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Original Article

Stochastic Activity-Based Time and Cost (S-ATC) Model for Oil Wells: Case Study of Niger Delta Onshore, Nigeria

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Abstract *- Oil and gas well drilling and completion times and costs estimate has a large impact on the capital investment decisions in exploration and production (E&P) projects. Their good estimate is one of the main purposes of engineers in the economic evaluation of oil field development projects. Several techniques (deterministic and probabilistic) that are mainly cost-per-footage-based are available for oil wells' time and cost estimation. This study aims to propose a technique called the "Stochastic Activity-Based Time and Cost (S-ATC) Model" for oil and gas well investment. This model sets a probabilistic comprehensive activity-based technique that provides single values, P10, P50 and P90, for the oil well's time and cost estimate. A case study is performed for the onshore Niger Delta, Nigeria. The advantage of this model is its ability to furnish much more accurate outputs. The model has been tested with two wells within the Niger Delta region in Nigeria. The estimation errors range between 0.2 and 5.96 percent, which proves the efficiency of the S-ATC model.*

Keywords *- Oil well, S-ATC Model, Deterministic parametrization, Stochastic parametrization, Niger delta, Nigeria.*

1. Introduction

An oil or gas well is a borehole drilled in the subsoil to reach a hydrocarbon deposit. [4] stated that the primary objective may be exploration (prospecting for a deposit) or development (bringing a deposit on stream). Oil wells drilling cost represents up to 40% of the total exploration cost and 25% of the total oil field exploitation cost. A good estimate of a well's cost is one of the main purposes of engineers in the economic evaluation of oil field development projects. In fact, drilling and completion costs estimate can have a large impact on the capital investment decisions in exploration and production (E&P) projects [37]. Therefore, the preparation and defense of the Authorization for Expenditure (AFE), also called Authority to Procure Expenditure, is a hard task for the drilling management team. The AFE is a budgetary document, usually prepared by the operator, to show the estimated expenses of drilling a well to a specified depth, casing point or geological objective and then either completing or abandoning the well [33]. It is a spreadsheet that summarizes the costs of the activities/operations to be performed over the well drilling and completion and the different materials and services to be used. The drilling management team of the operator should not only justify the allocation of different funds [34] but also show the significance of the overall well cost (amount to invest) to the company leaders and the host country representatives. Early in the oil industry, the difference noticed between the actual and planned well times, and costs led to the continuous research of much more accurate well time and cost estimation models.

Over the past several decades, various methods (deterministic and probabilistic) have been proposed to evaluate drilling time and cost. Traditionally, the drilling time and cost have been estimated on a deterministic basis, providing a single number for the time and the total cost for drilling a well [18].

The common deterministic models used in the oil and gas industry for well time and cost estimation are the different variants of cost per foot or cost per meter formulae ([5], [11], [12] and [36]), simple and multiple linear regressions [27], polynomial regressions [7], logarithmic regressions [31] and exponential regressions [7]. These methods do not reflect the full range of possible outcomes and the likelihood of any particular outcome. The probability that the actual well cost will be the same or close to the predicted value is not quantified [33].

Probabilistic well time and cost estimates, or at least an understanding of the potential well time and cost range, is required as a part of the internal procedures of the E&P companies [26]. As a result, probabilistic time and cost estimates have quickly become a common business practice in the well construction industry [3]. The most probabilistic model on which engineers rely for well cost and duration estimation are combinations of Monte Carlo simulation to the existing deterministic models ([1], [3], [18], [21], [24], [26], [29], [33] and [35]).

Few models are performed to be applied to every world area (or basin), and most are built to be used for specific areas or basins. Whatever the well time and cost estimation model, the information on former drilled wells called offset wells, needs to be used—the more the number of offset wells, the better the outputs of the estimation model. From 2010 to 2017, ninety-five (95) wells are drilled on average per year in Niger Delta, Nigeria [30]. [30] highlights that more than a thousand wells have been drilled in the onshore Niger Delta, which constitutes a great resource for well time and cost estimation model building. Through the literature review, the stochastic approach has not been applied to a well drilling activity-based time and cost estimation model in Niger Delta (Nigeria) or elsewhere.

This study aims to propose a technique called the "Stochastic Activity-Based Time and Cost (S-ATC) Model" for oil well operation schedules and cost estimation. This model will set a probabilistic comprehensive activity-based technique that provides single values, P10, P50 and P90, for the oil well's time and cost. A case study will be performed for the onshore Niger Delta, Nigeria.

2. Well-Drilling Operations and Cost

2.1. Well-Drilling Operations

Drilling an oil or gas well consist of making a borehole in the subsoil to reach a hydrocarbon deposit [4]. The drilling operations are the implementation of the well plan set by the collaborative team of geologists, geophysicists, well engineers, reservoir engineers and other relevant competencies.

Operators rely on drilling companies for oil and gas well drilling projects through contracts of different types. The main phases of a drilling contract are pre-spud (rig mobilization, site preparation and rig demobilization), drilling phase and well completion [16].

In summary, the drilling phase operation is performed as follows [22]:

- The bit and drill string is inserted into the hole and drilled to a certain depth.
- The drill string is removed from the hole.
- The casing is put into the hole to line it and, in most cases, is cemented to the wall of the hole.
- The bit re-enters the hole, repeating the process until the target is reached.

2.2. Well Cost

There is a number of ways in which drilling cost can be classified based on functional category, time or depth dependency, or variable or fixed cost classification [22].

[22] states that the usual procedure is to decompose costs into general categories of (1) site preparation, (2) mobilization and rigging up, (3) drilling, (4) tripping operations, (5) formation evaluation and surveys, (6) casing placement, (7) well completion, and (8) drilling problems. [32] recognizes two types of well cost: the cost comprising the goods and services cost (consumables and tangibles) and the rig spread cost (i.e., the costs attributable to accomplishing each phase of drilling). [19] states that drilling cost for a hydrocarbon well can be subdivided into five origins:

- pre-spud cost: cost of move-in and move-out, site preparation and well design;
- casing and cementing cost: cost of casing and cementing materials as well as running casing and cementing in place;
- drilling-rotating costs: all costs related to the rate of penetration, such as bits and mud costs;
- drilling-non-rotating costs: tripping, well control, waiting, directional control, supervision and well evaluation (logging, measurement, test, coring, etc.); and
- trouble costs: costs related to stuck pipe, twist-offs, fishing, lost circulation, hole stability problems, well control problems, cementing and casing problems and directional problems.

When the well is designed to be completed, the completion cost, which gathers all costs involved in setting equipment in the well and the wellhead (gravel pack, production casing, production tubing, liner, valves, packer, Christmas tree, etc.), must be added to Hossain's cost structure [19].

Each of the cost structures defined above can be rearranged into the following (equation 1) on which the S-ATC model will rely:

$$Well\ Cost = Pre\ spud\ Cost + Drilling\ Cost + Completion\ Cost \tag{1}$$

Where: Drilling cost is the sum of casing and cementing cost, drilling rotation cost, drilling non-rotation cost and trouble cost.

The most difficult to be estimated is the drilling cost. This approach, the S-ATC model, will provide a stochastic method of forecasting the drilling cost and the related time. This cost depends mainly on the drilling contract type, the day rate contract being suitable for S-ATC model design. However, an existing S-ATC model for a specific area or basin can help operators and drilling companies estimate well operation time and cost before any drilling contract negotiation.

3. Materials and Methods

3.1. Materials

The design of the approach proposed in this study (S-ATC model) requires data on drilling operations time and cost of the area of interest offset wells. The main reports from which the key activities information, time and cost can be gotten are the Daily Drilling Report (DDR), cost computation spreadsheet and Final Cost Report (FCR) of offset wells. As far as using the S-ATC model for future wells times and cost estimation is concerned, only a well program is needed.

3.2. Methods

The essence of the approach called the *Stochastic Activity-Based Time and Cost (S-ATC) Model,* is the application of Monte Carlo Simulation to the combination of a comprehensive drilling cost per foot (or cost per unit footage drilled method) and the proposed new variant of Activity Based Costing (ABC) techniques. The existing comprehensive drilling cost-per-foot models in the literature propose determining the cost per foot for different hole sections or activities. For instance, [11] points out that the hole section-based cost-per-foot model is much more accurate than the global cost-per-foot technique proposed by [5], [12] and [36].

Activity-based costing is a technique used to estimate a process or project cost by identifying the key activities that lead to the whole process (project) completion and determining the costs thereof. Operators in the oil and gas industry rely heavily on activity-based costing since it is easy to formulate if accurate data is kept on all activities [17]. *S-ATC model* will set a step-by-step procedure for estimating times and costs of process or project key activities and, therefore, the whole project time and cost as well as P10, P50, and P90.

S-ATC model must normally be built on specific areas or basins and helps estimate well drilling time and cost at the AFE writing stage when the well program is ready. When data are available, the S-ATC model should be designed differently for onshore and offshore (shallow, deep, ultra-deep) areas, the different types of wells (exploration, appraisal, development, vertical, deviated or horizontal) and the different types of rigs and drilling contracts. Indeed, as [27] highlights, drilling time and cost depend on location (onshore, offshore), the purpose of the well (exploration, delineation, development), trajectory (vertical, directional, horizontal), borehole size and complexity (two-dimensional, three-dimensional, extended reach), well type (original, sidetrack), drilling plan, etc. In the absence of a large amount of data for each of these factors, whole models making no breakdown of these dependent factors can be conceived.

