—BUFDG and HESPA in the UK, ATEM and AAIR in Australasia, AIR in the United States.

Level 5: Custom calibration and the Board Pack. At the most advanced level, the Calibrate Your Data tab (Figure 4) accepts a two-column CSV file—year and full-time equivalent headcount, minimum four rows—and re-estimates T and Ω from the institution’s own enrolment history, propagating the custom calibration across all simulation tabs. The resulting Board Pack PDF carries the institution’s name, its bespoke matrices, and a posture trajectory derived from its own enrolment dynamics—the fullest governance output the framework provides, a two-page, committee-ready record with a complete methodological lineage.

Session plans for governance bodies. Three structured session formats support institutional and professional use: a *finance committee demonstration* (30 minutes, Levels 1–3, ending in a Board Pack download); a *planning team workshop* (90 minutes, all five levels, Level 5 conducted with a real institutional CSV via the local Mac launcher so uploaded data stays on institutional infrastructure); and a *conference workshop* (50 minutes, Levels 1–3) for institutional researchers and planning professionals at sector meetings, prompting

Table 3: Five-level governance adoption pathway

Level	Name	Time	Governance output	Audience
1	Explore the baseline	10 min	Recommended posture and entropy level for a pooled Russell Group institution	Finance director, board member
2	Simulate a scenario	15 min	Strategy rankings across four institutional archetypes	Planning manager, finance director
3	Stress-test with Monte Carlo	20 min	Pareto dominance evidence across 500 simulated futures	CFO, audit committee
4	Configure your institution	15 min	Customised starting belief; shareable URL for governance documentation	Planning team
5	Calibrate with your own data	30–45 min	Institution-specific T and Ω ; Board Pack PDF for finance committee	Institutional research team and finance director

participants to identify their institution’s closest archetype before a facilitated discussion of the governance implications.

6 Management Implications

6.1 What the four archetypes reveal about institutional governance

The four pre-loaded institutional archetypes are not stylised examples designed to demonstrate software functionality. They are calibrated trajectories drawn from the HESA Russell Group panel (2014/15–2024/25), corresponding to verifiable patterns of enrolment change at identifiable institutions. Each archetype surfaces a governance principle that extends beyond the specific institutional case from which it was drawn.

Post-2022 Shock. The archetype approximating the trajectory of institutions with high international student exposure—marked by two years of enrolment decline from 2022 followed by slow and partial recovery—produces the most instructive comparison among the six strategies. Under this path, the Unified Framework recommends Conserve in Years 1 and 2, when entropy is highest and the direction of regime change is evidentially unresolved. Strategies that optimise without uncertainty conditioning continue to recommend Invest or Recruit throughout this period, committing resources against a regime they cannot yet confirm. By Year 4, as accumulated Weak and Moderate signals have concentrated the belief distribution toward Stable and entropy has fallen below the SR3 threshold, the framework transitions to Maintain and subsequently Recruit. Across 500 Monte Carlo realisations of this archetype, the framework’s financial crisis rate is 1.1 per cent against rates of 8–15 per cent for non-entropy-conditioned comparators. The governance implication is structural: under conditions of high evidential ambiguity, the expected cost of making an irreversible commitment that proves incorrect exceeds the opportunity cost of conservative waiting. This is not a general argument for institutional caution; it is a quantified argument for *calibrated* caution, operative only during the period for which entropy provides evidential warrant.

