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Benchmarking a Concept — Data-Driven Commercial Valuation of a Hypersonic Impact Drilling Concept

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Abstract

Commercial valuation of a technology in Proof-of-Concept stage is often based on limited case study data, and then extrapolated to a hypothesized total market demand for that technology. The methodology presented in this paper uses a bottoms-up, data-driven, well-by-well valuation using a 60,000+ well industry benchmarking data set. The methodology was developed to support the valuation of a new technology concept using hypersonic impact drilling, then at API-17N Technology Readiness Level 1.

Any new technology has a low definition of operational performance and technical capability by virtue of being in concept stage. The well dataset used for valuation analysis is relatively high-level, resulting in a significant number of assumptions and limitations. Nonetheless, the combination of a granular technology model with a large actual dataset provides insights into sensitivities and uncertainties which are unobtainable with a broad-brush, high-level approach.

Based on the information available in the database, the methodology constructs a synthetic time-depth curve for drill and case operations after removal of non-productive time. Synthetic time and cost for each section are calculated for both the actual well and the technology model allowing section-by-section 'bench-marking' of the technology. The combined savings from technology-positive sections gives the size of the prize or commercial margin available to be shared between Operator and Supplier.

We present a case study in which we modelled the initial new technology deployment concept, showing this concept to have an operational sweet spot with value rapidly decreasing away from it. An alternative, downhole deployment concept resulted in a multiple times wider applicability and a multi-billion-dollar un-risked value proposition indicative of a potentially game changing technology. Based on this new insight, the technology developer was able to pivot early on, probably avoiding costly dead-end development and market disappointment, and increase industry and investor confidence and investment.

The methodology can be used to gain actionable insights at multiple levels:

- To obtain a mature market valuation, mature technology parameters such as reliability, directional drilling capability and all applicable hole sizes and depths are invoked.

- To aid the technology development and design decisions, sensitivity analyses can be performed on design parameters.
- To guide development requirements, a Minimum Viable Product analysis provides insight to the minimum technical requirements necessary and the de-risking work required before a technology can gain acceptance in the marketplace.
- To explore early applications and potential sponsoring projects, clusters of potential high-value and/or early-applications can be identified.
- The results from this valuation model provide insights into the potential of wells at or beyond the fringes of the database, i.e. complex wells that require extraordinarily long net times to drill.

Introduction

The entrepreneurial journey of transforming an innovation into a workable business offering "is not a straight line, but a drunkard's walk" (Satell 2012). To investigate if (further) investment is warranted to develop a portfolio of attractive long term options, whilst preventing the passing of judgement on the innovation in the absence of information, early-stage innovations require specially designed processes to survive their first steps towards realization (Conser et al. 2013). This is especially true if the innovation has the characteristics of a game changer: an innovation that has the potential to make a dramatic difference by opening-up large new growth options in existing business sectors or to create a new business sector from scratch.

Early-stage innovations are typified by individual and collective uncertainties (Vasconcelos Gomes et al. 2018). According to Jalonen (2012), we can map these uncertainties into eight uncertainty areas: technological, market, regulatory/institutional, social/political, acceptance/legitimacy, managerial, timing, and consequence uncertainty. Early-stage innovations need to be de-risked in all eight areas whereby the preliminary focus should be on areas where the uncertainty is largest. By their nature, transformative innovations face many unknown unknowns, increasing the uncertainty levels even further. For example, for these types of innovations, a truthful market evaluation is virtually impossible given the lack of market data (O'Connor et al. 2008). To cope with the uncertainties-induced difficulties of progressing innovation, Wang et al. (2015) introduced a Real Options approach, while Brasil et al. (2018) review the rationale behind the Real Options approach. Sequeira et al. (2017) also presented a more holistic approach to oilfield technology development that considers both technical and non-technical aspects.

For over 100 years, oilfield drilling is predominantly done by rotary drilling. The widespread industry acceptance of this rotary-based approach makes the introduction of non-rotary based methods a challenging undertaking. Several novel technologies have aimed to remove rock by other than mechanical rotary means; abrasive fluid (Wyllie 1971), projectile impacts (Dardick 1977), spallation (Potter and Tester 1998), chemical (Polizzotti et al. 2003), particle impact (Tibbitts and Galloway 2008), laser (Hafez et al. 2015), plasma (Kocis et al. 2017), pulsed arc plasma shockwave (Cai et al. 2018) and percussion (Li et al. 2019). Of all these technologies, so far only percussion drilling has been successful in field applications (Ziani et al. 2018). The biggest competitor to any novel new technology might well be the steady continuous improvement of conventional rotary drilling (Dykstra et al. 2018, Galymzhan et al. 2019). One recent contender is a new technology concept using repetitive hypersonic impact to remove rock at the bottom of the wellbore.

In this article, we describe a data-driven Real Options-like method of de-risking the technology by establishing market value dimensions of this hypersonic impact drilling concept, which at the time was at API RP 17N Technology Readiness Level 1 (technology demonstrated, feasibility study completed). The approach taken is a bottoms-up, well-by-well valuation using a 60,000+ well industry benchmarking data set. The aim of the data-based modelling approach described in this paper is to answer the following question: "If we had had this concept as a mature technology for the past 10 years for these wells, what would have been its indicative unrisked commercial value relative to existing technology."

Methodology

Because of the individual and collective uncertainties and lack of actual performance data, a standardized approach for the commercial valuation for early-stage technology does not exist. Commercial valuation in the context of this paper is defined as an unrisked value estimate based on drilling cost differentials after an assumed successful development process from the idea stage into a mature marketplace.