This work proposes a three-step procedure: (1) data collection and processing, (2) S-ATC modelling and (3) well time and cost estimation with S-ATC Model.

3.2.1. Data Collection and Processing

Data collection and manipulation is a crucial step of an S-ATC model design. It can actually be performed through some key tasks.

Data Collection

Data collection consists of gathering the Daily Drilling Report (DDR) for all the areas of interest drilled wells. When the detailed costs are not put in the DDRs, cost computation spreadsheets and/or Final Cost Reports (FCR) are needed. Since oil and gas industry data are under great confidentiality, it is often difficult to get all data on an area or basin. In such a case, a representative and random sample should do the business.

A sample is a subset of the drilled wells population [13], while a random sample is one in which all members of a population have an equal chance of being sampled [28]. If the total number of wells drilled in the area of interest is N, an n-size random sample is gotten by numbering the wells (from 1 to N) and generating an n-size sample of {1, …, N} with a random number generator. A sample is supposed to be representative when its size is greater than a specific number which depends on the statistic to be estimated [13].

Data Processing

The completion of the following main tasks will lead to well data processing.

a) Activities Starting and Ending Tasks Identification

As stated later, the S-ATC model proposes a technique for estimating well-drilling time and cost. Being a variant of the activity-based costing method, the drilling operation activities it considers, which are called S-ATC model activities, are four aggregated activities:

- conductor pipe pilling activity: the set of related conductor pipe pilling tasks;
- drilling activity: the set of related borehole sections drilling tasks;
- casing running activity: the set of related casing running tasks; and
- cementing activity: the set of related cement operation tasks.

The tasks that the S-ATC model considers belong to each aggregated activity are summarized in Table 1.

b) S-ATC Model Activities Time and Cost Computation

At the current stage, the S-ATC model activities times and costs must be computed for different conductor pipes, hole sections, and casing sizes present in the dataset. The information required for that purpose are the activities' starting and ending dates and durations as well as the well's daily cumulative costs. Even though detailed costs are often available, the easiest way to compute an activity time and cost is given by equations 2 and 3.

Table 1. S-ATC model activities and tasks

S-ATC model activities	Activity tasks
Pipe pilling	Loading conductor pipe, pilling, welding, cutting excess pipe, waiting to cool, pressure test on pipe, setting pipe head, the test of BOP, etc.
Drilling	Drilling, tripping, reaming, drill string connection, well control, waiting, directional control, supervision and open hole well evaluation (logging, measurement, test, coring, etc.), trouble management, etc.
Casing running	Casing operation, material and crew preparation, casing running, casing connection, casing operation trouble management, casing cutting, mulling windows, etc.
Cementing	Cement material and crew preparation, cement pumping, waiting on cement (WOC), cement adhesion test, cased hole test, etc.

$$D = (Date_{end} - Date_{start} - 1) + \frac{D_{start} + D_{end}}{24} \qquad (2)$$

$$C = \left(CC_{end} - CC_{beforestart}\right) * \frac{D}{ROUND(D)} \qquad (3)$$

Where**:** D, the activity duration in days; $Date_{start}$, the activity starting date; $Date_{end}$, the activity ending date; D_{start}, the activity duration over the starting date, in hours; D_{end}, the activity duration over the ending date, in hours; C, the activity cost; $CC_{beforestart}$, the well cumulative cost at the end of the day before the activity starting date; and CC_{end}, the well cumulative cost at the end of the activity ending date.

c) Cost Normalization

Drilling costs can vary significantly over time. If the wells of the dataset are not drilled in the same year, the costs must be adjusted to a common year [37]. The process is called cost normalization. It consists of normalizing the inflation into or out of the data, depending on which reference year the model should be set to [31].

The formula for cost normalization is given by equation 4.

$$C_R = C_w * (1 + i_R)^{Y_R - Y_w} \qquad (4)$$

Where C_w is the well cost at the year, it is drilled; C_R is the well cost at the reference year; Y_w is the year the well is drilled; Y_R is the reference year, and i_R is the mean inflation rate.

d) Relevant S-ATC Model Activities Parameters Computation

The relevant model activities indicators to be computed are:

- conductor pipe length (PL) for different conductor pipe sizes in the dataset;
- footage drilled (F) for different hole section sizes;
- casing length (CL) for different casing outer diameters (OD);
- open hole height (OH) after setting casing for different casing outer diameters;
- drilling time per footage drilled unit (TuF) for different hole section sizes;
- conductor pipe pilling time per conductor pipe length unit (TuPL) for different conductor pipe sizes;
- casing running time per casing length unit per open hole height unit (TcsuCLuOH) for different casing outer diameter (OD) for casing operations;
- cement operation time per casing length unit per open hole height unit (TcmuCLuOH) for different casing outer diameter (OD) for cement operations;
- drilling cost per time unit (CduT) for different hole section sizes;
- conductor pipe pilling cost per time unit (CpuT) for different conductor pipe sizes;
- casing running cost per time unit (CcsuT) for different casing outer diameter (OD) for casing operations; and
- cement operation cost per time unit (CcmuT) for different casing outer diameters (OD) for cement operations.

For cost calculation, normalized costs are used. The equations for PL, F, CL, OH, TuF, TuPL, T_{cs}uCLuOH and T_{cm}uCLuOH computation are as follow (equation 5 to 12).

$$PL = PSD - WHD \qquad (5)$$

Where PSD is the conductor pipe shoe depth, WHD is the wellhead depth.

$$F = TD - CSD_p \qquad (6)$$

Where TD is the hole section total depth; CSDp is the previous casing shoe depth.

$$CL = CSD - WHD \qquad (7)$$

Where CSD is the casing shoe depth.

$$OH = TD - CSD_p \qquad (8)$$

Where TD is the hole section total depth; CSDp is the previous casing shoe depth.

$$TuF = \frac{D}{F} \qquad (9)$$

$$TuPL = \frac{D}{PL} \qquad (10)$$

$$T_{cs}uCLuOH = \frac{D}{CL * OH} \qquad (11)$$

$$\mathrm{T_{cm}uCLuOH} = \frac{D}{CL * OH} \qquad (12)$$

The costs per time unit $\mathrm{C_duT}$, $\mathrm{C_puT}$ $\mathrm{C_{cs}uT}$ and $\mathrm{C_{cm}uT}$ are computed with equation 13.

$$CuT = \frac{C}{D} \qquad (13)$$

After computation, the different TuF, TuPL, $\mathrm{T_{cs}uCLuOH}$, $\mathrm{T_{cm}uCLuOH}$, $\mathrm{C_duT}$, $\mathrm{C_puT}$, $\mathrm{C_{cs}uT}$ and $\mathrm{C_{cm}uT}$ are gathered in a spreadsheet which constitutes the dataset for data manipulation.

e) Data Manipulation

In the context of S-ATC modelling, data manipulation consists of outliers detection in TuF, TuPL, $\mathrm{T_{cs}uCLuOH}$, $\mathrm{T_{cm}uCLuOH}$, $\mathrm{C_duT}$, $\mathrm{C_puT}$, $\mathrm{C_{cs}uT}$ and $\mathrm{C_{cm}uT}$ datasets as well as the treatment thereof. [25] define outliers as anomalies that do not follow an expected standard behavior. For [10], outliers are observations or measures that are suspicious because they are much smaller or much larger than the vast majority of the observations. In order words, an outlier is an observation that appears to deviate markedly from other members of the sample in which it occurs. Mathematically, an outlier is an observation that is less than the lower fence or greater than the upper fence of the dataset [20]. The lower (L) and upper (U) fences are respectively defined as: L = Q1 - 1.5*(Q3 – Q1) and U = Q3 + 1.5*(Q3 – Q1), with Q1 the lower quartile and Q3 the upper quartile.

There are several ways to detect outliers in a dataset. The most common is data visualization through boxplot. A boxplot (also called box-and-whiskiers plot) is a plot that depicts a summary of the lower quartile, median, upper quartile and the fences of a dataset ([2] and [34]).

Keeping the outliers in a dataset negatively affects the analysis result.

Outliers are either removed or corrected (replaced) by a specific statistic of the sample or dataset [2]. For the purpose of S-ATC modelling, we recommend replacing the outliers with the mean (or the center of the modal class) of the dataset.

3.2.2. S-ATC Modelling

It is obvious that:

- conductor pipe pilling operation time and cost depend on the pipe length to be pilled;
- drilling operation time and cost depend on the footage drilled;
- casing running operation time and cost depend on both the casing length and the open hole height;
- cement operation time and cost depend not only on the casing length but also the casing annular space and, therefore, the open hole height;

On the basis of the above, the S-ATC model states that an oil well drilling operation time (or duration) and cost can be respectively forecasted with equations 14 and 15.

$$\mathrm{T_w} = \mathrm{T_p} + \mathrm{T_d} + \mathrm{T_{cs}} + \mathrm{T_{cm}} \qquad (14)$$

$$\mathrm{C_w} = \mathrm{C_p} + \mathrm{C_d} + \mathrm{C_{cs}} + \mathrm{C_{cm}} \qquad (15)$$

Where the *model activities times* or *model time components* $\mathrm{T_p}$, $\mathrm{T_d}$, $\mathrm{T_{cs}}$ and $\mathrm{T_{cm}}$ are respectively the duration of conductor pipe pilling, drilling, casing running and cement operations and the *model activities costs* or *model cost components* $\mathrm{C_p}$, $\mathrm{C_d}$, $\mathrm{C_{cs}}$ and $\mathrm{C_{cm}}$, the conductor pipe pilling, drilling, casing running and cement operations cost respectively. There are eight different cases for times and sixteen for costs. According to the S-ATC model, the model time and cost components $\mathrm{T_p}$, $\mathrm{T_d}$, $\mathrm{T_{cs}}$, $\mathrm{T_{cm}}$, $\mathrm{C_p}$, $\mathrm{C_d}$, $\mathrm{C_{cs}}$ and $\mathrm{C_{cm}}$ are defined in Tables 2 and 3 for different cases.

