A Real Options Comparative Analysis of Desulphurisation Compliance Pathways

Abstract

The introduction of the 2020 IMO sulphur regulation has significantly changed the strategic decision-making environment for shipowners. Compliance strategies such as retrofitting scrubbers, switching to low-sulphur fuel (LSFO / MGO) or converting vessels to liquefied natural gas (LNG), represent capital-intensive decisions with uncertain future payoffs. This paper employs a real options framework to evaluate these investment choices under market uncertainty. The study integrates regime-switching jump-diffusion processes and continuous-time Monte Carlo valuation to capture the complexities of real-world compliance decisions. We re-cast maritime sulphur-compliance as a high-dimensional American real-option whose underlying state is the stochastic spread between high- and low-sulphur bunker fuels. Scrubber retrofits, low-sulphur switching and LNG conversion are treated as mutually exclusive, yet sequentially exercisable compound options embedded in vessel cash flows that evolve with both fuel prices and age-adjusted earnings. The spread process will be estimated from daily Platts indices using a regime-switching jump-diffusion calibrated by exact-likelihood methods and subjected to likelihood-ratio diagnostics, thereby capturing mean-reverting shocks triggered by regulatory interventions and oil-market turbulence. Optimal stopping regions will be obtained by solving the associated Hamilton–Jacobi–Bellman variational inequality through a Longstaff–Schwartz Monte-Carlo scheme augmented to handle path-dependent scrappage and carbon-levy triggers in continuous time. This integrated framework is designed to yield empirically grounded exercise boundaries, comparative-static sensitivities to volatility, jump intensity, carbon pricing and CAPEX uncertainty, and a mapping from policy instruments such as sulphur-spread floors or carbon-price corridors, to shifts in those boundaries. By fusing state-of-the-art stochastic calibration with advanced real-options numeric, the project aims to furnish both shipowners and regulators with a decision-analytic apparatus capable of aligning private investment timing with globally efficient emissions trajectories. This work aims to contribute to a detailed and dynamic framework for evaluating maritime investments in emissions compliance, enhancing decision quality under uncertainty.

1 Introduction

1.0 Background

Maritime transport is the backbone of world trade, carrying over 80 percent of all the merchandise by volume (UNCTAD, 2024). Yet it is also a significant source of sulphur-oxide (SO_x) pollution, accounting for roughly 12% of global anthropogenic sulphur dioxide (SO_x) emissions, and the proportion is increasing (Fan et al., 2020). Sulphur oxides (SO_x) pose a serious environmental threat, causing an estimated 50,000 premature deaths annually in Europe (Airclim, 2011). To curb these impacts, the International Maritime Organisation amended MARPOL Annex VI, introducing the "IMO 2020" sulphur cap that took effect on 1 January 2020. The amendment lowered the global sulphur limit in marine fuels from 3.5 percent to 0.5 percent (IMO, 2020).

To comply with this stricter regulation, shipowners have three compliance strategies (Li et al., 2020). One is to keep burning high-sulphur fuel oil (HSFO) and fit vessels with exhaust-gas cleaning systems known as scrubbers, which remove most sulphur dioxides but require significant upfront investment (Abadie et al., 2017). A second option is simply to switch to low-sulphur distillates such as LSFO or marine gas oil (MGO); these fuels meet the limits without retrofitting, albeit at a considerably higher price per tonne. The third option is to adopt alternative fuels with inherently low sulphur content, most notably liquefied natural gas, whose sulphur level is below 0.1% but whose use necessitates purpose-built cryogenic tanks and handling systems (Zhu et al., 2020).

The maritime compliance strategies therefore present several uncertainties due to changing policies. A high degree of uncertainty remains on the differential between the prices as well as on the reliability of the supply chain. There are also flexibilities as the shipowners can for instance choose to delay capital-intensive retrofits (eg. scrubbers or LNG engines) until market signals become clearer. Conventional discounted cash flow (DCF) or net present value (NPV) methods often fall short under uncertainty, especially in the context of irreversible and capital-intensive decisions. Further, such methods do not explicitly incorporate the value of managerial flexibility.

Real options theory, pioneered by Dixit and Pindyck (1994) and Trigeorgis (1996) provides a structured way to value flexibility in investment timing. It tells us that when a project is irreversible and prices are uncertain, the option to delay can have significant value. Previous studies applying real options analysis, such as Abadie et al. (2017), Li et al. (2020) and Zhu et al. (2020) have compared these options using static or scenario-based analyses.

