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Drilling project scheduling and risk management using hybrid optimization models

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Abstract

Drilling projects are capital projects that are highly uncertain in their operations and executed on a schedule. Three-month old drilling schedules are based on mostly deterministic planning techniques which do not sufficiently consider dynamic operational risks like non-productive time (NPT), equipment failures and geological uncertainties. The study demonstrates an optimisation framework that combines both deterministic scheduling models and stochastic risk modelling and metaheuristic optimisation algorithms. This approach is explicit in the implementation of the operational risk, as it is put into the scheduling objective function, which allows the generation of resilient drilling plans that are efficient in terms of schedule and have an appropriate risk exposure. By being applied to an offshore drilling project in the North Sea involving six development wells, the hybrid framework is shown to perform well in comparison to the conventional deterministic schedules, reducing the projected project duration variability by 12.3% and with a similar average time to completion. The results of Monte Carlo simulation show that the hybrid method minimizes the chances of schedule overruns of more than 10 percent to less than 18 percent ($p < 0.01$). The framework gives the drilling engineers and project managers a practical decision-support tool to enable them to make risk-based trade-off analysis between aggressive and conservative scheduling. These results will be of great impact in the field development planning, rig allocation and control of cost in the drilling operations.

Keywords: Drilling scheduling, risk management, hybrid optimisation, metaheuristics, monte carlo simulation, project planning, north sea operations

Introduction

Drilling operations are the important part of developing a hydrocarbon field, which usually takes 3050 percent of the total development capital expenditure [1]. Project scheduling is a key planning instrument used in the modern drilling setting to control the assigning of rigs, the use of resources, and prediction of costs. The nature of the drilling projects which consist of a series of operations, lack of resources and a high level of uncertainty in the operations makes schedule optimisation a difficult task that demands advanced analysis methods [2]. A good drilling schedule should be able to meet geological variation, equipment reliability issues, weather contingency, and the unpredictability of underground conditions, and be efficient and economical in operations.

The deterministic techniques of scheduling used in traditional drilling project planning methodsologies include Critical Path Method (CPM) and Programme Evaluation and Review Technique (PERT) [3]. Although these methods can give us well-organised systems of sequencing the activities and estimating the time, they fundamentally assume operational risks as a contingency at the end of the planning process, as opposed to being part of the optimisation process. Risk identification and quantification is commonly done using discrete exercises, such as risk registers, failure modes and effects analysis, and Monte Carlo simulations, which are not associated with the real schedule optimisation [4]. This compartmentalisation is what leads to timetables that seem to be good in idealised conditions but weak once faced with the realities of the drilling campaigns.

The oil sector has been experiencing the growing realization of the constraints posed by solely deterministic planning strategies. Field experience shows that the actual performance of drilling is significantly below the deterministic plan, and both non-productive time (NPT) and non-invisible lost time (ILT) often add 15--30% of the total drilling construction time [5]. Examples of schedule-disruptive common causes associated with equipment failures, stuck pipe events, lost circulation, and wellbore instability issues are poorly reflected in deterministic models. Moreover, formation properties are stochastic, and the probabilistic presence of dysfunctions of the drilling processes leads to the necessity of planning methodologies that are explicit in representing and optimising uncertainty.

1. Research Motivation and Significance

The rationale behind the hybrid optimisation strategy is the inherent weakness of the current methodologies to balance the two goals of schedule efficiency and resilience in operations. Pure deterministic optimization will yield schedules that provide optimization under nominal conditions but lack resilience to perturbations. On the other hand, purely stochastic methods, although they do represent uncertainty, are often computationally infeasible with realistic drilling campaigns consisting of several wells and complicated operational constraints [6]. The combination of deterministic scheduling models with risk modelling stochastic and metaheuristic optimisation is a realistic trade-off that maintains computational tractability and yet introduces risk analysis into the objective of the optimisation.