The approach bases the valuation on a large industry-wide dataset to begin with and builds the valuation bottoms-up as methodically as possible. It was clear from the beginning that the methodology would be subject to several substantial assumptions and limitations, both due to the technology being in the concept stage and the reference dataset being relatively high-level. Thus, the objective was not to obtain an absolute or precise monetary answer. The question was whether a combination of a fit for purpose technology model with a large actual dataset could provide capabilities and insights into sensitivities and uncertainties unobtainable with a broad-brush, high-level valuation.

A multi-operator global industry drilling benchmarking performance dataset is available to operators who take part in and contribute to it (Rushmore 2011). With data going back to the late 1990s, at the time of this work the database contained over 60,000 wells from some 160 operators. Each participating operator can access data from the geographic areas where they also contribute to the dataset. It is important to appreciate that the dataset by no means contains all wells globally drilled. E.g. many National Oil Companies do not contribute to the database, leaving out a sizable proportion of all wells globally drilled. Moreover, unconventional shale wells are benchmarked in a separate dataset with a focus on shale well parameters (IHS Markit w.d.) and were not included here. As such, the outcome from this analysis does not represent a hypothetical total available market (Blank and Dorf 2012).

Technically, the dataset focusses on 'dry-hole' drilling time and costs for benchmarking. 'Dry-hole' drilling time and costs in this well planning and accounting context are defined as being from spud to total depth and do not include completion. This should not be confused with a geological dry hole where no hydrocarbons are found.

There are several parameter limitations to this dataset that directly impacted how the method could work. While the dataset includes well information such as location, total depth, total time, total cost, dry-hole time and cost, number of casings and non-productive time (NPT), it does not include details such as NPT by section or rig rate. Also, NPT is an inconsistent measure across operators (Hsieh 2010). For many wells, as-drilled casing setting depths and/or hole sizes are not available, apart from final hole size.

A synthetic section by section performance analysis was performed for the as-drilled conventional base-case and for the new technology concept. The difference in performance is compared by section and, where positive for the new technology, summed per well. Summing over all wells gives the technology value over the data set used. The analysis was implemented using the R language and environment for statistical computing and graphics (R Core Team 2019) in the RStudio integrated development environment (RStudio Team 2019).

In its basic form, the analysis consists of the following steps:

1. Data cleansing.
2. Modeling of synthetic 'as-drilled' well section by section design, time and cost profile.
3. Modeling of concept (new) technology section by section-time and cost profile.
4. Calculation of the difference between the as-drilled and concept time.
5. Calculation of the difference between the as-drilled and concept costs.
6. Summing of positive sections in each well and summing over all wells.

Fig. 1 shows an example of a 'technology-positive' well, including the actual and synthetic time-depth curves. In this example well, the bottom three sections are time-positive for the new technology concept model.