S-ATC Model Design Relies on the Model Parametrization, which consists of:

(1) Computing the model deterministic parameters, that are the averages of the following indicators:
- TuPL for each conductor pipe OD class if it depends on conductor pipe OD;
- TuPL for the hole dataset if it does not depend on conductor pipe OD;
- CpuT for each conductor pipe OD class if it depends on conductor pipe OD;
- CpuT for the hole dataset if it does not depend on conductor pipe OD;
- TuF for each hole section size class if it depends on hole section size;
- TuF for the hole dataset if it does not depend on hole section size;
- CduT for each hole section size class if it depends on hole section size;
- CduT for the hole dataset if it does not depend on hole section size;
- TcsuCLuOH for each casing OD class if it depends on casing OD;
- TcsuCLuOH for the hole dataset if it does not depend on casing OD;
- CcsuT for each casing OD class if it depends on casing OD;
- CcsuT for the hole dataset if it does not depend on casing OD;
- TcmuCLuOH for each casing OD class if it depends on casing OD;
- TcmuCLuOH for the hole dataset if it does not depend on casing OD;
- CcmuT for each casing OD class if it depends on casing OD; and
- CcmuT for the hole dataset if it does not depend on casing OD.

Table 2. Formulae for S-ATC model time components computation

N°	**Model time component**	**Formula**	**Equation number**
1	Conductor pipe pilling time (or duration) T_p when TuPL depends on conductor pipe OD	$T_P = \sum_i TuPL_i * PL_i$	(16)
2	Conductor pipe pilling time (or duration) T_p when TuPL does not depend on conductor pipe OD	$T_P = TuPL * \sum_i PL_i$	(17)
3	Drilling time (or duration) T_d when TuF depends on hole section size	$T_d = \sum_j TuF_j * F_j$	(18)
4	Drilling time (or duration) T_d when TuF does not depend on hole section size	$T_d = TuF * \sum_j F_j$	(19)
5	Casing running operation time (or duration) T_{cs} when T_{cs}uCLuOH depends on casing OD	$T_{cs} = \sum_k T_{cs}uCLuOH_k * CL_k * OH_k$	(20)
6	Casing running operation time (or duration) T_{cs} when T_{cs}uCLuOH does not depend on casing OD	$T_{cs} = T_{cs}uCLuOH * \sum_k CL_k * OH_k$	(21)
7	Cement operation time (or duration) T_{cm} when T_{cm}uCLuOH depends on casing OD	$T_{cm} = \sum_l T_{cm}uCLuOH_l * CL_l * OH_l$	(22)
8	Cement operation time (or duration) T_{cm} when T_{cm}uCLuOH does not depend on casing OD	$T_{cm} = T_{cm}uCLuOH \sum_l CL_l * OH_l$	(23)

(2) Determining the model stochastic parameters that are P10, P50 and P90 of the model deterministic parameters.

S-ATC Model Deterministic Parametrization

As stated in the previous section, the deterministic model parametrization is the determination of TuPL, TuF, T_{cs}uCLuOH, T_{cm}uCLuOH, C_duT, C_puT, C_{cs}uT and C_{cm}uT averages for each corresponding independent parameter (conductor pipe OD, hole section size or casing OD) if there is the dependency on the independent parameter and single values if no dependency is noticed. As a result, it is obvious that one needs to check whether there is any significant dependency on the activities, times and costs before computing the model's deterministic parameters. Then, two tasks must be carried out: (a) model activities times and cost dependency verification and (b) model deterministic parameters computation.

a) Model Activities Times and Costs Dependency Verification

The activities' times and costs dependency verification can be performed either through a graphical analysis or a statistical test of equality of means.

Height statistical variables are concerned with times and costs dependency verification:

- conductor pipe pilling time per conductor pipe length unit (TuPL);
- conductor pipe pilling cost per time unit (CpuT);
- drilling time per drilled footage unit (TuF);
- drilling cost per time unit (CduT);
- casing running time per casing length unit per open hole height unit (TcsuCLuOH);
- casing running cost per time unit (CcsuT);
- cement operations time per casing length unit per open hole height unit (TcmuCLuOH); and
- cement operations cost per time unit (C_{ms}uT).

The graphical analysis consists of plotting the boxplots of different subgroups (classes) for the given variable and observing the graph's shape.

i) Rule of Thumb of Boxplot Analysis

If the boxplots median bars are significantly at the same level, then the given variable is supposed to be independent of the explicative variable attributes; otherwise, it depends on the explicative variable attributes.

For example, if the TuPL boxplot median bars level is almost at the same level for different conductor pipe ODs, then one can conclude that the TuPL average does not depend on conductor pipe ODs.

If a boxplot analysis cannot help conclude the variable dependency, a statistical test for equality of means is required. A statistical test or test of hypotheses is a mathematical method for using sample data to choose one of two hypotheses on one or two populations [13]: the null hypothesis denoted $H_{0,}$ and the alternative hypothesis noted H_1. [13] define a statistical hypothesis as an assertion or conjecture concerning one or more populations. The null hypothesis is the claim on which to test, and the alternative hypothesis is the assertion that contradicts H_0.

Table 3. Formulae for S-ATC model cost components computation

N°	Model cost component	Formula	Equation number
1	Conductor pipe pilling costs C_p when: - TuPL depends on conductor pipe OD; and - C_puT depends on the conductor pipe OD.	$C_P = \sum_i TuPL_i * PL_i * C_puT_i$	(24)
2	Conductor pipe pilling costs C_p when: - TuPL depends on conductor pipe OD; and - C_puT does not depend on conductor pipe OD.	$C_P = C_puT * \sum_i TuPL_i * PL_i$	(25)
3	Conductor pipe pilling costs C_p when: - TuPL does not depend on conductor pipe OD; and - C_puT depends on the conductor pipe OD.	$C_P = TuPL * \sum_i PL_i * C_puT_i$	(26)
4	Conductor pipe pilling costs C_p when: - TuPL does not depend on conductor pipe OD; and - C_puT does not depend on conductor pipe OD.	$C_P = TuPL * C_puT * \sum_i PL_i$	(27)
5	Drilling cost component C_d when: - TuF depends on hole section size; and - C_duT depends on hole section size.	$C_d = \sum_j TuF_j * F_j * C_duT_j$	(28)
6	Drilling cost component C_d when: - TuF depends on hole section size; and - C_duT does not depend on hole section size.	$C_d = C_duT * \sum_j TuF_j * F_j$	(29)
7	Drilling cost component C_d when: - TuF does not depend on hole section size; and - C_duT depends on hole section size.	$C_d = TuF * \sum_j F_j * C_duT_j$	(30)
8	Drilling cost component C_d when: - TuF does not depend on hole section size; and - C_duT does not depend on hole section size.	$C_d = TuF * C_duT * \sum_j F_j$	(31)
9	Casing running operation cost C_{cs} when: - T_{cs}uCLuOH depends on casing OD; and - C_{cs}uT depends on casing OD.	$C_{cs} = \sum_k T_{cs}uCLuOH_k * CL_k * OH_k * C_{cs}uT_k$	(32)
10	Casing running operation cost C_{cs} when: - T_{cs}uCLuOH depends on casing OD; and - C_{cs}uT does not depend on casing OD.	$C_{cs} = C_{cs}uT * \sum_k T_{cs}uCLuOH_k * CL_k * OH_k$	(33)
11	Casing running operation cost C_{cs} when: - T_{cs}uCLuOH does not depend on casing OD; and - C_{cs}uT depends on casing OD.	$C_{cs} = T_{cs}uCLuOH * \sum_k CL_k * OH_k * C_{cs}uT_k$	(34)
12	Casing running operation cost C_{cs} when: - T_{cs}uCLuOH does not depend on casing OD; and - C_{cs}uT does not depend on casing OD.	$C_{cs} = T_{cs}uCLuOH * C_{cs}uT * \sum_k CL_k * OH_k$	(35)
13	Cement operation cost C_{cm} when: - T_{cm}uCLuOH depends on casing OD; and - C_{cm}uT depends on casing OD.	$C_{cm} = \sum_l T_{cm}uCLuOH_l * CL_l * OH_l * C_{cm}uT_l$	(36)
14	Cement operation cost C_{cm} when: - T_{cm}uCLuOH depends on casing OD; and - C_{cm}uT does not depend on casing OD.	$C_{cm} = C_{cm}uT * \sum_l T_{cm}uCLuOH_l * CL_l * OH_l$	(37)
15	Cement operation cost C_{cm} when: - T_{cm}uCLuOH does not depend on casing OD; and - C_{cm}uT depends on casing OD.	$C_{cm} = T_{cm}uCLuOH * \sum_l CL_l * OH_l * C_{cm}uT_l$	(38)
16	Cement operation cost C_{cs} when: - T_{cm}uCLuOH does not depend on casing OD; and - C_{cm}uT does not depend on casing OD.	$C_{cm} = T_{cm}uCLuOH * C_{cm}uT * \sum_l CL_l * OH_l$	(39)

For instance, in the context of S-ATC modelling, the null hypothesis of conductor pipe pilling time per pipe length unit (TuPL) test for equality of means is H_0: “The mean of TuPL is independent of conductor pipe OD”, that is $\overline{\mathrm{TuPL}_1} = \overline{\mathrm{TuPL}_2} = \cdots = \overline{\mathrm{TuPL}_n}$ (with $\overline{\mathrm{TuPL}_i}$ the mean of TuPL for different conductor pipe ODs and n the number of conductor pipe ODs in the dataset) and its alternative is H_1: “TuPL depends on conductor pipe OD”.