1.1 Compliance Strategies and Trade-offs

Shipowners typically consider one of three main strategies for sulphur emissions compliance:

- **Fuel Switching:** Using compliant fuels such as LSFO or marine gas oil (MGO) requires no capital investment but significantly increases operating costs.
- **Scrubber Installation:** Installing exhaust gas cleaning systems allows continued use of cheaper high-sulphur fuel oil (HSFO) but involves substantial capital expenditure and maintenance.
- **LNG Conversion:** LNG offers long-term environmental benefits and potential cost savings but requires the highest upfront investment and depends on bunkering infrastructure.

Each strategy presents trade-offs among cost, environmental compliance, operational complexity and long-term strategic alignment. Choosing among them requires careful evaluation under uncertain future conditions.

1.2 Research Question

Given the stochastic dynamics of the HSFO–VLSFO price spread and the evolving sulphur regulatory landscape what is the value-maximising choice of compliance pathway; scrubber retrofit, low-sulphur fuel switching or LNG conversion, for a representative vessel of a given age and class?

1.3 Objectives and Contributions of the Study

This study aims to develop and apply a real options model to evaluate the economic viability of different sulphur compliance strategies in the maritime sector. The specific objectives are to:

- Model fuel price spreads using stochastic processes that capture market volatility and regime shifts.
- Quantify the value of managerial flexibility using Least Squares and Monte Carlo simulation.
- Compare the real option value of fuel switching, scrubber installation and LNG conversion under different market and regulatory scenarios.

- Provide actionable insights for shipowners, policymakers and financial stakeholders on optimal investment strategies.

The contributions of this research extend beyond academic theory. By integrating real options analysis with practical maritime decision-making, this study offers a valuable framework for aligning environmental compliance with financial performance. It also informs regulatory design by illustrating how policy instruments can influence strategic behavior.

1.4 Structure of the Paper

The paper is organized as follows:

- Section 2 reviews existing literature on sulphur compliance strategies and real options applications in maritime and energy economics.
- Section 3 outlines the methodology, including model specification, stochastic assumptions, and valuation techniques.
- Section 4 presents a case analysis applying the model to a Panamax-class vessel.
- Section 5 discusses the broader implications for strategy, policy, and future research.
- Section 6 concludes the study and outlines directions for future work.

2.0 Literature Review

2.1 Regulatory and Technological Setting for Sulphur Compliance

Relentless regulatory ratcheting has rendered sulphur compliance less a one-off engineering choice than a dynamic gamble in which investment irreversibility collides with volatile fuel-price spreads, forcing owners to treat technology adoption itself as an option on uncertain policy trajectories. The International Maritime Organization (IMO) has progressively tightened Annex VI "In 2005 capped the SOx emissions to 4.5%; in 2012, it was reduced to 3.5% [and] a further significant reduction to 0.5% with implementation from 1 January 2020" (Shi et al., 2025) while leaving a still-stricter "0.1 % cap in sulphur emission control areas" untouched (Shi et al., 2025). These inflections echo broader signals: "Two critical points in time were the 1st of January 2015 and the 1st of January 2020 when, respectively, limits within (1 % to 0.1 %) and outside ECAs (3.5 % to 0.5 %) were significantly lowered" (Zis et al., 2022), and the IMO's 2016 resolution confirmed that "a global sulphur cap of 0.50 per cent m/m [would] be set by 2020" (Abadie et al., 2017). Because further ECA extensions are "under discussion, such as Australia, Japan, Singapore, the Mediterranean Sea and Mexico" (Abadie et al., 2017) compliance geography itself remains elastic. Parallel heterogeneity in enforcement instruments "economic instruments have been introduced... environmentally differentiated fairway dues... differentiated tonnage tax... shore power incentives" (Wang et al., 2007) magnifies strategic uncertainty.