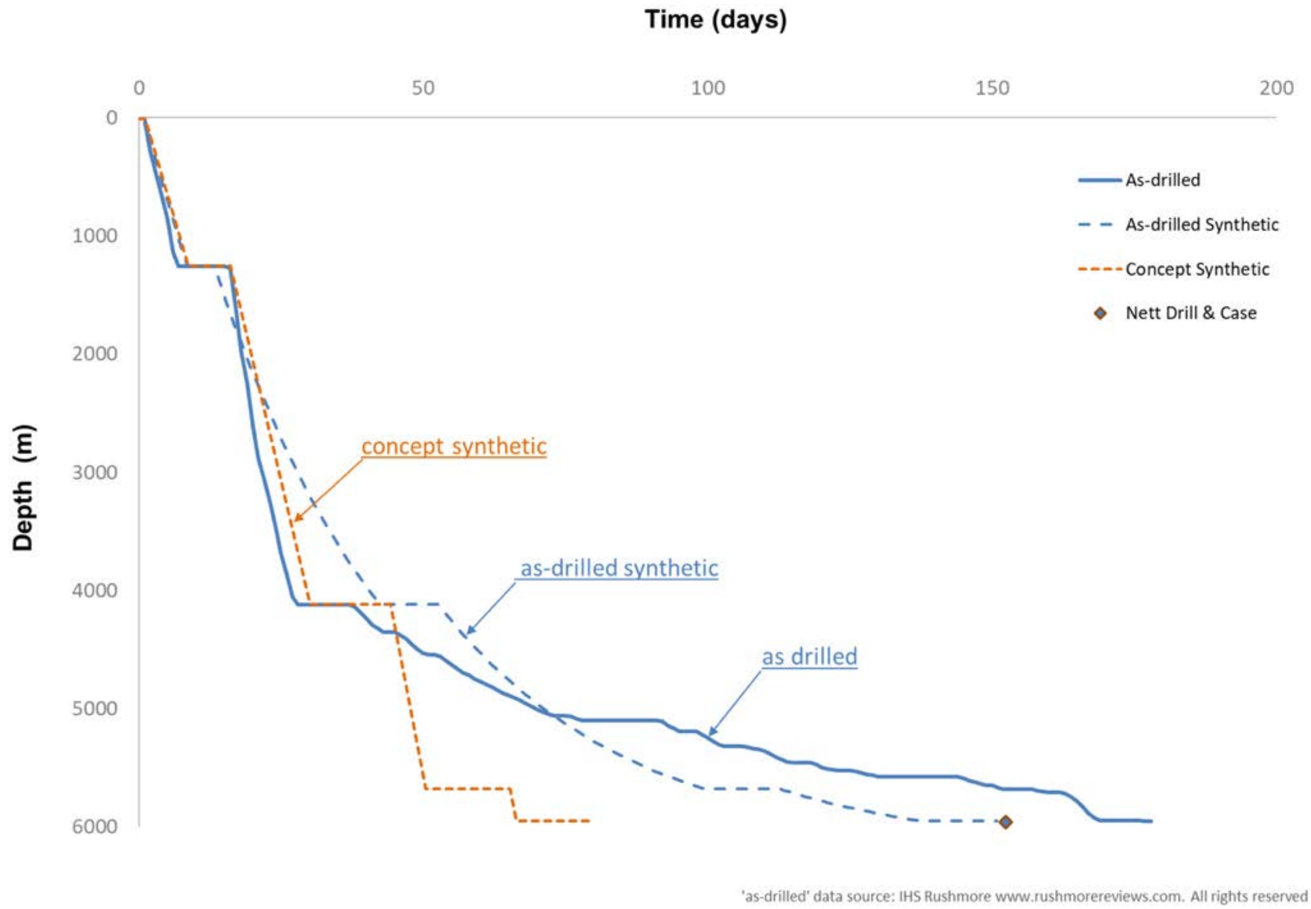

Figure 1—Net drill & case time-depth curves for as-drilled, synthetic as-drilled and new technology concept

Data selection, cleansing and imputation

Not all wells in the data set are useable, either due to the type of well or due to data quality. Some well types are too complex to suitably re-create with the data available, such as multi-laterals, geological sidetracks and/or wells with a pilot hole. Consequently, the method was limited to be applied only to new single-bore wells, drilled from surface/seabed to total depth. Many wells, typically fast and of repetitive nature, are reported with very limited 'lite' data while confidential 'tight' wells have virtually no information. Neither have enough information to re-create a synthetic wellbore. However, as the new technology concept under investigation targets conventionally slow drilling wells, the above exclusions were not foreseen to exclude a significant number of 'technology suitable' wells. Other wells excluded had corrupt, missing or internally inconsistent data. Some missing data were substituted (imputed) by using field or country means. Two specific geographical areas have thousands of extremely fast drilling wells and were excluded to improve computational performance. Finally, the model was run over the last ten full years of data (2005-2014). The resulting cleaned data set had less then 30% of the total wells remaining. However, as only a few of the wells in the likely envelope of interest to hard-rock technology had been removed it looked like this would not substantially affect the outcome (and this was confirmed afterwards).

Synthetic 'as-drilled' well design, time and cost profile

A synthetic 'as-drilled' well profile was calculated in five steps:

a. Extract Net Drill & Case time: Dry-hole time – NPT – log & core time.
b. Calculate Net Drill & Case cost: Total cost – NPT × spread rate – log & core cost.
c. Model casing setting depths where not available: equidistant depth model.

d. Model flat time per section: case & cement model.
e. Model section time: exponential rate of penetration (ROP) model.

Time model. The concept technologies of interest this methodology was developed for were 'making hole' projects, applied to a range of hole sizes and depths. As such section depths and hole sizes are a key parameter. Where actual depths and hole sizes were not available, section depths (excluding conductor) were assumed to be spread evenly along the wellbore, and hole sizes modelled based on the listed conductor or largest casing size and final hole size.

The dataset has no detailed time breakdown during drilling operations other than the total dry hole time, total time of logging and coring and total time of NPT. To get to net drill time from total time, NPT was split time-weighted between 'drill & case' and 'log & core'. A check on extremes, with NPT being wholly in one or the other, showed this approach to be reasonable. A model was developed to estimate 'flat time' operations (casing, cementing, wellhead, blowout preventer). Time for other 'non-making-hole' operations during the net drill time were incorporated with the simple assumption that a fixed ratio of the drilling time is spent doing other non-NPT but non-hole-making operations. The model does not explicitely account for 'invisible lost time', nor does it identify or use a conventional Maximum Theoretical Performance (de Wardt, Rushmore and Scott 2016) or similar.

Nearly 10% of the wells used were cored, and in several cases a substantial length of the entire well was cored. The net drill time was calculated excluding the listed coring time but without excluding the coring interval. This results in a higher synthetic 'as-drilled' ROP and thus a conservative approach to the new concept benefit.

Cost model. Costs were converted to present-day (2015) values using the publicly available IHS Upstream Capital Cost Index (IHS Markit w.d.). With the new technology concept value directly based on the cost of time saved, the daily operating cost of the drilling operations or spread rate, is a key parameter. The spread rate as used here is the well's time-related costs divided by the well drilling duration. Without a breakdown of cost in the data set, the cost model uses a fixed ratio for time-based as part of total cost. For slow drilling wells, a larger-than-average proportion of total time is spent 'making hole'. Consequently, spread rate and thus calculated value of a time saving new technology for those slow wells are likely under-estimated.

New technology concept time and cost profile

A performance model for the concept technology had to use only well parameters available in the reference dataset as input and output 'saved days'. Time performance was built bottoms-up with as much detail as available, including items such as mobilization and demobilization, off-line preparation and on-line rig-up, tripping speed, connection time, on-bottom ROP model and reliability risked trip time. Cost elements consist of capital equipment & depreciation, crew, consumables and logistics. Profit was specifically excluded from the cost so that it could be used to evaluate the value proposition in various contexts (see later). As such the costs are those 'to buy and run the equipment to the supplier'.