A statistical test is characterized by a test statistic which is a function of the sample data on which the decision (reject H_0 or do not reject H_0) is to be based [13] and a rule of decision set from a critical value or a p-value at a given significance level α. The p-value is the probability, assuming H_0 to be true, that the test statistic would have a value whose disagreement with H_0 is as great as or greater than that actually observed.

ii) Rule of Decision

H_0 is accepted when the test statistic is less than the critical value, or the p-value is greater than the significance level and is rejected otherwise [8].

There are several tests for equality of means. For S-ATC deterministic parametrization, the proposed tests are the most common tests used in case the explicative variable has more than two attributes (classes or groups): one-factor or one-way Analysis of Variance (ANOVA) and the Kruskal-Wallis test.

According to [13], single-factor ANOVA focuses on a comparison of m independent and normally distributed groups means $\bar{y}_1, \bar{y}_2, \dots, \bar{y}_m$ (m ≥ 3) of a random variable Y. The hypotheses to be tested are [13]:

- H_0: $\bar{y}_1 = \bar{y}_2 = \cdots = \bar{y}_m$; and
- H_1: at least two means $\bar{y}_i$ are different.

Let n_j $(1 \leq j \leq m)$ the group's size, $n = \sum_{j=1}^{m} n_j$, and y_{ij} The i-th observations of the j group.

The ANOVA test statistic F is given by equation 40.

$$\mathrm{F} = \frac{\mathrm{SSB}/(\mathrm{n}-\mathrm{m})}{\mathrm{SSW}/(\mathrm{m}-1)} \tag{40}$$

Where:

- SSB is the between-group sum of squares computed with equation 41;

$$\mathrm{SSB} = \sum_{j=1}^{m} n_j \left(\bar{y}_j - \bar{y}\right)^2 \tag{41}$$

- SSW, the within-group sum of squares (equation 42);

$$\mathrm{SSW} = \sum_{j=1}^{m} \sum\nolimits_{i=1}^{n_j} \left(y_{ij} - \bar{y}_j\right)^2 \tag{42}$$

- the j-th group within group mean (equation 43); and

$$\bar{y}_j = \frac{1}{n_j} \sum_{i=1}^{n_j} y_{ij} \tag{43}$$

- the whole population mean known as the grand mean (equation 44);

$$\bar{y} = \frac{1}{n} \sum_{j=1}^{m} \sum\nolimits_{i=1}^{n_j} y_{ij} \tag{44}$$

When the groups are independent and normally distributed with the same variance, the test statistic F follows the law of Fisher with n-1 and n-m degree of freedom (dof) under the null hypothesis [28].

ANOVA results are relevant only when normal distribution and equality of variance conditions are satisfied. Then, one needs to check for that first.

An alternative to ANOVA is a Kruskal-Wallis test which does not require the satisfaction of these conditions.

Statistical software can help in performing ANOVA or Kruskal-Wallis test.

b) Model Deterministic Parameters Computation

At this stage, for TuPL, TuF, T_{cs}uCLuOH, T_{cm}uCLuOH, C_duT, C_puT, C_{cs}uT, and C_{cm}uT within the group means $\bar{y}_j$ are calculated for those for which there is a dependency on independent parameters (conductor pipe OD, hole section size or casing OD) and grand means $\bar{y}$ if no dependency is noticed.

These quantities are the S-ATC model deterministic parameters since a sample empirical mean is an unbiased estimation of the population mean [6].

S-ATC Model Stochastic Parametrization

The model stochastic parametrization consists of evaluating its stochastic parameters, that are P10, P50, and P90 of deterministic parameters, that is:

- P10(TuPL), P10(TuF), P10(T_{cs}uCLuOH), P10(T_{cm}uCLuOH), P10(C_duT), P10(C_puT), P10(C_{cs}uT) and P10(C_{cm}uT);
- P50(TuPL), P50(TuF), P50(T_{cs}uCLuOH), P50(T_{cm}uCLuOH), P50(C_duT), P50(C_puT), P50(C_{cs}uT) and P50(C_{cm}uT); and
- P90(TuPL), P90(TuF), P90(T_{cs}uCLuOH), P90(T_{cm}uCLuOH), P90(C_duT), P90(C_puT), P90(C_{cs}uT) and P90(C_{cm}uT).

The probabilistic approach to be used for P10, P50 and P90 computation is Monte Carlo simulations. It is a series of techniques used to solve complex problems, often deterministic, by introducing random sampling, developed in 1949 by the American mathematicians John Von Neumann and Stanislav Ulam [15]. In the case of this study will consist of generating large random numbers of well times and costs parameters from their probability density functions (PDF). This task is carried out in two steps: (1) S-ATC model activities time and cost probability distributions determination and (2) S-ATC model stochastic parameters computation.

a) S-ATC Model Activities Time and Cost Probability Distributions Determination

The knowledge of their random variables' distributions is needed to generate the model activities times and costs parameters. The first task is to determine these statistical functions of the model activities times and costs parameters. Model activities times and costs parameters variables must follow one of the existing theoretical distributions. Frequency and cumulative density function (CDF) analyses coupled with a statistical test of distribution (Chi-square test, for instance) are used for probability distribution determination. Frequency and CDF analyses consist respectively of plotting the empirical frequency and CDF and checking which theoretical probability density function (PDF) and CDF comes closest to the empirical one.

In the case of S-ATC model activities times and costs parameters probability distributions determination, the Central Limit Theorem (CLT) comes and eases the business since the model variables TuPL, TuF, $\mathrm{T_{cs}}$uCLuOH, $\mathrm{T_{cm}}$uCLuOH, $\mathrm{C_{d}}$uT, $\mathrm{C_{p}}$uT, $\mathrm{C_{cs}}$uT and $\mathrm{C_{cm}}$uT are the averages of corresponding samples got from the area of interest wells population.

The Central Limit Theorem (CLT) states that for a huge number of independent random variables. $X_1, X_2, \dots, X_n$ identically distributed under a probability law of average μ and standard deviation σ, the random variable $\bar{X} = \frac{X_1 + X_2 + \cdots + X_n}{n}$ follows approximatively the normal (Gauss) law of mean μ and variance $\frac{\sigma^2}{n}$, even though the variable X does not follow the normal law [8]. For the purpose of our study, the model activities times and cost parameters sample sizes are often large. Therefore the CLT can be applied, that is, TuPL, TuF, $\mathrm{T_{cs}}$uCLuOH, $\mathrm{T_{cm}}$uCLuOH, $\mathrm{C_{d}}$uT, $\mathrm{C_{p}}$uT, $\mathrm{C_{cs}}$uT, and $\mathrm{C_{cm}}$uT random variables follow the normal distribution of means their corresponding model activities deterministic parameters and variances. $\frac{S^2}{n}$, with S the empirical variances of activities times and costs samples.

For instance, if $\overline{\mathrm{TuPL}_J}$ and $S^2(\mathrm{TuPL}_j)$ are respectively, TuPL variable average and standard deviation of the j-th conductor pipe OD sample, then the TuPL variable of j-th conductor pipe OD follows the normal distribution of mean $\overline{\mathrm{TuPL}_J}$ and standard deviation $\frac{S^2(\mathrm{TuPL}_j)}{n_j}$ (with n_j, j-th conductor pipe OD sample size). That is, TuPL ~ $N\left(\overline{\mathrm{TuPL}_J}, \frac{S^2(\mathrm{TuPL}_j)}{n_j}\right)$.

The empirical variance of a random variable X sample $X_1, X_2, \dots, X_n$ is defined by equation 45. It is an unbiased estimator of the population variance.

$$\mathrm{S}^2 = \frac{1}{\mathrm{n}-1}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{X_i} - \overline{\mathrm{X}})^2 \tag{45}$$

Where $\bar{X}$, the sample average.

i) S-ATC Model Stochastic Parameters Computation

The model stochastic parameters are P10, P50, and P90 of deterministic parameters as listed in the previous section. For a random variable, X, P10, P50 and P90 are respectively defined as the value for which any realization of X has a 10 percent, 50 percent and 90 percent of chance to be greater than. There are obtained by solving the mathematical equations 46, 47 and 48.

$$\mathrm{P}(\mathrm{X} \geq \mathrm{P10}) = 0.1 \tag{46}$$

$$\mathrm{P}(\mathrm{X} \geq \mathrm{P10}) = 0.5 \tag{47}$$

$$\mathrm{P}(\mathrm{X} \geq \mathrm{P10}) = 0.9 \tag{48}$$

[14] have pointed out that the advantage of computing P10, P50 and P90 is that they give the expected minimum values of the parameter of interest with respectively low, moderate and high chances.

Since $P(X \geq P10) = 1 - P(X \leq P10)$, $P(X \geq P50) = 1 - P(X \leq P50)$, and $P(X \geq P90) = 1 - P(X \leq P90)$, we have $P(X \leq P10) = 0.9$, $P(X \leq P50) = 0.5$, and $P(X \leq P90) = 0.1$.