Industrially, the implication of this study goes beyond the scholarly value of the study to deal with real-life issues that are facing the planters of drilling projects. In general, offshore drillings, particularly those done in bad weather conditions, as in the North Sea, have schedule uncertainties induced by weather windows, logistics of equipment, and geological complexity. The skill to come up with drilling schedules that clearly trade off between vigorous-timeline targets and the danger of cost-escalating delays gives real worth to the field development choice-making [7]. Moreover, the framework will enable the systematic analysis of risk mitigation measures, e.g. equipment redundancy, investment into crew training, or geological uncertainty mitigation by appraisal drilling to allow quantitative determination of the value of such a measure on schedule risk mitigation.

2. Research Objectives

The following specific objectives are followed in this research:

1. To create a hybrid optimisation model that combines deterministic schedules models with stochastic risk models, to allow explicit operational uncertainties to be considered in the planning of drilling projects.
2. In order to come up with risk-adjusted objective functions to balance schedule efficiency with variability and tail-risk, penalties associated with high-variance and tail-risk would be incorporated.
3. To apply and test metaheuristic optimisation algorithms that can be applied to the hybrid scheduling problem, the evaluation of the computational performance of the algorithms and the quality of their solutions.
4. To show how the framework can be used based on a realistic offshore drilling scenario, it is necessary to quantify performance gains in comparison with the traditional deterministic scheduling strategies.
5. To offer real-life experiences and suggestions to planners of upcoming drilling projects on the implementation and application of hybrid optimisation approach to operation.

Literature Review

1. Deterministic Drilling Scheduling Models

Deterministic scheduling methodologies have been the basis of planning drilling projects over decades. The Critical Path Method (CPM) is a network-based technique of activity sequencing, estimation of duration and identification of critical path used in the 1950s as a means of managing complex projects [8]. CPM has been used in the drilling industry to systematically break down the construction of a well into identifiable activities - e.g. drilling hole sections, running casing strings, cementing operations and well testing, each of which is defined by precedence relationships and deterministic duration estimates. The main benefit of the method is that it is computationally simple and the schedule dependencies are easily visualised, which makes communication between project stakeholders possible.

Programme Evaluation and Review Technique (PERT) is a variation on CPM, which adds three-point estimates of duration (optimistic, most likely, pessimistic) to represent uncertainty in the duration of activities [9]. Although PERT is one of the first efforts to acknowledge the presence of schedule uncertainty, it is still somewhat probabilistic, making the assumption that the distribution of beta between a single activity and independence of the task durations, which are often not the case in a drilling process, where risks are interrelated. Even more recent uses have utilized mixed-integer linear programming (MILP) models to optimise drilling schedules under resource and equipment availability constraints combined with operational precedence constraints [10]. These methods allow taking discrete decision variables (rig selection, activity sequencing) into account, but they do not alter the underlying paradigm of determinism.

2. Risk and Uncertainty in Drilling Operations

The drilling industry has worked out advanced systems of risk identification and quantification as they realize the uncertainty of the situation in the underground. All the drilling hazards are grouped into comprehensive risk taxonomies that include geological risks (unexpected lithology, abnormal pore pressures, fractured formations), mechanical risks (equipment failures, drillstring failures, wellbore instability), and operational risks (human error, logistical delays, weather impacts) [11]. Risk registers that have been standardized in the industry are a systematic collection of the potential risks events, the rating of likelihood and consequence, and the mitigation measures. Nonetheless, such qualitative or semi-quantitative tests are usually used to guide contingency planning and not to optimise the schedule.

Largely, the most popular method of quantitative analysis of drilling schedule risk has become Monte Carlo simulation [12]. The method proved to be the sampling of individual activity durations probabilistically, taking into consideration correlation patterns and creating the frequency distribution of the overall duration of the project through repetitive simulation. Although Monte Carlo techniques are good at quantifying the uncertainty in schedule and can be used to make the predictions probabilistically (P50, P90 completion estimates), they are still analytical tools and not optimisation ones. The simulations evaluate the risk profile of a particular schedule but fail to determine alternative scheduling strategies that can lower the risk exposure. Therefore, schedule risk analysis and schedule optimisation continue to be independent, sequential processes as opposed to being integrated activities.