As mentioned above, the model baseline assumes the concept technology being mature, i.e. with an operational risk profile equal to conventional. Hence no 'cost of risk' is included for the new technology. Concept savings was defined as the days saved times spread rate, and the concept value as savings minus cost. The new technology concept value was calculated on a section by section basis, with mob/demob accounted for on a whole-well basis. This 'sharing' of mob/demob allows for a marginal well to achieve positive value with multiple sections where a single section might not.

The new technology concept value must not only be positive but also have a sufficiently high margin to make the technology attractive to both the operator and the technology provider. A well with a small positive new technology concept value but relatively high cost (e.g. USD 1 value against USD 1 million cost) has an unprofitable margin and thus is still an unsuitable candidate. Gross margins were therefore calculated as dollars per day operating (supplier-focused) and as dollars per well day saved (operator-focused).

Sensitivities and Rankings

Sensitivity analysis were performed for technology depth and hole size capability, as well as individual model parameters. Combined parameter sensitivity was done using a Monte Carlo approach. Outputs can be ranked and/or summarized by any of the available parameters, such as location (onshore, offshore fixed, offshore floating) or geographic area (field, country, region).

The methodology can be used to obtain objective comparisons between different concept technologies. To use the methodology with another drilling concept, which still uses the same section by section structure, only the new concept performance model must be implemented. This was demonstrated when the method was able to rapidly turn-around a valuation for a completely different drilling concept in the operator's portfolio following the work described in the case study below. If another new technology concept addresses different components of the well construction than 'making hole', then also a new conventional model incorporating those components needs to be implemented.

Case Study: A Hypersonic Impact Drilling Concept

The method was initially developed for and first used on a new technology concept which aims to 'drill' hard rock using hypersonic impact technology. "Hypersonic" is defined generally as a velocity at or above Mach 5 (Galison and Roland 2000), being approximately 1 715m/s at sea level. The Hypersonic Impact Drilling Concept (HIDC) 'drills' hole by means of repetitive hypersonic hydroelastic impacts of expendable penetrators. At these velocities, the strength of materials is so small compared to the stresses upon impact that both impactor and target are significantly eroded and may be at least part vaporized (Air Force Institute of Technology (U.S.) 1991).

In its first iteration (HIDC_1), the system consisted of a ram-accelerator (University of Washington w.d.) at surface accelerating the penetrators, a dual string with internal guide pipe for penetrator travel and between-pipe annulus for drill fluids, and a BHA with a sealing barrier after each projectile. Projectiles are designed to be auto-loaded at surface. Each penetrator impact on the bottom of the wellbore creates a full diameter 'crater' over 2X larger than the projectile diameter whilst fully eroding the penetrator (Russell 2017), as shown in Fig. 2. To maintain penetrator velocity on the way down, the inner pipe must be pulled to a low vacuum for each shot. A dynamic 'end-cap' seals the tube at the bottom as each penetrator passes to keep the launch tube bore clear and separated from pressurized drilling fluids to allow for acceleration and passage of projectiles. After each impact, the firing process is repeated.

Figure 2—HIDC_1 concept model and impact analysis.

Performance model

Desktop engineering feasibility work had already demonstrated that in principle HIDC_1 could technically reach most well depths and profiles currently drilled conventionally. Consequently, no 'technical' constraint was set on wells from the data set. A detailed performance model was developed, and Fig. 3 shows the resulting ROP model including connection times against hole size and depth.