Within this shifting policy envelope, three pathways dominate. As early syntheses observed, "the most realistic alternatives are three... The first is the switch to higher-quality fuels... The second is the use of exhaust gas cleaning systems... And the third one is the use of vessels operating on LNG" (Chen et al., 2018). Yet each carries asymmetric cash-flow profiles. Distillates promise immediacy "The switch to distillates is the measure that generally carries the lowest capital costs" (Acciaro, 2014) explaining why "shifting to low-sulphur fuels is more often considered than scrubbers or LNG" (Li et al., 2020). Scrubbers invert that balance: "Scrubber installation entails a relatively high capital expenditure \$2.5 to \$4.5 million" (Shi et al., 2025) and even "around \$10 million" for ultra-large newbuilds (Zis et al., 2022), but " allow avoidance of purchasing expensive low-sulphur fuel" (Li et al., 2020). LNG offers deeper abatement yet faces diffusion bottlenecks "Only a handful of ships is running on LNG... Costs, availability and technical maturity appear to be the most critical issues" (Acciaro, 2014). Methodologically, the literature maps these options through static cost accounting, and even voices scepticism that "the use of scrubbers at sea is not well established due to the lack of detailed technical studies and accurate cost figures" (Chen et al., 2018). Where dynamics do surface, they appear in analogues: policy is itself "valued... as put options" (Trigeorgis, 1993) and compliance resembles the U.S. allowance market in which "considerable uncertainty over the future prices... and an investment in scrubbers is irreversible" (Dixit and Pindyck 1994).

Crucially, however no empirical study yet stitches together regime-switching fuel-spread volatility and compound exercise sequencing; most stop at deterministic break-evens or one-shot binomial trees, leaving unanswered how option value shifts when "installing sulphur oxide scrubbers" must be timed relative to "switching to low-sulphur fuels" or "running on liquefied natural gas" (Li et al., 2020). Our study aims to fill this gap by designing a high-dimensional jump–diffusion real-options framework that combines the dynamic policy shocks and their interactions with technologies.

2.3 Stochastic Modelling of Bunker-Fuel Price Spreads

The economic calculus of sulphur compliance turns on whether the HSFO–LSFO spread drifts like a brownian tide or ruptures in jump-like squalls because investment timing becomes optimal only when the governing stochastic lens can register both moods of the sea. Classic real-options theory first cast such uncertainty in the "quantitative origins" of continuous Black–Scholes/Merton diffusion (Trigeorgis, 1993) a lineage the maritime field initially adopted by modelling fleet earnings as "bivariate geometric Brownian motions" that decline along life-cycle paths in the manner of dividend yields (Bendall and Stent, 2007). Yet purely Gaussian drift soon proved tone-deaf to the anchoring forces of cost-parity and policy, prompting a mean-reversion turn: "Two common forms of such processes are the Geometric Brownian Motion with drift and the Ornstein-Uhlenbeck mean-reverting process" (Chen et al., 2018) and distillate as well as LNG prices are accordingly tethered to long-run equilibria in Chen et al.'s fuel-switching calculus Abadie et al. (2017) refine the motif by decomposing spot prices into Brent plus a stochastic spread whose "Ornstein–Uhlenbeck processes . . . enable this behaviour" while letting Brent itself wander under an inhomogeneous GBM thereby preserving cross-commodity co-movement in a diffusion-only scaffold.

The covid-era and war-time market, however, exposed the insufficiency of continuous pens: the VLSFO–HSFO differential "has been highly volatile, ranging from roughly \$50 to more than \$350 over the period 2020–2024" (Shi et al., 2025) and its once-robust 67% Brent correlation (Shi et al., 2025) "seems to have been broken" in the face of geopolitical shocks (Shi et al., 2025). Such structural fractures echo Dixit and Pindyck's (1994) early counsel that investment drivers may combine "Brownian motion and Poisson processes" yet maritime scholarship has rarely operationalised the Poisson half. Instead, scenario lattices persist: annual up/down nodes built from IEA/EIA statistics substitute for continuous shocks even while admitting that "accurate fuel price predictions are very challenging" and that assuming perfect oil-gas correlation would "limit the benefits of applying ROA" (Acciaro 2014). Likewise, forecasts of a "trending increase in MGO/LSFO prices and a drop in HFO prices" (Zis and Cullinane 2020) steer drift parameters but leave jump intensity implicit, despite evidence that widening spreads "almost \$50 per barrel . . . more than twice the average of 2010–2018" (Li et al., 2020) magnify option value precisely when volatility spikes.