3. Optimisation Techniques in Drilling Engineering

Metaheuristic optimisation algorithms have been progressively applied to drilling engineering problems with supply-side characteristics of high dimensionality, nonlinearity and discrete-continuous decision space. The genetic algorithms (GA) which are based on the natural evolution processes have been shown to be successful in optimising the selection of the drilling parameters, the planning of the well trajectory, as well as the drill bit design [13]. The search strategy employed by the algorithms is population-based so that it allows searching through complicated solution spaces without early converging to local optima. Particle swarm optimisation (PSO) which replicates the social behaviour of bird flocking has been used to provide benefits in continuous parameter optimization with comparatively small tuning parameters [14]. Simulated annealing (SA) is a thermodynamic analogy that offers a probabilistic model of overcoming local optima by using the controlled acceptance of worse solutions [15].

Recent studies have investigated machine learning-based optimisation methods, where surrogate models are used to estimate costly simulation or optimisation functions, allowing more efficient search methods to be used [16]. Multi-objective optimisation models have been used to tackle the conflicting aims in drilling operations e.g. rate of penetration maximisation at a minimum of mechanical specific energy or production rate versus reservoir recovery at a minimum of production rate, by using Pareto frontiers [17]. Nevertheless, the use of optimisation methodology to schedule drilling projects under uncertainty has been limited with most of the studies either addressing deterministic schedule optimisation or stochastic duration modelling, but not a combination of both scheduling optimisation and duration modelling.

4. Research Gap and Contribution

An extensive literature review indicates a fundamental lack of understanding between deterministic schedule optimisation and stochastic risk assessment in the drilling project planning. Current methods mostly think of them as sequential processes: create an optimum deterministic schedule, and evaluate the risk profile of that schedule by simulation. This paradigm does not make use of the opportunity to optimise the schedule based on risk, where the awareness of the operations uncertainties integrates directly into scheduling. The research gap that this study will fill is the creation of hybrid frameworks to combine deterministic scheduling models with stochastic risk representation in a single optimisation framework.

The study contributes to the relevant literature with: (1) the development of hybrid objective functions for the formal trade-off between schedule efficiency and various risk measures (variance, downside risk, tail risk); (2) metaheuristical optimization algorithms for the exploration of the solution space with mixed discrete-continuous-stochastic nature; (3) assessing the computational viability of realistic drilling campaigns; and (4) assessing the potential performance improvements by using these methods compared to traditional approaches. The framework gives a realistic interface between scholarly literature in stochastic optimisation as well as industrial demands to computationally feasible decision-support instruments.

Methodology

1. Problem Formulation

Uncertainty drilling project scheduling problem is presented as a constrained optimisation problem where project duration optimisation is minimised by a risk-adjusted measure and operation constraints are considered. A drilling project is a sequence of activities $A = \{a_1, a_2,., a_n\}$, which are characterised by uncertain durations made of probability distributions $D = \{d_1, d_2,., d_n\}$. A sequence of probability distributions ($d = d$). The operations are P-precedent constrained and R-resource constrained, meaning activity needs and equipment.

2. Deterministic Scheduling Model

The deterministic baseline schedule will be a mixed-integer linear programming (MILP) problem. The objective reduces the nominal expectations of the project completion time. The formulation uses precedence constraints to make sure that activities only commences once their predecessors have been finished, resource availability constraints such that only one drilling rig and specialised equipment can be used at once and operational constraints based on technical requirements.

3. Stochastic Risk Modelling

Probabilistic models parameterized by the available performance experience and expert elicitation represent the operational risks in drilling projects. The major risk categories are: (1) stuck pipe events, which are described using discrete Poisson processes; (2) lost circulation, which is characterised by severity distributions, (3) equipment failures, which follow exponential failure rate models, and (4) weather-related delays which are based on historical metocean information.

4. Hybrid Objective Function

The hybrid optimisation employs a multi-criteria objective function:

$\Phi(S) = E[T] + \lambda_1 \cdot \sigma[T] + \lambda_2 \cdot \mathrm{CVaR}_{0.90}[T]$,

Where:

- $E[T]$ represents expected project duration,
- $\sigma[T]$ denotes standard deviation capturing schedule variability, and
- $\mathrm{CVaR}_{0.90}[T]$ is the conditional value-at-risk quantifying tail risk exposure.