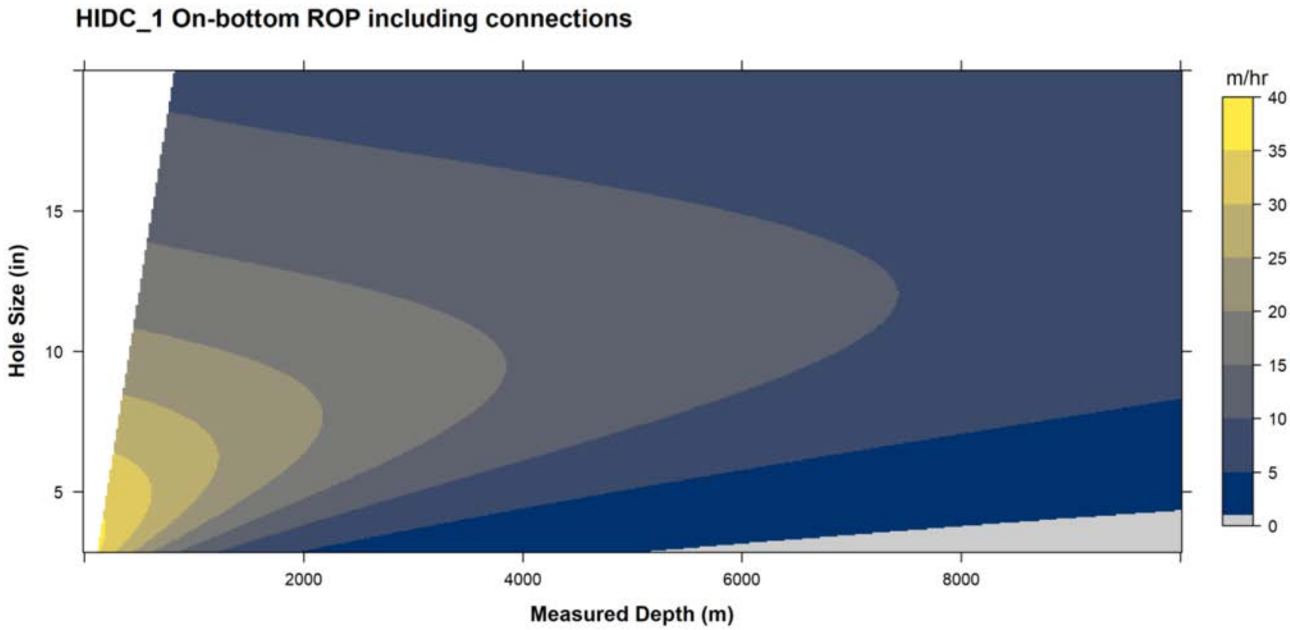

Figure 3—HIDC_1 on-bottom ROP (including connections) vs depth and hole size

The ‘mature technology’ premise assumes that the general operational reliability of the concept under investigation is mature and in line with conventional industry drilling equipment. Hence, no incremental penalty or bonus is given to general reliability in the valuation.

Hypersonic impact drilling consists of a very large number of highly dynamic and critically reliant events, including a downhole barrier seal with every shot. For example, a 1 000 m $8^1/_2$ in section would take over 1,750 shots. In case of a shot failure, the model assumes that the assembly needs to be round-tripped for repair, akin to a bit or Bottom Hole Assembly (BHA) trip. The statistical number of trips per section is equal to the probability of failure per shot times the number of shots. For HIDC_1, a shot reliability of 99.999% was used (1 failure per 100,000 shots).

Mature Valuation

Running the model over the cleansed data set of 16,800 wells yielded a combined un-risked value of nearly USD 4 billion in the 10-year period, spread over 2,384 wells that were technology-positive. Fig. 4 shows graphically the value for each well cross-plotted against its measured depth and as-drilled net drill & case duration. The light-grey points are wells without HIDC_1 value. Density curves along both axis, grouped by well location, show that the bulk of the technology-negative wells are both relatively shallow and fast.

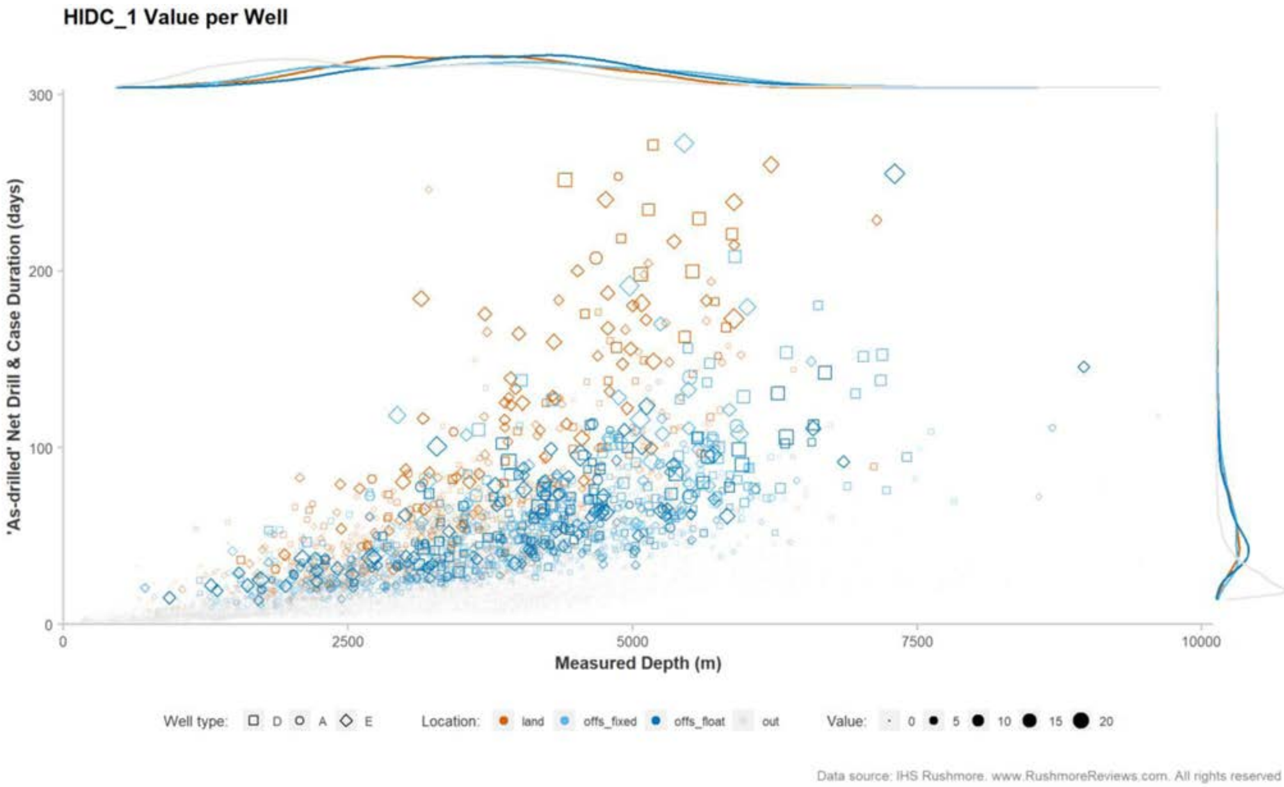

Figure 4—HIDC_1 un-risked modelled value per well (size indicative of value)

Fig. 5 shows the technology-positive wells ranked by value from high to low; the first half dozen wells have a very high value of over USD 20 million each, after approximately 1,000 wells the value drops below USD 1 million each, and after approximately 2,000 wells the value margin per well drops sharply below USD 10,000 per well. The required time saved to obtain certain savings is highest for land wells and lowest of offshore floating rigs. This is as expected with the higher operating costs offshore.