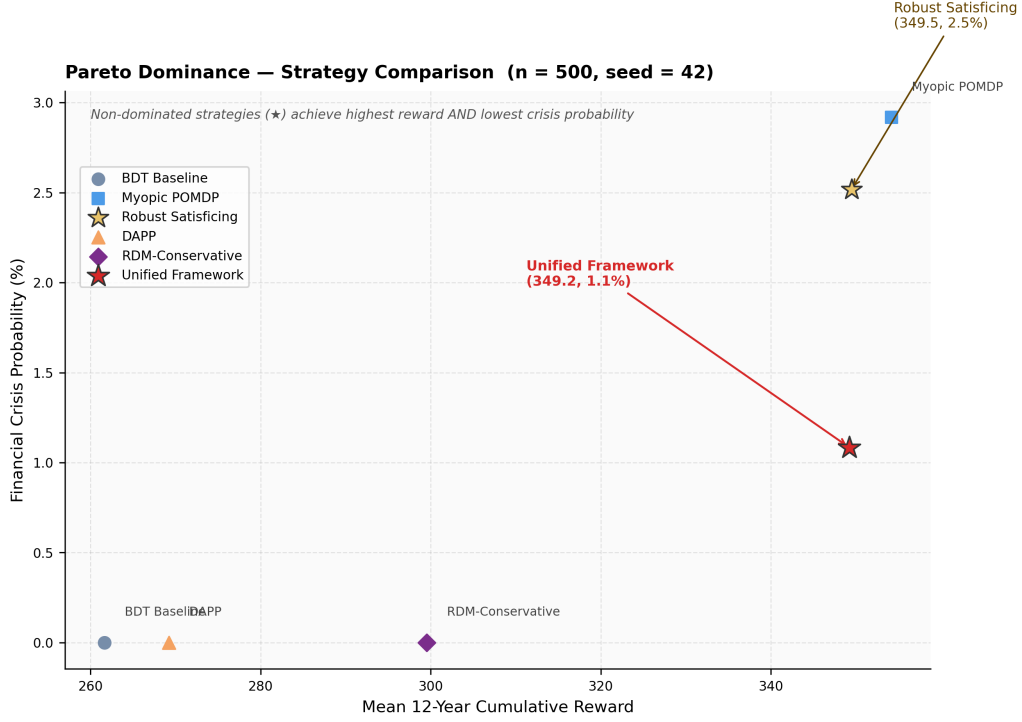


Figure 3: Pareto dominance scatter from the Strategy Comparison tab ($n = 500$, seed = 42). The x -axis shows mean 12-year reward; the y -axis shows financial crisis probability (percentage of paths where cumulative reward falls below the distress floor). The Unified Framework (★) achieves 349.2 mean reward at 1.1 per cent crisis probability; Robust Satisficing (★) achieves 349.5 at 2.5 per cent. Both are non-dominated: no other strategy achieves higher reward and lower crisis probability simultaneously. This reproduces Schetinin [6, Table 4].

Shock and Recovery. The archetype corresponding to a sharp enrolment decline followed by a clear recovery signal in Year 3 tests the framework’s capacity to respond to positive evidence after a period of constraint. The SR3 satisficing gate releases as entropy falls when consecutive Moderate signals arrive, and the framework moves from Conserve to Recruit within a single period. Strategies that invested aggressively during the decline phase face balance-sheet constraints that prevent them from fully exploiting the recovery; strategies that maintained blanket conservatism recover more slowly than entropy-conditioned repositioning warrants. The governance lesson is temporal rather than directional: what distinguishes sustainable recovery from prolonged balance-sheet impairment is the *timing* of reinvestment, not its aggregate level. An entropy-triggered release of the satisficing gate enables reinvestment to begin at exactly the moment evidential support for regime recovery arrives, without either the premature commitment that precedes confirmed recovery or the institutional inertia characteristic of governance processes dependent on committee attention and approval cycles [17, 18].

Sustained Growth. Under conditions of persistent above-trend enrolment—consecutive Strong and Moderate signals across five or more years, approximating the Exeter trajectory from 2015 to 2022—the framework converges to Invest by Year 4 or 5. The option-value penalty (SR5) prevents structural capital commitment in the early years of growth before sufficient evidence of regime persistence has accumulated. An institution that observes growth in Year 1 and immediately expands infrastructure incurs option-value costs that