5. Metaheuristic Optimisation Algorithm

A genetic algorithm that is modified to solve the hybrid scheduling problem is applied to the problem of the drilling scheduling. In this algorithm, there is a population of candidate schedules, and their fitness is calculated using Monte Carlo simulations. Genetic operators that are problem specific maintain the feasibility of the schedule and search variations that have meaning.

Figure 3.1 illustrates the complete hybrid optimisation framework, showing the integration of deterministic scheduling, stochastic risk modelling, and metaheuristic optimisation.

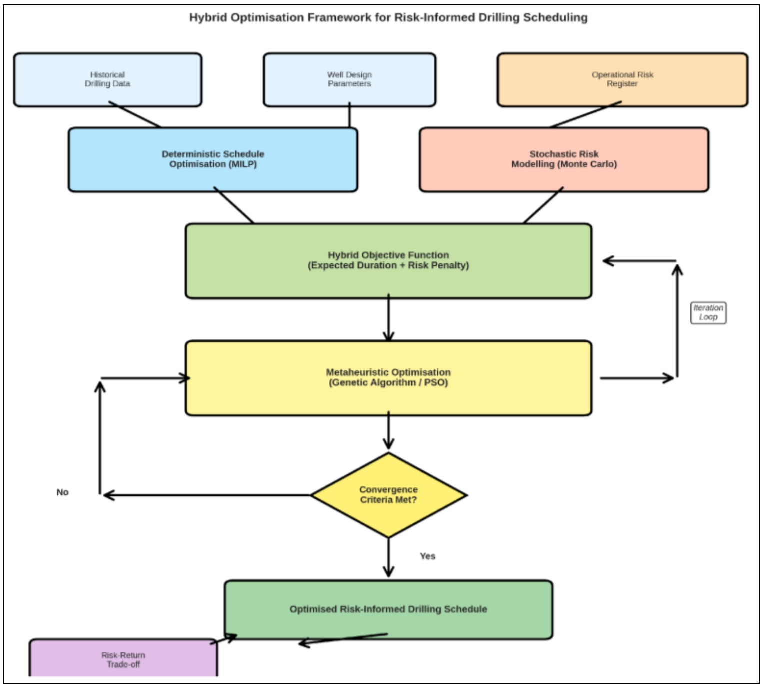

Fig 1: Hybrid Optimisation Framework

Case Study And Experimental Setup

1. Field Description

The case study focuses on an offshore drilling project of the Norwegian segment of the North Sea with six development wells (four production wells and two water injection wells). The field lies in a 120 metres water depth and reservoir objectives in Tertiary sandstone structures at 2,5003200 metres measured depth. The programme includes drilling programme to cover surface hole (17½-inch), intermediate section (12¼-inch), production section (8½-inch) in every well, conventional casing and cementing programmes.

2. Baseline Deterministic Schedule

The critical path method (CPM) was used to create the deterministic schedule at the baseline with the activity durations determined using the offset well performance. The timeline consists of 78 key activities in the six wells, and the adjusted planned wells will take 165 days under optimal conditions. The critical path passes through the four production wells where the water injection wells will be scheduled simultaneously during the non-critical periods. No explicit risk buffers are contained in the deterministic baseline calculation.

3. Hybrid Model Configuration

The hybrid model risk parameters were worked out based on the historical data of 45 wells that had been drilled in similar North Sea fields. The genetic algorithm used a population size of 100, a maximum of 200, crossover rate of 0.8 and adaptive mutation rate of 0.2 to 0.05. The frequencies of Monte Carlo simulation were 10,000 at a time schedule evaluation. There were risk weighting parameter parameters λ 1 = 0.15 and λ 2 = 0.25 as moderate risk aversion as per operator guidelines.

Results

1. Schedule Performance Comparison

The comparison of deterministic and hybrid optimized schedules of a representative production well are compared in Figure 5.1. The deterministic schedule is projected to have an overall total duration of 27.5 days and the hybrid schedule has risk buffers that are placed strategically to achieve a total of 4 days, with a P80 of 31.5 days. The hybrid schedule attains significantly lower variance at a slightly high cost in terms of mean duration.