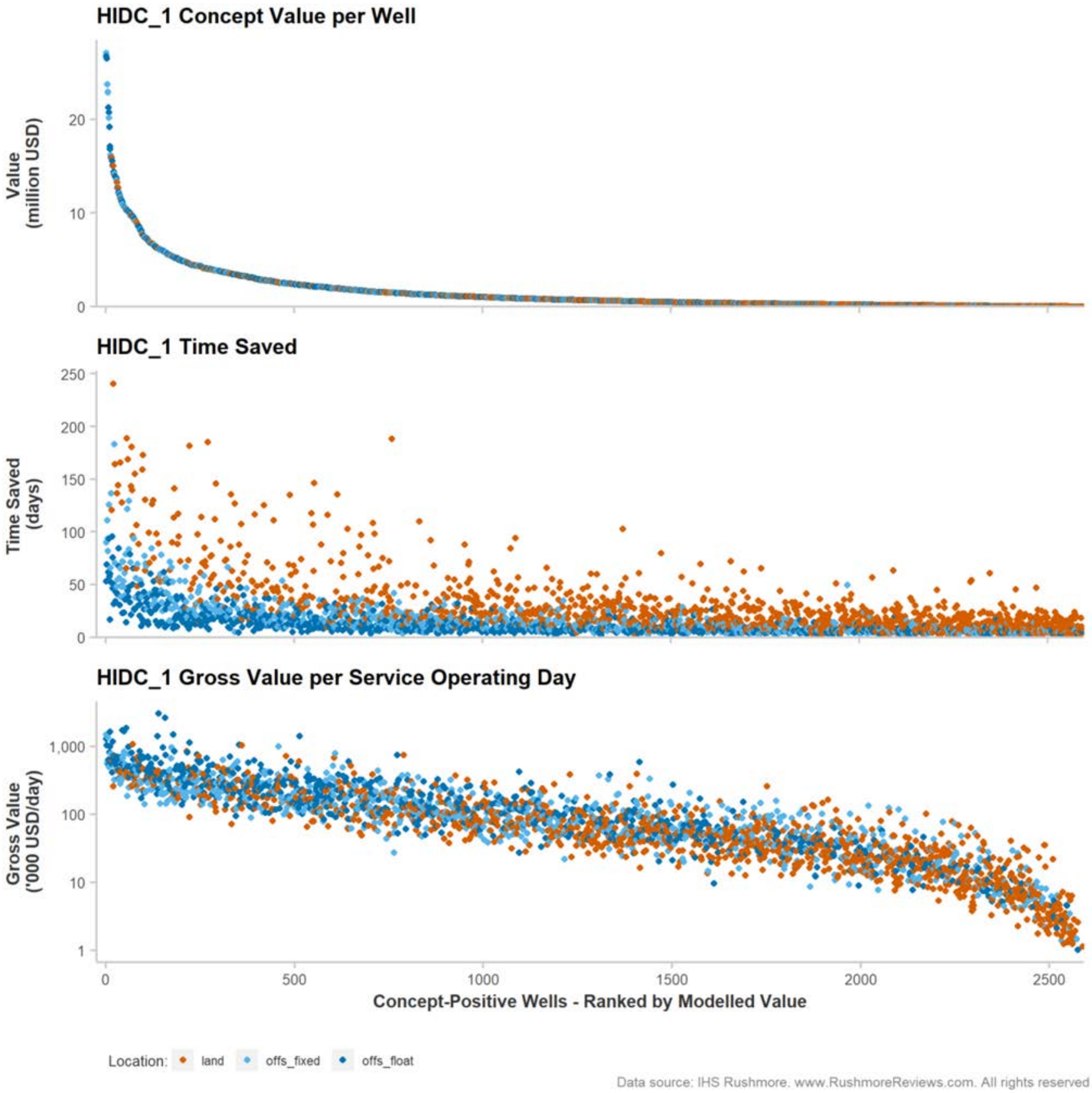

Figure 5—HIDC_1 selected outcomes for technology-positive wells ranked by value.

Concept Capability Analysis

An important question for technical development of an early stage new technology is to what depth and size capability it should be designed to. Too small an operating envelope and there is insufficient market, whilst too big a design envelope will add unnecessary complexity and cost without serving a matching market. Slicing the depth and size capability of the concept technology models various operating envelopes and provides insight into where the modelled value is concentrated (Fig. 6). Plot A shows as reference the 16,800 as-drilled wells against final hole size and depth. Plot B shows the technology-positive wells as the new technology concept capability increases with size and depth, summing to the total of 2,384 for the complete range. Plot C shows the unrisked modelled value against concept capability zone. Interestingly, the bulk of the HIDC_1 value is found not at the deep end of the wells (6+km) but at the deeper end of the mainstream wells (3-6km). The sheer number of wells on the fringe of the mainstream with some value outweigh the much lower number of wells with high value at great depth.