Calibrate Your Data Tab — Institution-Specific Parameter Estimation

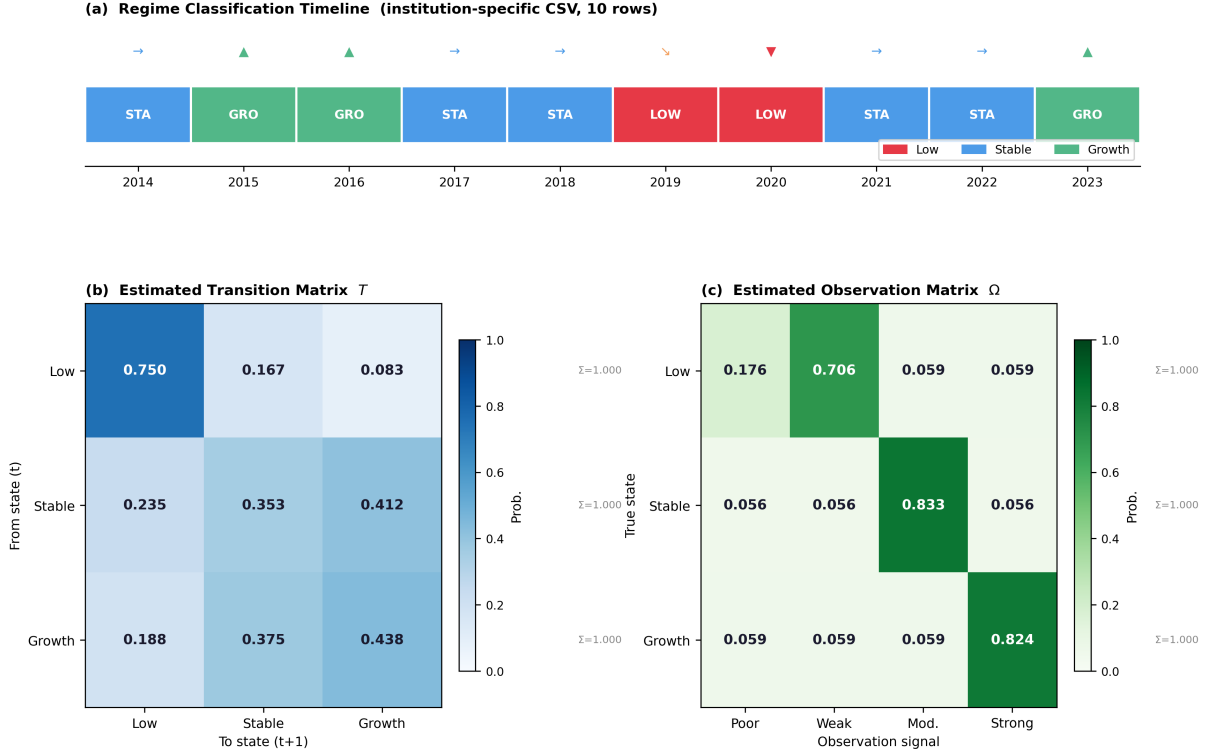


Figure 4: The Calibrate Your Data tab after uploading an institution-specific enrolment CSV (10 rows, 2014–2024). The regime timeline (top) shows the Low/Stable/Growth classification for each year. The estimated transition matrix T (bottom left) and observation matrix Ω (bottom right) replace the Russell Group panel parameters across all simulation tabs once the user activates the custom calibration.

become material if growth stalls in Year 3; the SR5 penalty operationalises the real-options principle that confirmation has value before commitment [38]. The framework’s delayed Invest recommendation is not a governance failure or excessive conservatism; it is the systematic application of a principle that governance bodies apply inconsistently when managing under informal judgement. Institutions following this archetype also illustrate that the entropy-conditioned framework is not structurally biased toward caution: once regime persistence is confirmed, it recommends the most aggressive available posture.

Volatile. When enrolment signals alternate without persistent trend—approximating an environment of maximum and irreducible entropy throughout the planning horizon—the satisficing gate remains permanently active and the framework never recommends Invest or Rationalise across the twelve-year horizon. The recommended posture oscillates between Maintain and Recruit, preserving structural optionality. This outcome may appear to governance observers as inconclusive, but it embodies the most important principle the framework encodes: under genuine and unresolvable regime ambiguity, the evidence-based governance posture is to preserve the capacity for future commitment rather than to commit to a strategic direction whose evidential basis does not exist. Governing bodies that interpret persistent Maintain recommendations as a framework failure have misread the governance signal. The framework is reporting that the institution’s enrolment environment does not, on available evidence, support confident commitment in either

direction—and that the appropriate institutional response is to continue generating and accumulating evidence rather than to act on insufficient grounds.

The four archetypes were deliberately selected to span materially different enrolment trajectories drawn from four separate institutions rather than to illustrate a single institutional case: the comparative design lets the same framework and the same evidentiary logic be evaluated against genuinely different governance situations, which is the basis for the transferability analysis in Section 6.3.

6.2 The Board Pack as a governance accountability instrument

The downloadable Board Pack PDF addresses a governance deficit distinct from the analytical gaps discussed in Section 2: finance committees face increasing expectations that strategic decisions be grounded in documented, independently reproducible analysis, which standard scenario planning documents satisfy poorly.