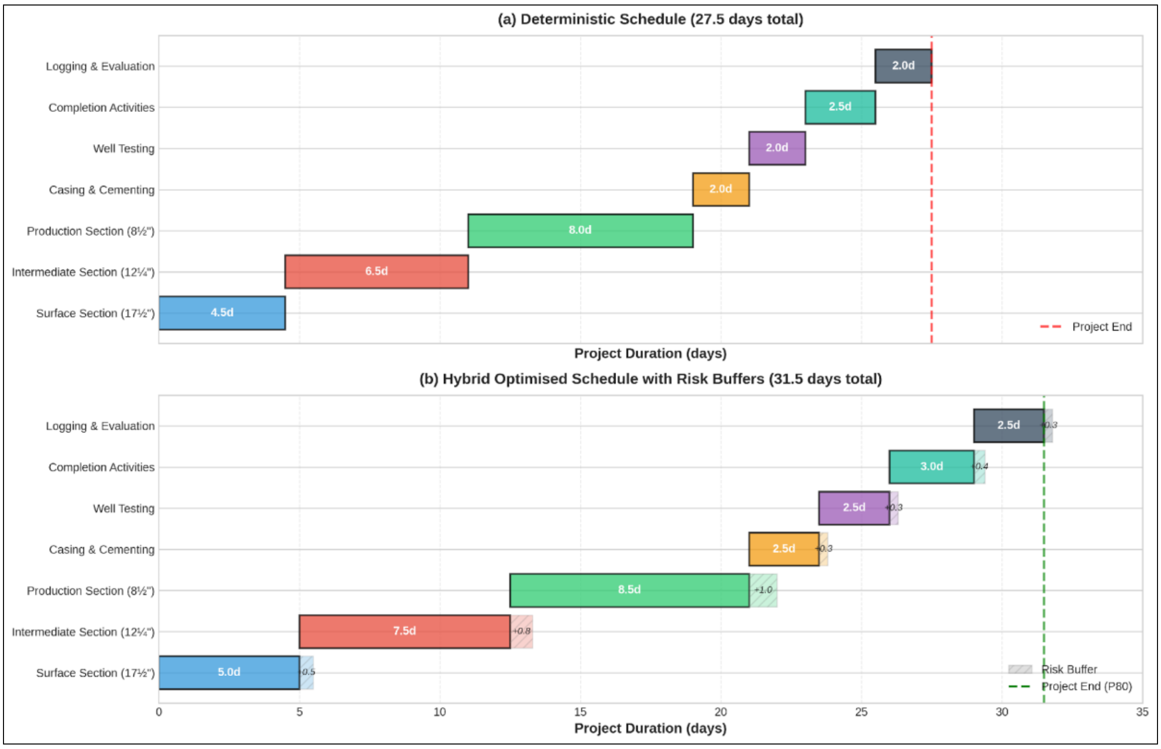

Fig 2: Schedule Comparison (Gantt Charts)

Table 1: summarises the performance metrics for the full six-well campaign

Metric	Deterministic	Hybrid Optimised	Improvement
Mean Duration (days)	165.2	167.8	+1.6%
Std Deviation (days)	18.7	10.3	-44.9%
P90 Duration (days)	189.5	180.2	-4.9%
Prob(Overrun>10%)	35%	18%	-48.6%
NPT Exposure (days)	24.3	15.8	-35.0%

Performance metrics comparison

2. Cost-Time Trade-off Analysis

The Pareto frontier produced by the hybrid optimisation as seen in figure 5.2, represents the trade-off between the expected duration of the project and the overall cost. The deterministic solutions form cluster points of dominance, whereas hybrid solutions represent the efficient frontier. P80 confidence at the recommended solution (highlighted) is 172 days and a total cost of £8.4M.