Crucially, Trigeorgis already sign-posted "alternative (e.g., jump) processes" as a "fruitful direction" (Trigeorgis, 1993) yet the empirical maritime literature still oscillates between over-smoothed diffusions and coarse binomials. The unresolved question, therefore, is how to estimate a regime-aware jump–diffusion that captures both the mean-reverting gravity of regulatory equilibria and the discrete shocks of sanctions, war or carbon-levy pivot points especially at the daily frequency where operational cash flows accrue. By fitting a likelihood-verified, regime-switching jump–diffusion to Platts indices and embedding it in a continuous-time American real-option, the present study answers that call, setting the stage for exercise boundaries that harmonise private retrofit timing with the turbulent, policy-punctuated soundtrack of fuel-price spreads.

2.4 Valuing Compliance via American-Style Real Options

The central dilemma framing sulphur-compliance investment is that capital must be sunk while the fuel-price spread it arbitrages is free to gyrate a setting that "undermines the simple net present value rule" (Dixit and Pindyck 1994) and compels recourse to American-style real options. Early contributions mapped managerial levers onto financial analogues-deferral as a call, abandonment as a put thereby rendering "the option to defer analogous to an American call option on the gross present value of the completed project's expected operating cash flows" (Trigeorgis, 1993) and showing how optimal triggers replace an NPV = 0 benchmark with "a more stringent" exercise premium (Dixit and Pindyck 1994). Subsequent maritime studies imported this logic: scrubber or trade-pattern switches are "valued as an American-style option over a 2.75-year period" with backward induction checking for early exercise "in the usual manner" (Bendall and Stent 2007), while LNG retrofits are treated as calls whose value turns on "the differential between today's option value to invest in q years and to invest today" (Acciaro, 2014).

Yet methods diverge sharply once numerical implementation is confronted. Discrete binomial trees offer transparency but scale poorly when uncertainty multiplies; even proponents concede the need for a "relatively fast converging numerical option valuation method" for higher-dimensional problems (Chen et al. 2018). Longstaff–Schwartz least-squares Monte Carlo (LSM) answers that call by simulating "multidimensional, path-dependent compliance options where analytic solutions are infeasible" (Chen et al. 2018) while dynamic programming remains attractive for low-state grids in which the option value is recursively defined as the maximum of immediate payoff and continuation value (Chen et al. 2018). Across these platforms, real-options theory gifts a common interpretive lens: embedded flexibilities "shift firms' investment thresholds away from the NPV_0 criterion" sometimes lowering thresholds when growth options dominate, sometimes elevating them when deferral value looms large (Tong and Reuer 2007).

Empirical calibration, however, lags methodological sophistication. Many maritime papers still rely on deterministic pay-back horizons whose sensitivity to fuel turbulence merely "foreshadows the need for flexible valuation" (Zis et al. 2022). Where stochasticity is admitted, analysts often freeze the feedback loop between investment and price formation; recent reviewers note that "market prices and scrubber investment may interact with each other" yet are "neglect[ed]" in extant models (Shi et al. 2025). Even studies that couple regime-switching fuel spreads to compliance choice typically evaluate a single option in isolation, ignoring portfolio effects whereby "options embedded in one investment may shape the value of other options held by the firm" (Tong and Reuer 2007). Moreover, realised post-installation cash flows remain unobserved and "none of the studies has observed the real financial benefits from scrubber investment" (Shi et al. 2025) leaving validation of theoretical thresholds conspicuously absent.

Taken together, the literature converges on the insight that sulphur-compliance decisions behave like early-exercise calls and switches whose value is acutely sensitive to volatility, path dependence and option interactions. It diverges on how to parameterise the stochastic drivers and on whether numerical techniques can scale to compound policy-laden contexts. The unresolved agenda therefore centres on empirically grounded, multidimensional valuation frameworks capable of endogenising investment–price feedbacks and benchmarking model-predicted exercise boundaries against observed behaviour. Again, this is the gap the present study seeks to close.

2.5 Empirical Evidence on Maritime Compliance Choices

Despite the intuitive fit between sulphur-compliance decisions and option theory "not many have fully explored the scrubber installation as an investment decision based on financial foundations" (Shi et al., 2025) leaving the field suspended between conceptual promise and empirical under-reach. Early exemplars such as Acciaro's lattice of deferral options opened the dialogue. Acciaro (2014) proposes a decision support model for shipowners based on the use of an option to defer. He did so under deliberately austere assumptions: "only two possible investment horizons were selected" (Acciaro 2014) the LNG-distillate spread was treated as a single draw, and exercise regions were inferred from static breakeven rules. Subsequent probes incrementally loosened these strictures. Chen et al. identify the shift from fixed to annually resetting spreads as a necessary but partial advance "the limitation was overcome in Acciaro (2014) by making the price differential change yearly, [yet] prices of LNG and distillates are just one sample of the fuel price distributions" (Chen et al., 2018, p. 3) and respond with 300-path Monte Carlo valuations that they frame as "the first time such an option methodology has been considered in deferring an investment in a LNG powered new ship" (Chen et al., 2018, p. 18).