The Board Pack closes this gap in three respects. It presents all six comparator strategies alongside the Unified Framework recommendation, documenting which alternatives were considered and their expected costs and crisis probabilities—a record of deliberation governance accountability requires. It reports the Monte Carlo crisis probability alongside the expected twelve-year reward, making the risk–return trade-off an explicit quantified input rather than a qualitative judgement in scenario prose. And because all configuration parameters are encoded in the URL at generation, any auditor, regulator, or peer institution that replicates the URL reproduces an identical document—an analytical lineage that paper-based planning cannot provide.

A further extension concerns the Board Pack’s suitability as a substrate for interaction with a large language model (LLM). Because the Board Pack PDF already consolidates the Unified Framework recommendation, the six comparator strategies, and their quantified crisis probabilities and expected rewards into a single reproducible document, it can be provided directly to an LLM, enabling committee members to interactively query, explore, and interrogate the reported insights in natural language. A committee member might, for instance, ask why the recommended posture is Maintain rather than Invest in Year 3; a grounded response would cite the specific values recorded in that year’s Board Pack—88 per cent belief mass on the Stable regime, entropy $H = 0.442$, and the consequent release of the SR3 satisficing gate (Figure 1)—rather than reasoning generically from training-corpus knowledge about university finance. This capability is complementary to, rather than a substitute for, the framework’s Bayesian architecture: the LLM would operate over analysis the entropy-indexed POMDP has already produced under a documented, auditable calibration, rather than generating the underlying probability judgements itself. The value the Bayesian method adds beyond an LLM used in isolation is precisely this auditable, regime-conditioned analytical content that grounds the LLM’s responses.

6.3 Limitations and appropriate scope

Three limitations define the governance scope within which the framework’s recommendations should be interpreted, and institutions should understand them before acting.

The reward matrix R_{net} —the net financial impact of each posture under each regime—is estimated from the HESA Russell Group panel and reflects the marginal costs and revenues of the four calibration institutions. Post-1992 universities, specialist and small providers, and institutions whose programme mix, staffing ratios, or capital structures

differ substantially from the Russell Group average will face different marginal impacts from identical postures, and should treat the reward matrix as indicative. Extending it to institution-specific income and expenditure data requires account-level financial data beyond enrolment counts, and is beyond the scope of the present implementation.

The framework observes only annual full-time equivalent enrolment as its external signal, incorporating no tuition fee income, research grant income, staff cost ratios, or capital expenditure. An institution that has materially offset enrolment contraction through research funding, commercial income, or philanthropic endowment will appear more financially distressed to the framework than its actual balance-sheet position warrants. Users should treat the framework’s regime inference as one evidential input to a broader financial assessment, not a self-contained account of institutional health.

The planning horizon is fixed at twelve years to match the HESA panel used for calibration. Institutions whose planning cycles operate on a three- to five-year basis may find the later years of the trajectory less directly actionable; for them, the most governance-relevant outputs are the Year 1 recommended posture, the entropy trajectory over Years 1–4, and the corresponding segment of the Board Pack posture strip, where entropy most strongly influences posture selection and near-term resource decisions.

A final observation concerns transferability beyond the UK system on which the framework was calibrated. Nothing in the architecture is UK-specific: the hidden regimes, the signal categories, and the Bayesian update operate on any annual enrolment series, and the calibration tab accepts institutional data from any national collection. The decision environment the framework addresses is also not uniquely British. Australian universities’ dependence on international student fee income, and the recruitment volatility produced by recent visa-processing directives and proposed enrolment caps, closely parallel the UK’s post-2022 experience; the underlying pattern—policy-driven regime shifts in internationally exposed enrolment markets—is the wave structure that Choudaha [3] documents globally. Institutions in Australasia or elsewhere wishing to apply the framework would substitute their own enrolment history at the calibration stage; the reward matrix caveat discussed above applies with equal force, since marginal fee income per student differs across funding systems.

7 Deployment, Reproducibility, and Availability

The simulator’s public deployment and local Mac launcher are described in Section 4.3. Institutions wishing to run their own reproducibility check need only the URL or the launcher; no institutional account or software licence is required.