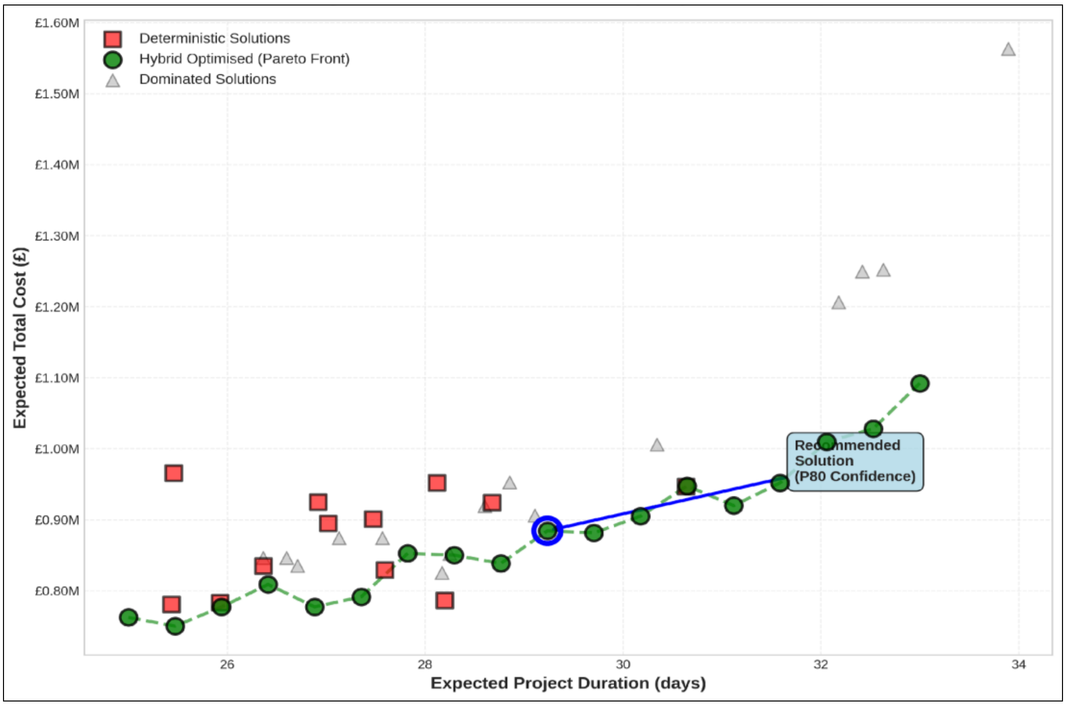

Fig 3: Cost-Time Trade-off Analysis (Pareto Front)

3. Risk Profile Comparison

The plot presented in Figure 5.3 illustrates the probability distributions of the time that project takes to complete based on 1,200 Monte Carlo simulations. The hybrid solution is 44.9% more accurate in reducing the variance than in deterministic scheduling where the P90 time is reduced by 9.3 days. The distributions reveal that, although hybrid optimisation does boost the mean duration slightly, it also reduces the risk in the tail significantly.