Methodological refinement has been mirrored by progressively subtler empirical insights. Acciaro's age-stratified findings "for the ship with the shortest remaining economic life, the call option price increases as the deferral horizon moves forward" (Acciaro 2014, p. 46) prefigure Abadie's vessel-lifetime conditionalities, where "fuel switching is preferable to scrubbers" only under volatility regimes that outlast the hull's economic life (Zis and Cullinane

2020, 71). Likewise, Jiang's deterministic payback heuristics for 5 000 TEU containerships (Zis et al., 2022, p. 9) are problematised when "stochastic modelling on Brent prices ... noted the several uncertainties that affect which decision is preferable" (Zis et al., 2022, p. 13), confirming that option value is inseparable from price-path uncertainty. Even seminal cross-sector analogues Kulatilaka's dual-fuel boiler where "the value of this flexibility far exceeds the incremental cost over a rigid, single-fuel alternative" (Trigeorgis 1993, p. 208) underscore how mis-specifying spread dynamics can dwarf capital-cost analytics.

Yet critical blind spots persist. Scrubber studies still lean on deterministic route assumptions (Abadie et al., 2017, p. 240); LNG analyses rarely couple fuel spreads with carbon-levy trajectories; and, as Li et al. note, the empirical link between "changing the fuel price differential ... and ship operators' compliance choices" (Li et al., 2020, 53) remains sketched rather than quantified across joint policy shocks. Moreover, the mutual exclusivity and sequential interplay of scrubber, low-sulphur fuel and LNG retrofits long recognised in broader maritime investment strategy (Bendall 2013, p. 14) have yet to be embedded within a single stochastic-control framework. The literature therefore converges on two insights: volatility confers strategic patience, and vessel age modulates its value; but it diverges or stays silent on how multi-regime price jumps, carbon levies and compound optionality re-shape exercise boundaries. This unresolved intersection between high-dimensional uncertainty and nested compliance choices crystallises the need for the present study's regime-switching jump-diffusion calibration and continuous-time Longstaff–Schwartz solution, promising decision rules that are as empirically elastic as the markets they aim to tame.

2.6 Numerical Methods for High-Dimensional Option Pricing

The quest to synchronise scrubber retrofitting, low-sulphur switching and LNG conversion with the spiky regime-switching gap between HSFO and LSFO exposes a methodological tension: the more faithfully we model interacting price, policy and age dynamics, the faster conventional solvers buckle under dimensionality. Early maritime studies embraced "a discrete binomial tree approach" (Acciaro 2014, p. 44) leveraging risk-neutral branching to test CAPEX sensitivities but implicitly assuming a single driver and thus suppressing cross-option feedbacks. The wider real-options canon has long warned that "in the more complex real-life option situations, such as those involving multiple interacting real options, analytic solutions may not exist" (Trigeorgis 1993, p. 207); indeed, even finite-difference grids falter once "the differential would be difficult to specify" (Chen et al. 2018, p. 7). Lattice refinements help but only to a point: a bivariate tree "captures correlated uncertainties in trading and chartering revenues" (Bendall & Stent 2007, 133) yet after "five hundred time steps" the state-space already strains memory (Bendall & Stent 2007, 135). Monte Carlo methods avoid grid explosion but traditional backward induction “requires foreseeing the expected continuation function” and is therefore “very high computational cost” (Chen et al. 2018, p. 7).