Thus, P10, P50 and P90 are, respectively the 90th, 50th and 10th percentile of X.

The following is the algorithm for computing the S-ATC model stochastic parameters.

***Algorithm for S-ATC Model Stochastic Parameters Calculation (fig. 1)*:**

Step 1: For each model activity time and cost parameter:

- If the parameter depends on the explicative variable, then for each of its attributes, generate a large-size sample $G = \{X_1, X_2, \dots, X_N\}$ from a normal distribution X of parameters, the corresponding model deterministic parameter and the empirical standard deviation;
- If the parameter does not depend on the explicative variable, then for the whole parameter dataset, generate a large-size sample $G = \{X_1, X_2, \dots, X_N\}$ From a normal distribution X of parameters, the

corresponding model deterministic parameter and the empirical standard deviation.

Step 2: For each model activity time and cost parameter, determine the 90th, 50th and 10th percentile of the generated G.

Step 3: Deduce P10, P50 and P90. They are, respectively, the 90th, 50th and 10th percentile of G.

3.2.3. Time and Cost Estimation with S-ATC Models

The purpose of the study is to propose the S-ATC model for oil well times and cost estimation. Once such a model is designed for an area of interest, it must help estimate future wells times and costs when the well programs are available. Here are the algorithms for estimating wells times and costs from an S-TAC model.

An S-ATC model parameter is the TuPL, TuF, T_{cs}uCLuOH, T_{cm}uCLuOH, C_duT, C_puT, C_{cs}uT, C_{cm}uT and P10, P50 and P90 thereof.

Algorithm for Computing Wells Times and Costs from an S-ATC Model (fig. 2):

Step 1: Compute conductor pipe lengths (PL_i) for each conductor pipe OD using equation 5.

Step 2: Compute the footage drilled (F_j) for each hole section of the well with equation 6.

Step 3: Compute the casing length (CLk) for each casing OD of the well with equation 7.

Step 4: Compute the open hole height (OH_l) for each casing OD of the well with equation 8.

Step 5: Compute the well time using the S-ATC model deterministic parameters and the equations of Table 2.

Step 6: Compute the well time P10, P50 and P90 using the S-ATC model stochastic parameters and the equations of Table 2.

Step 7: Compute the well cost using the S-ATC model deterministic parameters and the equations of Table 3. This cost is for the reference year of the model.

Step 8: Convert the cost to the actual year using the average inflation rate from the model reference year to the actual year.

Step 9: Compute the well cost P10, P50 and P90 using the S-ATC model stochastic parameters and the equations of Table 3. These costs are for the reference year of the model.

Step 10: Convert the cost P10, P50 and P50 to the actual year using the average inflation rate from the model reference year to the actual year.

3.3. Case Study: S-ATC Model for Onshore Niger Delta Nigeria

The use of the proposed approach in this study requires data on well drilling operations times and costs. For the Niger Delta model built, information has been brought from the Daily Drilling Reports (DDRs) and well cost computation spreadsheets for *hundred and two (102) of Nigeria's Niger Delta onshore development wells*. The data processing (manipulation) was made using Microsoft Excel and Jupyter Notebook, an interactive computing notebook dedicated to data analysis. Data manipulation, computing and simulations were made on Jupyter Notebook through Python programming language. The model efficiency test has been carried out with two (02) other wells that have not been included in the model-building dataset.

4. Results and Discussion

4.1. Data Collection and Processing

The completion of the following main tasks will lead to well data processing.

4.1.1. Activities Starting and Ending Tasks Identification

The ST-ABC model activities (conductor pipe pilling, drilling, casing running and completion operations) starting and ending tasks are identified in each well DDR. The results of that work are summarized in Table 4 and fig. 3.

4.1.2. S-ATC model Activities Times and Costs Computation

Once the activities starting and ending tasks have been identified, the activities' durations and actual costs have been computed with Microsoft Excel.

4.1.3. Cost Normalization

The dataset wells have been drilled in different years (2008 to 2020). The normalized costs are calculated with a Nigeria average inflation rate of 14% (set by Wikipedia, 2023 over that period of time) and a reference year of 2023.

4.1.4. Relevant S-ATC Model Activities Parameters Computation

At this stage, the model activities parameters have been computed from the durations and costs dataset through the appropriate formulae defined in the methodology section.
That is:

- conductor pipe length (PL) for different conductor pipe sizes in the dataset;
- footage drilled (F) for different hole section sizes;
- casing length (CL) for different casing outer diameters (OD);
- open hole height (OH) after setting casing for different casing outer diameters (OD);
- drilling time per drilled footage unit (TuF) for different hole section sizes;
- conductor pipe pilling time per conductor pipe length unit (TuPL) for different conductor pipe sizes;
- casing running time per casing length unit per open hole height unit (T_{cs}uCLuOH) for different casing outer diameters (OD) for casing operations;
- cement operation time per casing length unit per open hole height unit (T_{cm}uCLuOH) for different casing outer diameters (OD) for cement operations;

- conductor pipe pilling cost per time unit (C_puT) for different conductor pipe sizes;
- drilling cost per time unit (C_duT) for different hole section sizes;
- casing running cost per time unit (C_{cs}uT) for different casing outer diameters (OD) for casing operations; and
- cement operation cost per time unit (C_{cm}uT) for different casing outer diameters (OD) for cement operations.

4.1.5. Data Manipulation

It has consisted of identifying the outliers in the datasets and their treatments (replacing them by means of the datasets). Fig. 4 shows the boxplots of model activity parameters. We can notice the presence of outliers for some activities. This has led to their replacements. The first treatment has not been sufficient to get any outliers. The process has been repeated three times. The boxplots after the third trial are the ones in fig. 5.

4.2. S-ATC Modelling

4.2.1. S-ATC Model Deterministic Parametrization

Activities Times and Costs Dependency Verification

The first thing to check here is the times and costs dependency. The graphical analysis of fig. 5 boxplots has helped for that purpose. Indeed, for:

- TuPL boxplots median bars levels are largely different for the pipe diameters;
- CpuT boxplot's median bars levels are significantly different for the pipe diameters;
- TuF boxplot's median bars levels are largely different for the hole section sizes;
- CduT boxplots median bars levels are significantly different for the hole section sizes;
- TcsuCLuOH boxplots median bars levels are largely different for the casing ODs;
- CcsuT boxplots median bars levels are significantly different for the casing ODs;
- TcmuCLuOH boxplot's median bars levels are largely different for the casing ODs;
- CcmuT boxplot's median bars levels are significantly different for the casing ODs.

Table 5 summarizes the results of this analysis.

Model Deterministic Parameters Computation

Since dependencies are noticed for all model activity parameters, the deterministic model parameters have been computed for different independent attributes of the variables. Table 6 summarizes the model deterministic parameterization result.

4.2.2. S-ATC Model Stochastic Parametrization

S-ATC Model Activities Time and Cost Probability Distributions

Central Limit Theorem (CLT) in the methodology section proves that each model activity parameter follows the normal distribution of the mean, the corresponding deterministic parameter and its empirical standard deviation. These parameters' empirical standard deviations are computed and summarized in Table 7.

S-ATC Model Stochastic Parameters Computation

The stochastic model parameters are the P10, P50 and P90 of different activities parameters for each sample. For that purpose, Monte Carlo simulations are used. For each, 100,000 random numbers of a normal distribution of parameters variables are generated, and P10, P50 and P90 are determined. The results are those of Table 8.

Table 4. Summary of dataset activities, tasks characteristics

Pipe pilling			**Drilling**		
Pipe diameter	**Time sample size**	**Cost sample size**	**Hole section size**	**Time sample size**	**Cost sample size**
16 inch	22	0	12 1/4 inch	71	25
20 inch	13	6	8 1/2 inch	65	13
24 inch	11	11	17 1/2 inch	26	23
30 inch	10	6	16 inch	16	3
26 inch	9	0	26 inch	9	6
Casing running			**Cement operations**		
Casing OD	**Cost sample size**	**Cost sample size**	**Casing OD**	**Cost sample size**	**Cost sample size**
9 5/8 inch	68	24	9 5/8 inch	68	24
7 inch	46	5	7 inch	46	6
13 5/8 inch	42	24	13 5/8 inch	42	23
20 inch	9	6	20 inch	9	6