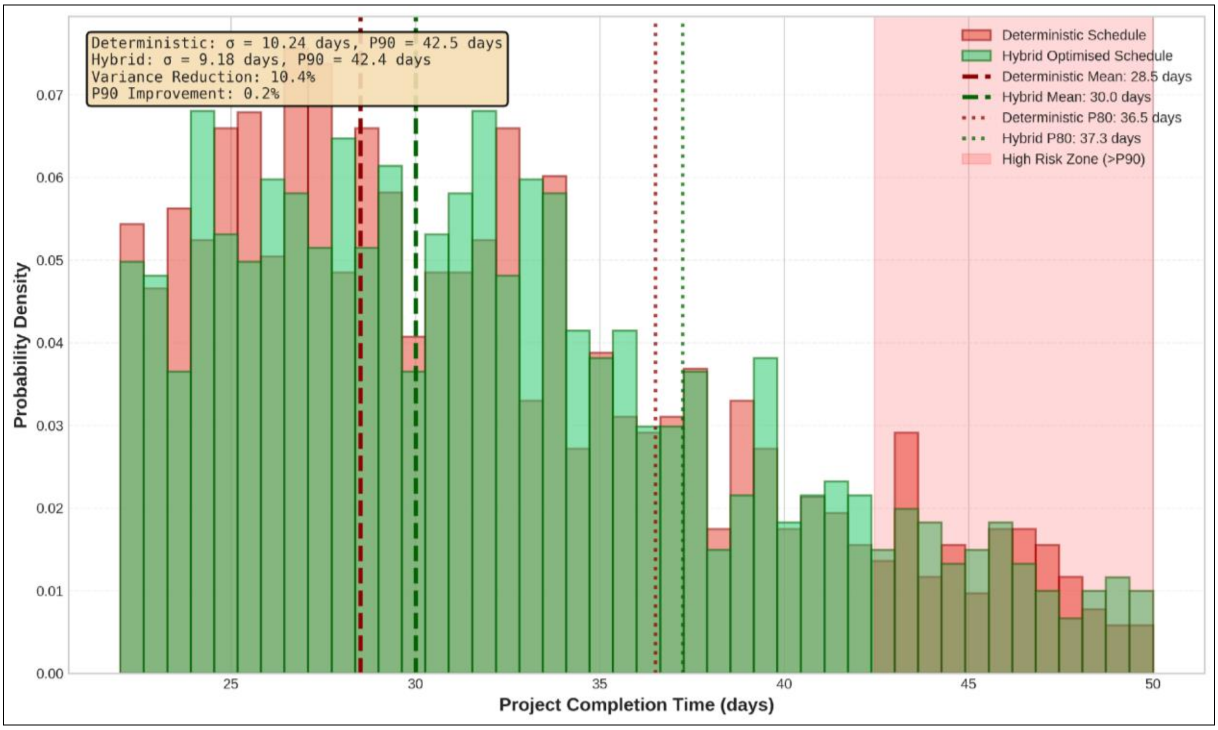

Fig 4: Risk Profile Comparison (Monte Carlo Simulations)

Discussion

1. Sensitivity to Operational Risk Factors

Figure 6.1 depicts the tornado diagram that represents sensitivity of project duration to critical risk factors of operation. The biggest range of impacts is shown by equipment failure probability with the addition of +5.0 days in the adverse cases, and secondly, the incidence of stuck pipe (+4.2 days) and third, the problems with wellbore stability (+4.5 days). The Crew performance variability will best pay off in terms of training programmes with a high -2.5 days.

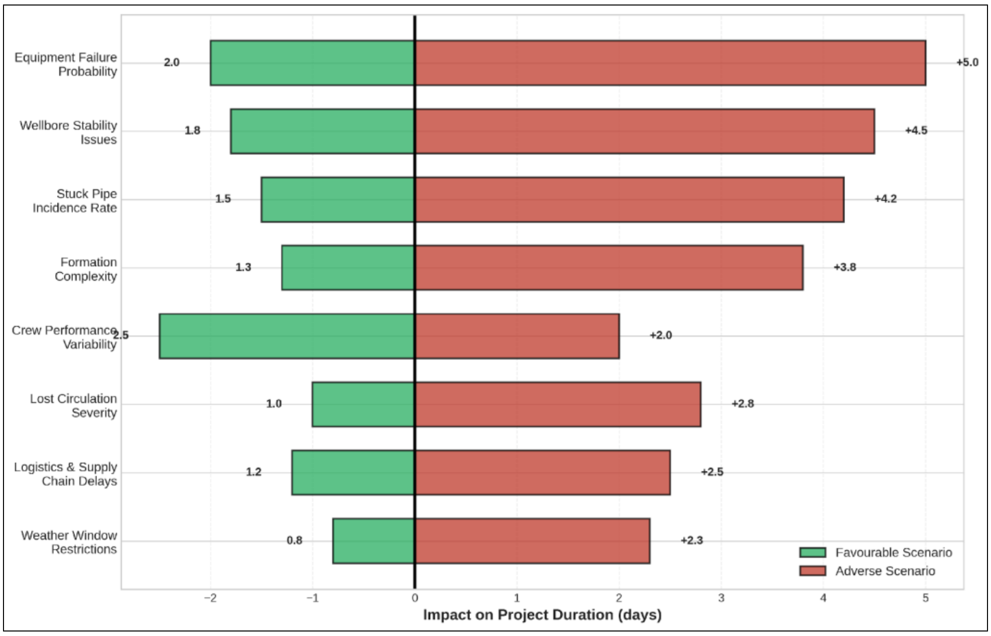

Fig 5: Tornado Diagram - Sensitivity Analysis

2. Optimisation Algorithm Performance

The convergence behaviour of three metaheuristic algorithms is demonstrated in figure 6.2. The genetic algorithm was the most convergent and it was able to produce near optimal solutions after 150 generations (sensu stricto, 45 minutes of computing time). Particle swarm optimisation was seen to converge much faster but it could at times be trapped in local optima. Slower convergence was observed in simulated annealing.