The Longstaff–Schwartz remedy is to regress continuation values so that “LSM reduces the computational cost by using least squares regression at each intermediate step, based on the results of the following future time step along all the simulation paths” (Chen et al. 2018, p. 7). Such path-wise learning renders jump-diffusions and carbon-levy triggers tractable without resorting to heroic factor pruning. Parallel advances on the operational side reinforce the case for high-dimensional engines: speed-routing models that vary velocity leg-by-leg (Zis and Cullinane 2020, 93) and two-stage stochastic programmes for SECA compliance (Zis and Cullinane 2020, 94) show how regulatory path-dependency “gave rise to several optimization problems” (Zis and Cullinane 2020, 88) whose structure mirrors compound maritime fuel options. Likewise, commodity-spread calibration via Kalman filtering “a different model to estimate future marine fuel prices based on future crude oil quotas and the stochastic differentials between those marine fuels and crude oil” (Abadie et al. 2017, p. 240) supplies multi-factor diffusion estimates that feed seamlessly into Monte Carlo kernels. Yet unresolved frictions persist: binomial and finite-difference schemes “are not able to handle multidimensional variables very well” (Chen et al. 2018, p. 7); Black–Scholes intuition remains “too restrictive for pricing of real options” even if conceptually illuminating (Bendall 2013, 30); and portfolio interactions mean “a firm undertaking multiple investments at a point in time may also experience option portfolio interactions” whose combined value is non-additive (Tong and Reuer 2007, 20).

Dynamic programming promises theoretical unification “the fundamental equation of dynamic programming, and methods of solving it” (Dixit and Pindyck 1994, p. 8) but practical solvers still trade either granularity or speed. The present study therefore positions an LSM-augmented, regime-switching jump-diffusion within this lineage, seeking to convert the acknowledged “two types of numerical techniques” (Trigeorgis 1993, p. 207) into a hybrid engine that preserves path-dependency while sidestepping the grid curse. By quantifying how carbon corridors or sulphur-spread floors warp the optimal stopping regions, it addresses the lingering gap between elegant but brittle single-factor trees and brute-force simulations that drown in their own dimensionality, offering a calibrated bridge where regulatory design and shipowner timing can finally co-evolve.

2.7 Key Drivers of the Optimal Compliance Pathway

Optimal sulphur-compliance unfolds at the junction where volatile market signals meet the ship's evolving techno-economic physiology and the regulator's tightening grip, a junction whose co-ordinates shift fast enough to make timing as consequential as choice. When the spread between very-low- and high-sulphur fuel oil widens, the calculus tilts sharply: "scrubber installation is preferred ... when the fuel price spread is high ... [and] when the remaining lifetime of the vessel is long" (Shi et al., 2025, 25) a threshold Zis and Cullinane fix empirically at "more than €233 per ton" (Zis and Cullinane, 2020). Yet the spread is endogenous; every retrofit that materialises erodes tomorrow's incentive "if the scrubber-fitted fleet has increased by 1%, the income premium is expected to roughly decrease by 1.4% to 3.8%" (Shi et al., 2025, 78) embedding a competitive feedback loop that conventional static pay-back tables ignore.

Regulatory geography inserts a second lever. The moment a hull's trackline threads emission-control areas (ECAs) LNG or scrubber options accelerate: "an increase in the time spent in an ECA would increase the attractiveness of investing in a new LNG powered ship" (Chen et al., 2018, 15) while "longer vessels spend in ECAs ... the more attractive the option of investing in scrubbers becomes" (Abadie et al., 2017, 248). Because ECA exposure is itself path-dependent on trade patterns, owners prize timing flexibility; deferral "can be used to reduce ... technological uncertainties related to the supply cost of bunkering LNG" (Chen et al., 2018, 17), and for high-consumption tonnage "it is preferable to defer the decision to invest to the near future" (Acciaro, 2014, 47).

Such postponement is rational under real-options logic: "The option value increases with the sunk cost of the investment and with the degree of uncertainty over the future price" (Dixit and Pindyck, 1994, 7) and "The more uncertainty ... the greater will be the value of the real options" (Bendall & Stent, 2007, 6). Yet uncertainty does not uniformly defer action. When network externalities accumulate new bunkering hubs, learning-curve CAPEX declines "under high uncertainty, the strategic growth option often dominates the deferral option, thus reducing firms' investment thresholds and encouraging investments" (Tong and Reuer, 2007, 54). Correlation also blunts option value; "the more correlated are the underlying projects the less net value will be added" (Bendall and Stent, 2007, 183) implying that diversification across fuel types or charter markets can keep flexibility alive even as volatility falls.