The complete source code, documentation, and pre-computed parameter files are maintained at <https://github.com/ljakaite/he-finplanner> under an open-source licence. A 2 KB parameter cache (`paper_params.npz`) reproduces the calibrated parameters—including the Monte Carlo results in Schetinin [6, Table 4]—on first load, without requiring access to the underlying HESA data files, which are not publicly redistributable. Institutions with technical capacity may deploy the application on their own infrastructure.

When citing: this paper should be cited when referencing the simulator, the five-level engagement protocol, or the governance analysis of the institutional archetypes. Schetinin [6] should be cited when referencing the theoretical framework, its formal derivation, or its Monte Carlo validation. Both citations together constitute a complete methodological lineage for governance documentation purposes.

8 Conclusion

UK higher education institutions are navigating strategic decisions under conditions of deep uncertainty that conventional planning frameworks were not designed to address. Scenario analysis assigns equal or judgemental weight to futures whose relative likelihood is precisely what governance bodies need to determine; sensitivity testing varies factors one at a time in environments where correlated external shocks are the characteristic risk; satisficing approaches remain qualitative where quantification is both feasible and governance-relevant. The result is a persistent gap between the evidential basis that evidence-based management requires and the tools that institutional planning teams currently have available.

This paper has described an interactive simulator that operationalises a structured, evidence-based management decision-support instrument for closing that gap. The simulator implements an entropy-indexed POMDP framework calibrated on a decade of HESA Russell Group enrolment data, in which Shannon entropy of the Bayesian belief distribution serves as a continuously updated institutional uncertainty index. When entropy is high—as it characteristically is during the early phase of an enrolment shock—the satisficing gate constrains irreversible postures without requiring a governance body to form and defend a probability judgement. When entropy falls as evidence accumulates, the framework releases the constraint and recommends decisive action. The five-level engagement pathway makes this protocol accessible to a finance director in ten minutes and to a planning team in under an hour; the Board Pack PDF provides a reproducible, committee-ready governance output with a complete analytical lineage.

The comparative management analysis of four institutional archetypes reveals a consistent underlying principle: the framework’s value is highest precisely in the conditions under which governance bodies find unaided judgement most difficult—periods of genuine regime ambiguity following external shocks, and in volatile enrolment environments where no strategic direction is evidentially supportable. Shannon entropy operationalises the governance question that finance committees most need answered: not which scenario is most likely, but how confident the institution can be in any scenario—and how that confidence level should condition the range of strategic postures available to it.

Finance directors and planning managers—in the UK and in other national systems facing comparable enrolment volatility—are invited to use the simulator, to calibrate it to their institution’s enrolment history, and to report whether its regime classifications and posture recommendations correspond to their governance experience. Feedback of this kind is essential for the iterative refinement that will extend the framework’s applicability beyond the Russell Group institutions on which it was calibrated. Feedback through sector conference discussions, professional planning networks such as HESPA, ATEM, and AIR, and institutional research offices will be particularly valuable in extending the framework’s reach and in grounding its calibration in a broader range of institutional contexts.

Future development priorities include an adaptive reward matrix incorporating institution-specific income and expenditure data alongside enrolment counts; real-time recalibration of the transition matrix via SR7 Dirichlet updating as new annual data arrives; and a native desktop application for institutions whose IT governance does not permit web application access. The immediate aim, however, is more modest: to provide governance teams with a structured, transparent, and computationally reproducible starting point for strategic conversations that are currently conducted without one.

Data availability

The enrolment data used to calibrate this study’s model were obtained from the Higher Education Statistics Agency (HESA), UK. These data are used under licence and are not publicly redistributable in raw form; researchers wishing to reproduce or extend the calibration may request equivalent data directly from HESA (<https://www.hesa.ac.uk>) or use their own institution’s enrolment records. A pre-computed parameter cache (`paper_params.npz`, approximately 2 KB) that reproduces the calibrated model parameters and all Monte Carlo results reported in this study, together with the complete source code and documentation for the decision-support simulator, is freely available at <https://github.com/ljakaite/he-finplanner> under an open-source licence.

Author contributions

V.S. conceived the entropy-indexed POMDP framework and its application to university financial planning, performed the formal analysis, and wrote the initial manuscript. L.J. developed and deployed the decision-support simulator, conducted the HESA data calibration, and contributed to writing. M.C. contributed to formal analysis, methodology, and supervision, and reviewed and edited the manuscript. All authors reviewed and approved the final manuscript.

Competing interests

The authors declare no competing interests.

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