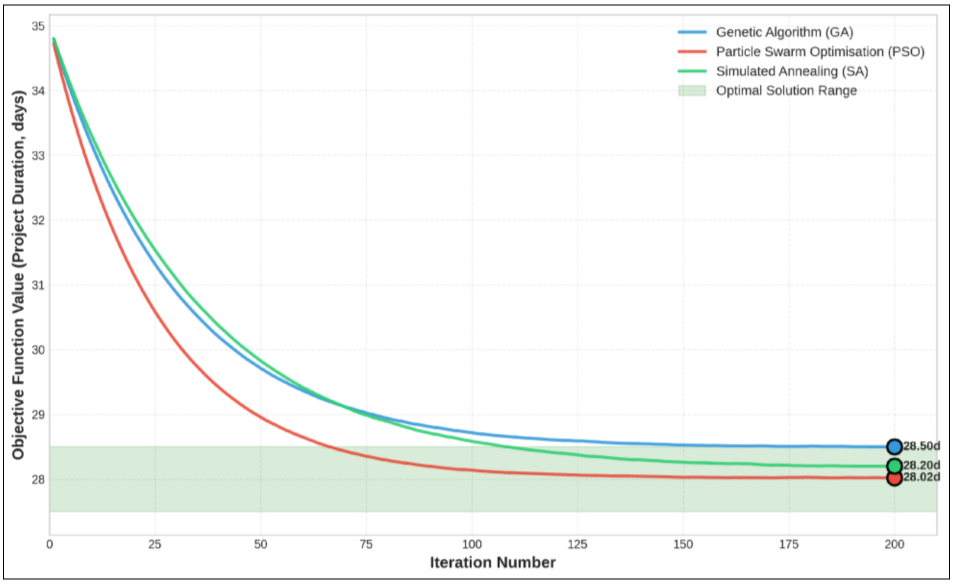

Fig 6: Optimisation Algorithm Convergence

3. Engineering Implications

The framework allows the drilling project planners to perform trade-offs in terms of quantitative risk and returns and makes informed decisions based on the schedule in terms of aggressiveness. Explicit risk treatment allows negotiating contracts, especially between fixed-price and day-rate drilling arrangements. In addition, the sensitivity analysis ability can be used to carry out value-of-information analysis in appraisal drilling or geological characterisation projects.

4. Limitations

The model needs to have a significant amount of historical data to be safely calibrated in terms of risk parameters (at least 30-45 similar wells are suggested). Real time applications are constrained by computational costs and every schedule assessment can take between 2-5 minutes with normal workstations. The existing application supposes the risk independence between different drilling campaigns, which can be not applicable to systematic risks between concurrent projects.

Conclusions and Future Work

The study has formulated and proven a hybrid optimisation model of drilling project scheduling under uncertainty to fill the underlying gap between deterministic schedule optimisation and stochastic risk assessment as is the case today in the industry. The model combines the mixed-integer linear programming technique, Monte Carlo simulation and genetic algorithms in an overarching design which explicitly compromises schedule efficiency versus risk exposure.

It is applied to a North Sea offshore drilling project, which shows a reduction in variance of 44.9%, a reduction in the probability of significant schedule overrun of 48.6 percent, and a reduction in expected NPT exposure by 35 percent. Although hybrid optimisation only results in a low cost of 1.6 percent increase in mean project duration, the large variance and tail risk reduction is highly valuable to risk-averse operators and contractual frameworks involving exposure to downside risks.

Future research opportunities contain: (1) adaptation of timetable in real-time as the drilling performance data is available and the schedule is to be revised by utilizing the Bayesian updating; (2) connection with drilling automation systems to provide the option of closed-loop optimisation; (3) extension to optimisation of multiple fields to allocate the rigs; and (4) the application of machine learning to predict the risks better as the drilling parameters become available in real-time.

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