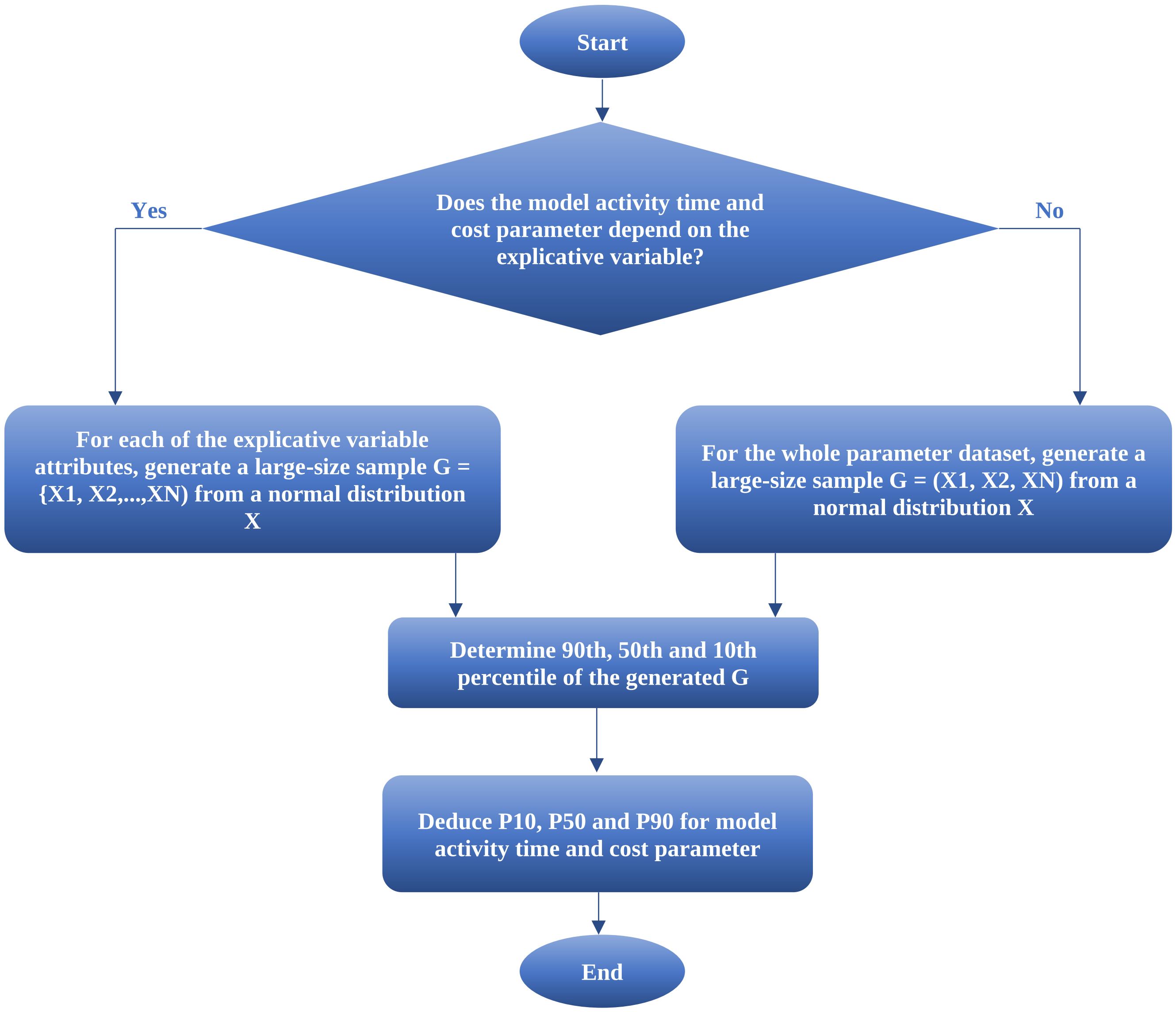

Fig. 1 Algorithm for S-ATC Model Stochastic Parameters Calculation

4.3. Model Efficiency Measurement

Nigeria's Niger Delta onshore S-ATC model is tested with the drilling data of two wells in that area (W-1 and W-2) which have not been used for the model building. Time and cost information is available for W-1, and only time information is for W-2. Thus, time and cost have been estimated for W-1 and only drilling operations duration W-2. The main information for these wells is those of Tables 9 and 10.

W-1 estimated time and cost with the S-ATC model are respectively 37.45 days and US$ 5 803 065.03 while W-2 estimated time is 47.34 days. W-1 time and cost estimation errors are 17.99% and 5.96%, respectively, when W-2 time estimation error is 0.2%. W-1 time P10, P50 and P90 are respectively 55.44 days, 35.36 days and 23.15 days while its cost has 10%, 50% and 90% of chance to be greater than US$ 15 273 814.8, US$ 5 039 839.85 and US$ 1 218 369.18 respectively. W-2 time P10, P50 and P90 are respectively 70.87 days, 44.32 days and 29.27 days.

W-1 cost P50 of US$ 5 039 839.85 has well predicted the well cost since the real W-1 cost is US$ 6 171 216.71, which is higher than US$ 5 039 839.85. Its time range is predicted by P90 of 23.15 days. In the same way, time W-2 real time of 47.34 days proved that its S-ATC model time P50 (44.32 days) is realistic because 47.34 days are higher than 44.32 days.

Based on the above, Nigeria's Niger Delta onshore S-ATC model efficiency is acceptable. The model would be much stronger if the database used for its design were larger.

Table 5. Activities times and costs dependency

N°	Model parameters	Dependency
1	Conductor pipe pilling time per pipe length unit (TuPL)	Depends upon the pipe diameter
2	Conductor pipe pilling cost per time unit (CpuT)	Depends upon the pipe diameter
3	Drilling time per drilled footage unit (TuF)	Depends upon the hole section size
4	Drilling cost per time unit (CduT)	Depends upon the hole section size
5	Casing running time per casing length unit per open hole height unit (TcsuCLuOH)	Depends upon the casing OD
6	Casing running cost per time unit (CcsuT)	Depends upon the casing OD
7	Cement operations time per casing length unit per open hole height unit (TcmuCLuOH)	Depends upon the casing OD
8	Cement operations cost per time unit (CcmuT)	Depends upon the casing OD

Table 6. Nigeria's niger delta onshore S-ATC model deterministic parameters

Pipe pilling			Drilling		
Pipe diameter	**10^3*TuPL (d/ft)**	**CpuT ($/d)**	**Hole section size**	**10^3*TuF (d/ft)**	**CduT ($/d)**
16 inch	8.233		12 1/4 inch	2.882	310 351.515
20 inch	10.351	384 572.678	8 1/2 inch	2.712	352 347.528
24 inch	14.733	282 063.058	17 1/2 inch	2.089	277 038.247
26 inch	7.731		16 inch	2.437	725 842.097
30 inch	18.491	210 188.163	26 inch	3.261	218 913.069
Casing running			**Cement operations**		
Casing OD	**10^8*TcsuCLuOH (d/ft/ft)**	**CcsuT ($/d)**	**Casing OD**	**10^8*TcmuCLuOH (d/ft/ft)**	**CcmuT ($/d)**
9 5/8 inch	5.169	601 907.421	9 5/8 inch	8.652	462 750.357
7 inch	5.422	269 200.908	7 inch	4.752	318 540.412
13 5/8 inch	9.102	485 571.713	13 5/8 inch	16.732	360 189.313
20 inch	0.838	198 681.695	20 inch	1.790	346 473.550

Table 7. Nigeria's niger delta onshore S-ATC model activities parameters empirical standard deviations

Pipe pilling			Drilling		
Pipe diameter	**10^3*TuPL (d/ft)**	**CpuT ($/d)**	**Hole section size**	**10^3*TuF (d/ft)**	**CduT ($/d)**
16 inch	3.713		12 1/4 inch	1.056	121 043.497
20 inch	2.681	136 836.518	8 1/2 inch	0.902	154 607.420
24 inch	1.895	213 298.125	17 1/2 inch	0.483	135 882.163
26 inch	3.502		16 inch	1.011	284 810.828
30 inch	8.915	66 507.34	26 inch	1.247	64 247.410
Casing running			**Cement operations**		
Casing OD	**10^8*TcsuCLuOH (d/ft/ft)**	**CcsuT ($/d)**	**Casing OD**	**10^8*TcmuCLuOH (d/ft/ft)**	**CcmuT ($/d)**
9 5/8 inch	3.14	490 485.785	9 5/8 inch	5.315	404 990.005
7 inch	3.141	55 695.825	7 inch	2.853	225 022.814
13 5/8 inch	4.846	420 575.820	13 5/8 inch	10.180	208 296.248
20 inch	0.180	50 004.577	20 inch	0.936	81 900.386