Technical and demographic heterogeneity further splinters the decision surface. Younger, asset-specific workhorses gravitate to capital-heavy compliance: "tankers, containers and Ro-Ros prefer scrubbers; gas ships prefer LNG; and offshore ships and ferries prefer LSF" (Li et al., 2020, 173). Conversely, scrubber energy penalties and nascent CO_2 pricing darken the retrofit ledger as "CO_2 emissions have to be paid for ... then the numbers may change"

(Abadie et al., 2017, 248). Interest-rate regimes, too, matter: low discount factors enlarge the option's present value and shorten its exercise lag (Shi et al., 2025, 25).

Taken together, the literature converges on fuel-spread volatility, ECA intensity, vessel age, capital cost trajectories and policy clarity as joint determinants; but it fragments on how feedback-induced spread compression, multi-pollutant trade-offs and correlated revenue streams reshape those triggers over time. These unresolved dynamics precisely the hysteresis and compound-option effects foregrounded by Trigeorgis (1993) underscore the need for the regime-switching, jump-diffusion real-options framework advanced in the present study, which can trace moving exercise boundaries rather than snapshot breakevens.

2.8 Limitations of the Previous Research Studies

Sulphur-compliance research stands at a methodological crossroads: the field recognises that investment timing under volatile fuel-price spreads is an inherently dynamic, option-laden problem, yet most empirical designs still mute that complexity, leaving regulators and shipowners without precise decision rules. The resulting tension is visible across three interlocking strands of limitation. First, data parsimony persists. Scrubber CAPEX is "not included ... since it is rather fixed, and no relevant time-series data are available" (Shi et al., 2025, 28) while retrofit dates for low-sulphur-fuel adopters remain patchy, forcing models to omit "fuel prices and consumption" (Li et al., 2020, 195). Such omissions encourage simplified econometrics that "deal satisfactorily with non-stationary variables" only rarely (Chen et al., 2018, 3).

Second, most option-valuation exercises still freeze core stochastic drivers or strategic flexibilities. Fixing the LNG-distillate differential, as in Acciaro's early model curtailed insight precisely where uncertainty bites hardest (Chen et al., 2018, 3) and simultaneously assessing alternatives over just "two possible investment horizons" (Acciaro, 2014, 42) precluded interaction effects. Bendall and Stent warn that "values of alternative flexible strategies are not additive" (2007, 182), yet extant studies seldom map such non-linearities. Third, the theoretical–empirical divide endures. While real-options theory now embraces "jump processes" and "competitive counteractions" (Trigeorgis, 1993, 210) "relatively few large-scale empirical studies" have validated these refinements (Tong and Reuer, 2007, 27); econometric testing remains "at a very early stage" (Dixit and Pindyck, 1994, 15). Managerial uptake thus lags: practitioners shun models deemed "complex and off-putting" (Bendall, 2013, 29), retreating to deterministic DCF calculations that risk "justify[ing] poor investments" when options are invoked only rhetorically (Bendall, 2013, 26).

These limitations propagate blind spots with tangible policy stakes. Unmodelled causal feedbacks mean that volatility itself may "further delay the transition towards net-zero shipping" by magnifying perceived risk (Shi et al., 2025, 102) while enforcement efficacy after the 2020 global cap remains largely conjectural (Zis and Cullinane, 2020, 232). Uncertainty also extends to market instruments: trading schemes must grapple with "transaction costs," "location-specific weighting" and rigorous "monitoring and verification" (Wang et al., 2007, 8236) yet operational decision models rarely endogenise those frictions. Even canonical real-options exemplars skirt important operationalities weather-induced consumption (Zis et al., 2022, 213), bunkering-hub resilience (Shi et al., 2025, 104) and new-build design pathways (Abadie et al., 2017, 249) thereby understating the multi-pollutant trade-offs that may "undermine ... CO_2 reductions" (Zis and Cullinane, 2020, 236).

Consequently, three research frontiers crystallise. Methodologically, robust regime-switching jump-diffusion calibrations are needed to tackle the "multiple causalities between green investment and market uncertainty" (Shi et al., 2025, 29) and to escape the strictures of stationarity. Empirically, high-frequency, vessel-specific panels capturing retrofit dates, carbon levies, and operational weather would enable the "systematic econometric testing" long envisioned (Dixit and Pindyck, 1994, 15) and finally probe "domain translation" hurdles (Tong and Reuer, 2007, 38). Strategically, integrated option portfolios must be valued under competitive games where the "option to defer" entwines with the "option to grow" (Acciaro, 2014, 48) respecting non-additivity and policy feedbacks. Only by animating these fronts can scholarship deliver the clear "pathway that decreases the market uncertainty associated with green investment" (Shi et al., 2025, 118) and furnish regulators with levers calibrated to real behavioural thresholds.