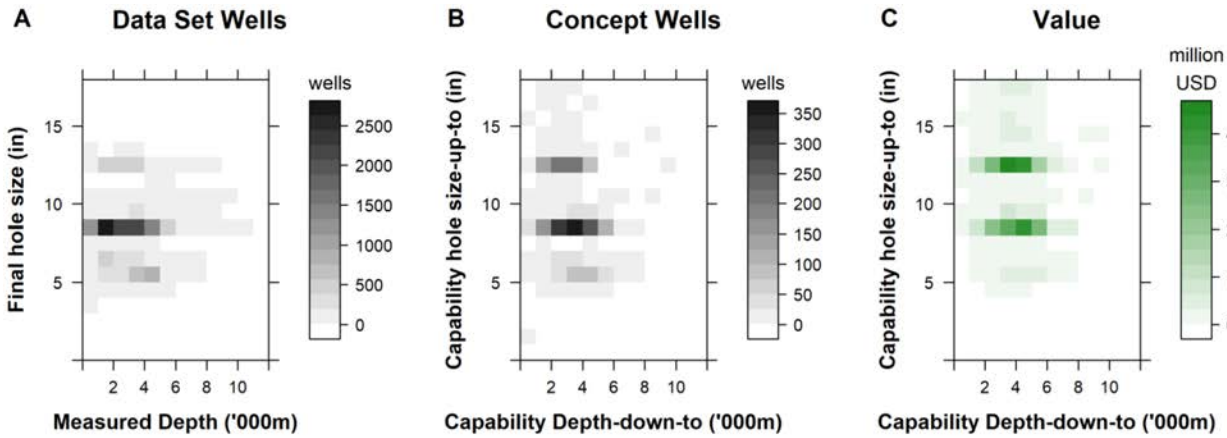

Figure 6—HIDC_1 outcomes by concept depth-size capability areas.

Parameter Sensitivity Analysis

Fig. 7 shows the sensitivity of the analysis to several design parameters. As might be expected, reducing cost, connection time and cycle time improves performance nearly linear. For the vacuum system, the upside curve is limited; the restriction caused by the length and size of downhole pipe negate increased capacity of the vacuum pump and piping at surface. On the other hand, reducing the surface system capacity does directly reduce performance. Shot failure rate is not sensitive around the selected base line; instead of near-linear, this failure mode is driven by orders of magnitude as shown in Fig. 7B (note the logarithmic x-axis in B).

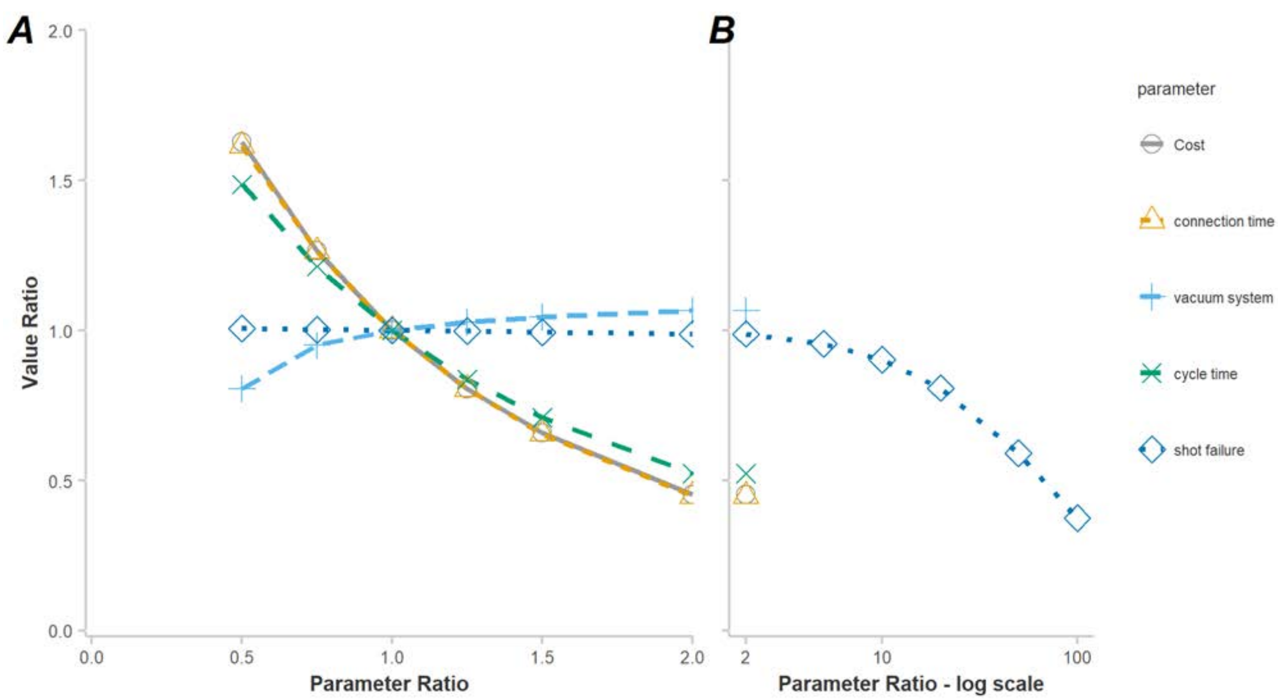

Figure 7—HIDC_1 single parameter sensitivity ratios

Minimum Viable Product

New technology concepts are, by definition, far from being mature. Each is therefore likely to experience an arduous development pathway during which the new technology provider needs to remain economically viable. To do so, it must provide an early product with a high chance of success in the market. A Minimum

Viable Product (MVP) is an early-stage product that has "just enough features to satisfy early customers and nothing more" (Ries 2011).