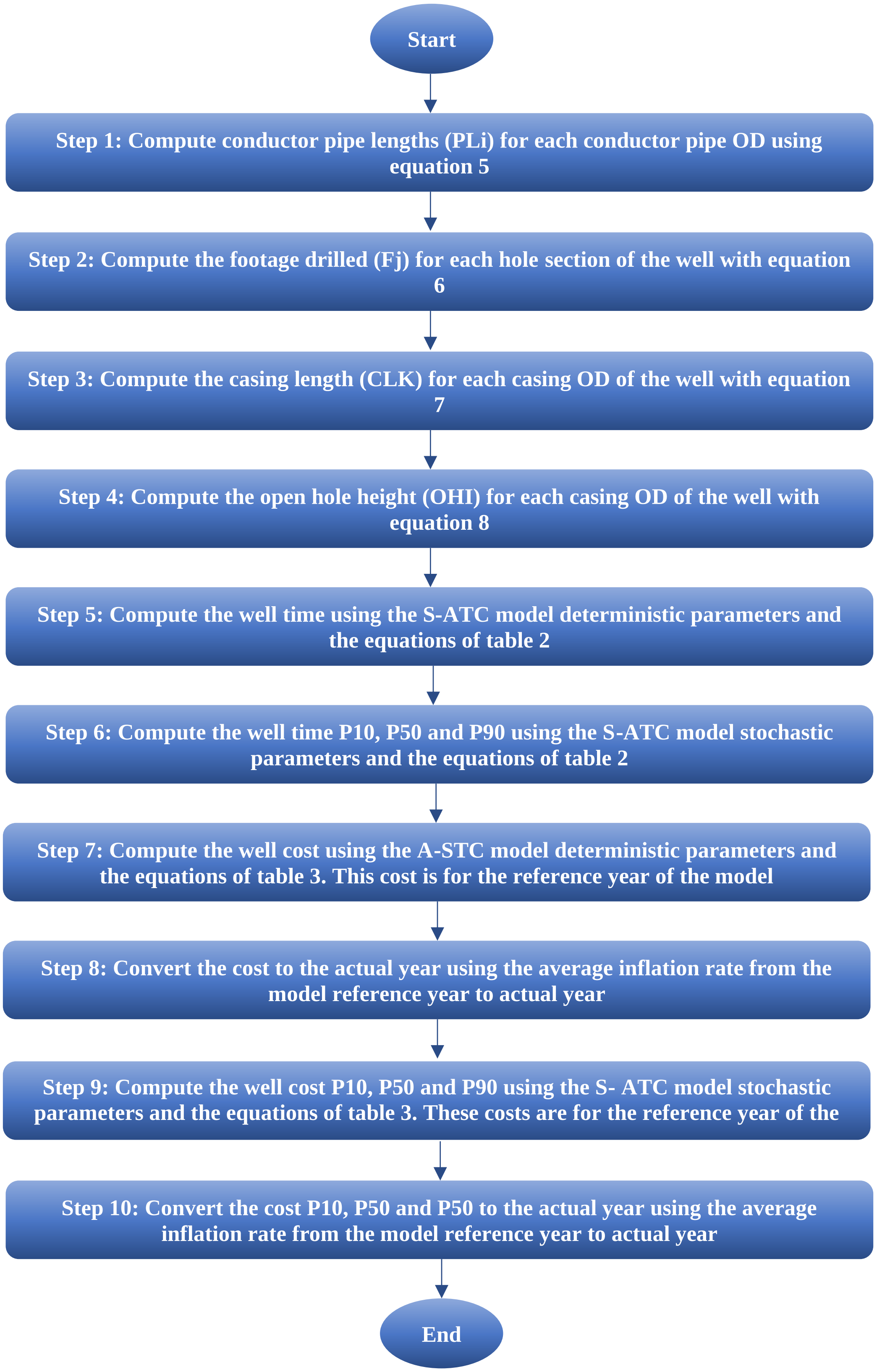

Fig. 2 Algorithm for computing wells times and costs from an S-ATC model

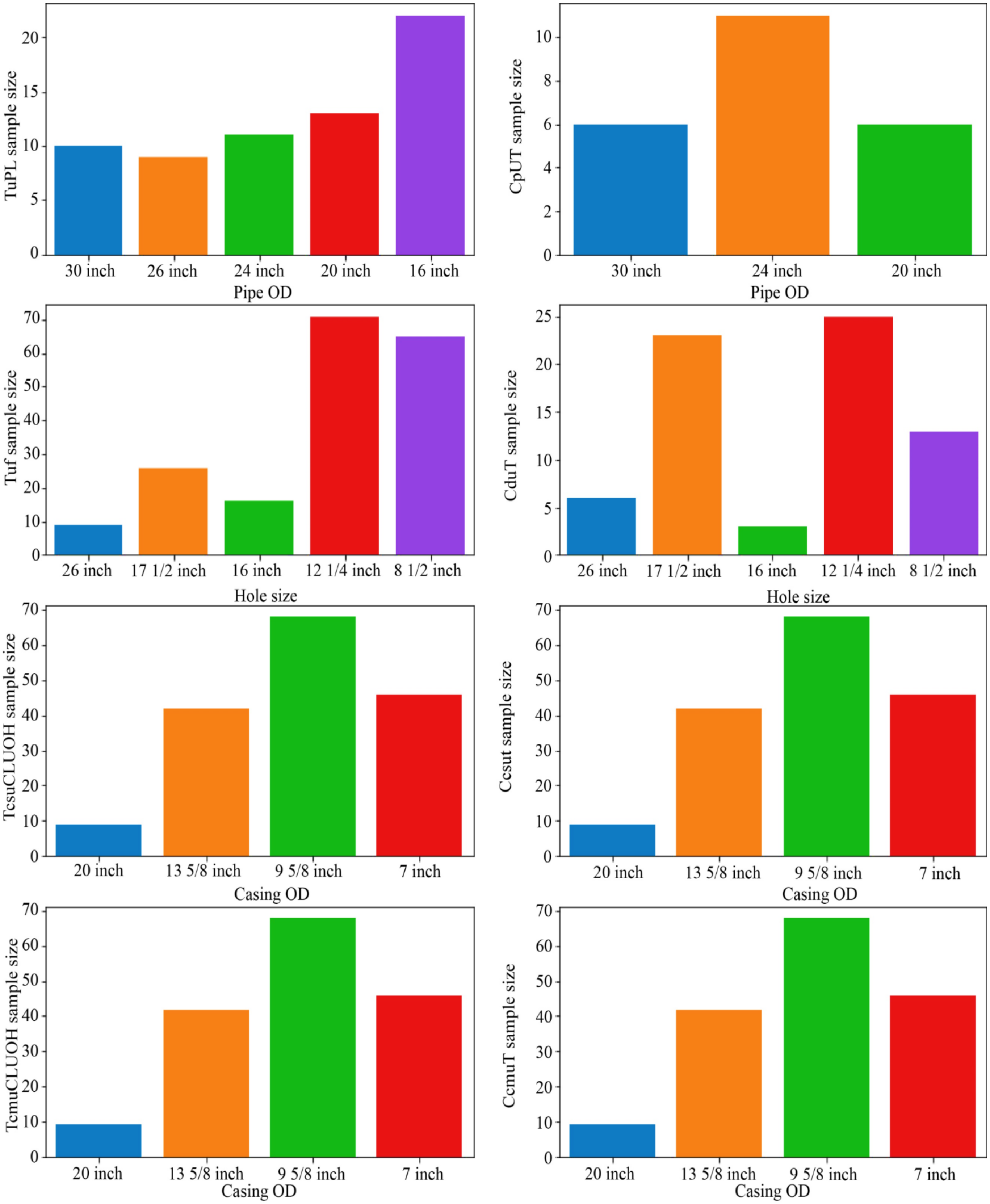

Fig. 3 Model activities parameters samples sizes

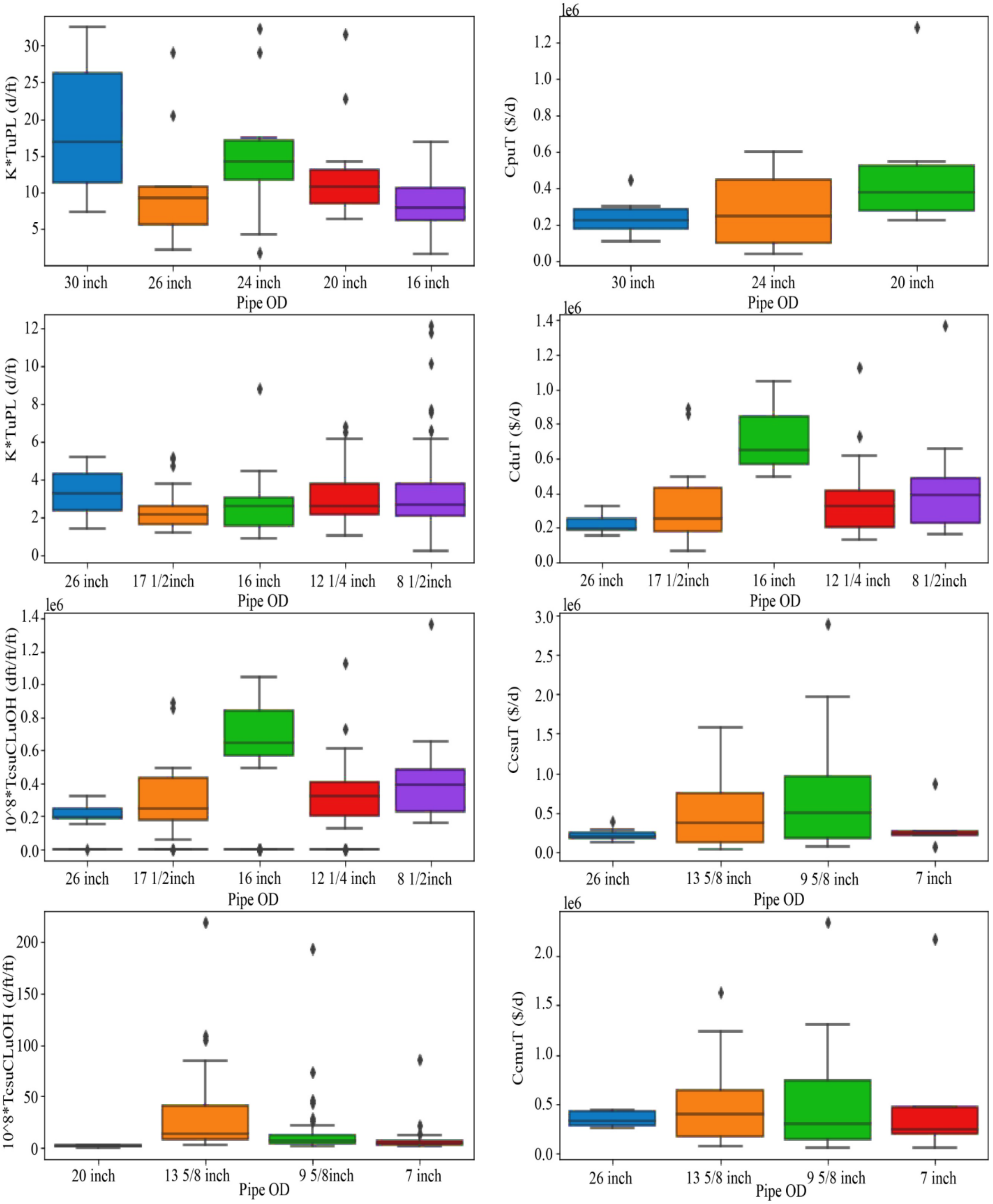

Fig. 4 Model activities parameters boxplots before outliers' treatment

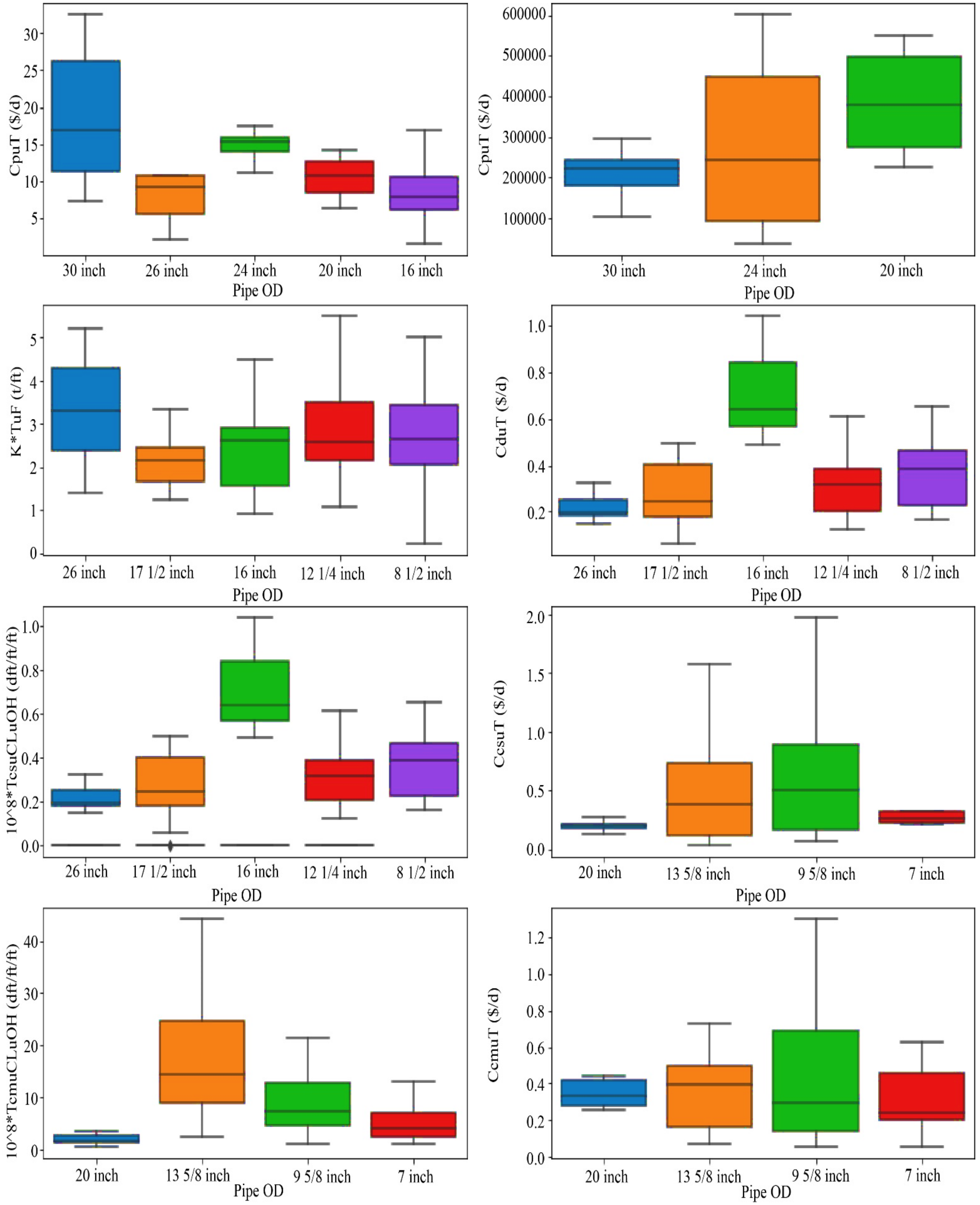

Fig. 5 Model activities parameters boxplots after outliers treatment

Table 8. Nigeria's onshore niger delta S-ATC model stochastic parameters

Pipe pilling						
Pipe diameters	**10^{3}*TuPL (d/ft)**			**CpuT ($/d)**		
	P10	**P50**	**P90**	**P10**	**P50**	**P90**
16 inch	28.136	7.859	3.444			
20 inch	10.826	10.836	6.766	531 343.457	378 228.304	244 146.271
24 inch	16.577	15.415	12.146	524 793.565	242 621.142	42 279.736
26 inch	12.886	9.134	2.329			
30 inch	28.136	16.906	10.525	270 012.218	221 600.477	138 951.794
Drilling						
Hole section size	**10^{3}*TuF (d/ft)**			**CduT ($/d)**		
	P10	**P50**	**P90**	**P10**	**P50**	**P90**
26 inch	4.524	3.311	1.807	295 225.499	194 081.924	167 431.782
17 1/2 inch	2.600	2.154	1.568	450 575.822	246 050.617	102 278.431
16 inch	3.647	2.607	1.177	962 899.114	643 627.265	521 671.013
12 1/4 inch	4.491	2.590	1.863	416 357.102	319 015.087	151 690.508
8 1/2 inch	3.789	2.651	1.718	510 492.601	387 768.324	172 992.438
Casing running						
Casing OD	**10^{8}*TcsuCLuOH (d/ft/ft)**			**CcsuT ($/d)**		
	P10	**P50**	**P90**	**P10**	**P50**	**P90**
20 inch	0.994	0.901	0.632	249 327	198 010.283	148 707.818
13 5/8 inch	16.457	7.433	3.586	970 174.8	377 367.956	102 778.506
9 5/8 inch	8.142	4.832	2.711	1 056 292	497 526.248	83 305.972
7 inch	10.454	4.220	2.168	327 118.9	258 057.515	215 478.587
Cement operations						
Casing OD	**10^{8}*TcmuCLuOH (d/ft/ft)**			**CcmuT ($/d)**		
	P10	**P50**	**P90**	**P10**	**P50**	**P90**
20 inch	2.842	1.405	0.953	441 643	330 318.342	267 459.315
13 5/8 inch	31.127	14.251	5.289	670 006.8	394 847.887	101 691.298
9 5/8 inch	16.240	7.218	2.683	1 208 081	295 282.713	104 886.269
7 inch	8.261	4.031	1.797	560 834.1	244 111.432	115 686.458

Table 9. W-1 main information

Activities	Pipe length (ft)	Drilled footage (ft)	Casing length (ft)	Open hole height (ft)	Time (days)	Cost ($)
24" CP pilling	276.9				2.031	314 065.014
Drilling 17 1-2" of the hole section		4 382			7.531	1 132 889.78
13 5-8" casing running			4 653.9	4 382	1.115	118 059.49