2.9 Research Gaps and Rationale for Current Study

Despite growing interest in real options for maritime decisions, several gaps persist:

- Most studies rely on simplified stochastic models that do not reflect the full range of market uncertainties.
- Comparative real options valuation of all three major sulphur compliance strategies (scrubbers, fuel switching, LNG conversion) under consistent assumptions is limited.
- Few analyses integrate carbon pricing, regulatory timing, and vessel-specific attributes into real options frameworks.
- There is limited methodological transparency and few case studies that apply advanced simulation techniques to real-world vessels.

This study addresses these gaps by using a regime-switching jump diffusion model for fuel price spreads, applying Least Squares Monte Carlo simulation, and conducting a case study of a representative Panamax-class vessel. This comprehensive approach enables more robust and policy-relevant valuation of green shipping investments.

3 Methodology

This section details the methodology developed to model and evaluate compliance strategies under the IMO 2020 sulphur regulation using a real options framework. The model accounts for market uncertainty, technological irreversibility, and regulatory flexibility. We describe the theoretical formulation, stochastic modeling of fuel price spreads, and numerical methods employed to derive optimal investment strategies.

3.1 Real Options Framework

The real options approach conceptualizes investment opportunities as financial options, wherein shipowners retain the right, but not the obligation, to undertake a specific compliance strategy at a future date. This is especially relevant when the investment involves high sunk costs, uncertain payoffs, and irreversible outcomes, as in the case of installing a scrubber or converting to LNG.

Let $V(t)$ denote the value of a given compliance strategy at time t, and let I be the required investment. The real option value $F(t)$ satisfies:

$$F(t) = \sup_{\tau \in [t,T]} E^Q \left[e^{-r(\tau - t)} (V(\tau) - I)^+ \right]$$

where τ is the stopping time (i.e., optimal investment time), r is the risk-free discount rate, and E^Q denotes the expectation under the risk-neutral measure.

3.2 Stochastic Modeling of Fuel Price Spread

The key uncertainty affecting the profitability of different strategies is the spread between high-sulphur fuel oil (HSFO) and compliant fuels like LSFO or LNG. Unlike traditional models that assume fuel prices follow a geometric Brownian motion, we adopt a regime-switching jump-diffusion (RSJD) process to capture abrupt shifts due to geopolitical events or regulatory changes.

Let $S(t)$ denote the fuel spread at time t. Then:

$$dS(t) = \mu_i S(t)dt + \sigma_i S(t)dW(t) + JdN(t)$$

where:

- μ_i and σ_i are the drift and volatility parameters in regime i
- $W(t)$ is a standard Brownian motion
- $N(t)$ is a Poisson process with intensity λ
- J is a random jump magnitude

Transition between regimes is governed by a finite-state Markov chain. This allows the model to reflect different economic or regulatory scenarios.

3.3 Compliance Strategy Valuation

We consider three strategies:

1. **Fuel Switching (LSFO):** Immediate compliance with no capital investment but higher operating costs.
2. **Scrubber Installation:** Upfront capital expense with potential long-term savings depending on fuel spread.
3. **LNG Conversion:** Highest CAPEX but possibly lower long-term costs and better emission performance.

Each strategy's cash flow is modeled over a discrete horizon (eg. 10 years) and its net present value (NPV) is calculated under various price scenarios. The option to defer is then valued using simulation.

3.4 Numerical Solution: Least Squares Monte Carlo (LSM)

To price the American-style option to defer the investment, we employ the Least-Squares Monte Carlo (LSM) technique developed by Longstaff and Schwartz (2001). The algorithm proceeds as follows:

1. Simulating multiple paths of $S(t)$ using RSJD

2. Computing payoffs along each path for each strategy
3. Using regression to estimate continuation values and identify optimal stopping times

This method is preferred for its flexibility in handling path-dependent features and multiple sources of uncertainty.

3.5 Model Calibration

Historical data for fuel prices (HSFO, LSFO, LNG) over the last 10 years were used to calibrate the RSJD parameters. Parameters were estimated using maximum likelihood methods and validated against observed fuel spread dynamics.

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