To provide additional insight for the development focus, the valuation model can be used to calculate the 'market' for various envisaged early product capabilities. If these can be matched to a good market application, then the commercial viability is more likely. More important, a poor early capability match to market can easily result in poor or no market uptake, a near-sure path to failure (Reis 2011). For HIDC and its sponsoring operator, a great MVP would be e.g. 8 ½ in. onshore, non-directional wells under 3 km (10,000 ft) depth in the sponsoring operators portfolio with reasonable value despite still less than fully mature shot reliability. Whilst Fig. 5 shows many high value wells, all of them require high-end technical capability and reliability.

Technology Pivot

The results from HIDC_1 were not considered overly positive, and the technology developer proposed a technical pivot. This new, downhole concept of the technology (HIDC_2) had the accelerator build into a dedicated BHA run on the rig's normal drill string, and still 'drilled' a full-size hole with each impact. Considered technically more complex with the ram accelerator downhole, shot reliability was reduced by a factor 10. Implementing this new concept, by adjusting relevant parameters from the existing HIDC_1 model, took very little time. Results were available within hours for discussion. The new concept model showed a 3X increase in the number of applications and a 3.5X increase in the unrisked modelled value figure.

Based on the insights obtained, the technology probably avoided costly dead-end development and market disappointment and was able to increase industry and investor confidence and investment.

Pushed by the insights obtained from the study, the HIDC_2 concept was subsequently further refined beyond this initial pivot into a rotating bit augmented with repeated hyper-impact projectiles pre-conditioning and pre-breaking the rock just ahead of the bit (HIDC_3), shown in Fig. 8.

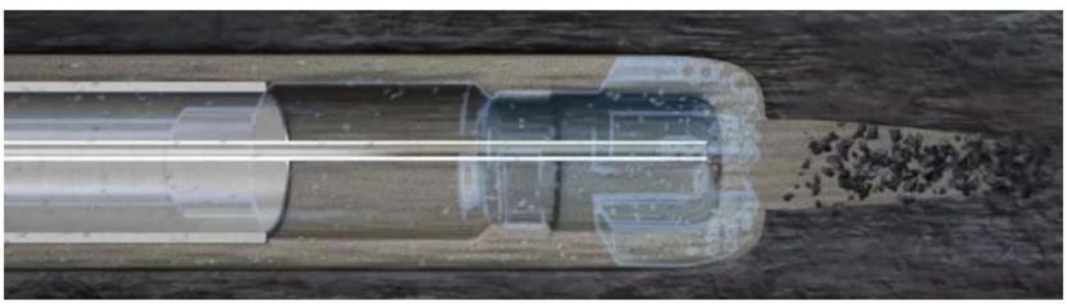

Figure 8—Concept of HIDC_3

Limitations

A hindsight exercise can and will provide information only for those wells that were actually drilled. Wells that would be perfect candidates for the technology but were not drilled because they did not make the economic hurdle due to a slow drilling estimate are simply not in the database.

The resulting cleaned data set had less than 30% of the total wells remaining. This was not a factor of concern in this application because the slow-drilling well types of interest remained. Using this data set to evaluate for example a concept aimed at fast-drilling wells, many of which have only limited 'lite' information in the dataset, might not be suitable.

The valuation also uses as-drilled data, whereas real-world decisions are made on upfront estimates based on a-priori data. A potentially improved method could be by feeding the model not with the hindsight actual drill time and cost, but with estimates based on the a-priori data contained in the database. Moreover, spread rate, a key parameter driving value, was derived in a simplistic manner in this current approach. A useful further enhancement would be to develop an improved sub-model to estimate the spread rate more accurately.

Finally, the methodology applies only to new single-bore wells, drilled from surface/seabed to total depth. Other types of wells (e.g. multi-laterals, side-tracks, pilot-holes) vary extensively in design and only limited, inconsistent design information is available. Inclusion was not considered automatable in a meaningful way.

Conclusions

The methodology, whilst by no means pretending to be accurate in absolute terms, can be used to gain actionable insights at multiple levels:

- To obtain a mature market valuation, mature technology parameters such as reliability, directional drilling capability and all applicable hole sizes and depths are invoked.
- To aid the technology development and design decisions, sensitivity analyses can be performed on design parameters.
- To guide development requirements, a Minimum Viable Product analysis provides insight to the minimum technical requirements necessary and the de-risking work required before a technology can gain acceptance in the marketplace.
- To explore early applications and potential sponsoring projects, clusters of potential high-value and/or early-applications can be identified.
- The results from this valuation model provide insights into the potential of wells at or beyond the fringes of the database, i.e. complex wells that require extraordinarily long net times to drill.

More generally, we have learned that

- There is much valuable information ‘hidden’ in data sets around the industry, waiting to be mined and utilized.
- To achieve insightful, actionable results, data science and technical experts must closely work together and have at least a basic understanding of each other’s fields.
- The use of script-driven data analytics software instead of a traditional spreadsheet resulted in a fast, automated workflow which is more usable, auditable and transferrable.

Suggested Future Work

Decisions to run a technology on a specific project are made not with hindsight but on the ‘a-priori’ information conventional time and cost estimate. The impact of a-priori vs hindsight on the model valuation could be investigated by feeding the model not with the actual drill time and cost, but with automated estimates based on the a-priori data contained in the database. This would require an automated offset well selection and time-cost estimate methodology. Initial work done on this following the scope described in this paper has shown this to be feasible and equally applicable to estimates for conventional wells.

Acknowledgements

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Nomenclature

BHA Bottomhole assembly

BOP Blowout preventer
D&C Drill and Case
HIDC Hypersonic Impact Drilling Concept
MVP Minimum Viable Product
NPT Non-productive time
ROP Rate of penetration (m/s)
TRL Technology Readiness Level

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