Cementing 13 5-8" CSG			4 653.9	4 382	2.156	520 086.158
Drilling of 12 1-4" hole section		3 690			13.958	2 587 045.57
9 5-8" casing running			8 328.9	3 690	1.010	331 620.427
Cementing 9 5-8" CSG			8 328.9	3 690	1.281	559 809.746
Drilling 8 1-2" of the hole section		1 500			2.656	607 640.53
				Total	**31.740**	**6 171 216.71**

Table 10. W-2 main information

Activities	Pipe length (ft)	Drilled footage (ft)	Casing length (ft)	Open hole height (ft)	Actual time (days)
24" CP pilling	273.9				0.5
Drilling 17 1-2" of the hole section		5 105			11.063
13 5-8" casing running			5 363.9	5 100	1.396
Cementing 13 5-8" CSG			5 363.9	5 100	4
Drilling 12 1-4" of the hole section		6 291			23.688
9 5-8" casing running			8 549.9	3 195	1.771
Cementing 9 5-8" CSG			8 549.9	3 195	1.323
Drilling 8 1-2" of the hole section		1 354			3.51
				Total	**47.25**

5. Conclusion and Recommendation

Oil and gas well drilling and completion time and cost estimate have a large impact on the capital investment decisions in exploration and production (E&P) projects. The preparation and defense of the Authorization for Expenditure (AFE) is a hard task for the drilling management team since well drilling operations time and cost estimation is difficult. There are a variety of deterministic and probabilistic models used for that purpose. This study proposes a technique called the "Stochastic Activity-Based Time and Cost (S-ATC) Model" for oil well drilling operations schedule and cost estimation. This model sets a probabilistic comprehensive activity-based technique that provides single values, P10, P50 and P90, for oil well times and costs. A case study has been carried out for the onshore Niger Delta, Nigeria, with a database of hundred and two wells. Its efficiency is acceptable due to the low estimation errors of two model test wells. However, the model would be much stronger if the database used for its design was much larger.

We recommend to:

- Build S-ATC model for areas, basins and regions where well drilling data are available, even a worldwide model to help in estimating much more accurate well drilling durations and costs;
- Use Nigeria's Niger Delta onshore S-ATC model built in this study for wells drilling time and cost forecast at the AFE stage;
- Design a new S-ATC model for Nigeria's Niger Delta onshore with a much larger dataset.

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