

Drilling Optimization Using New PDC ROP Model and Differential Evaluation Algorithms



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Ph.D. Proposal

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Outline

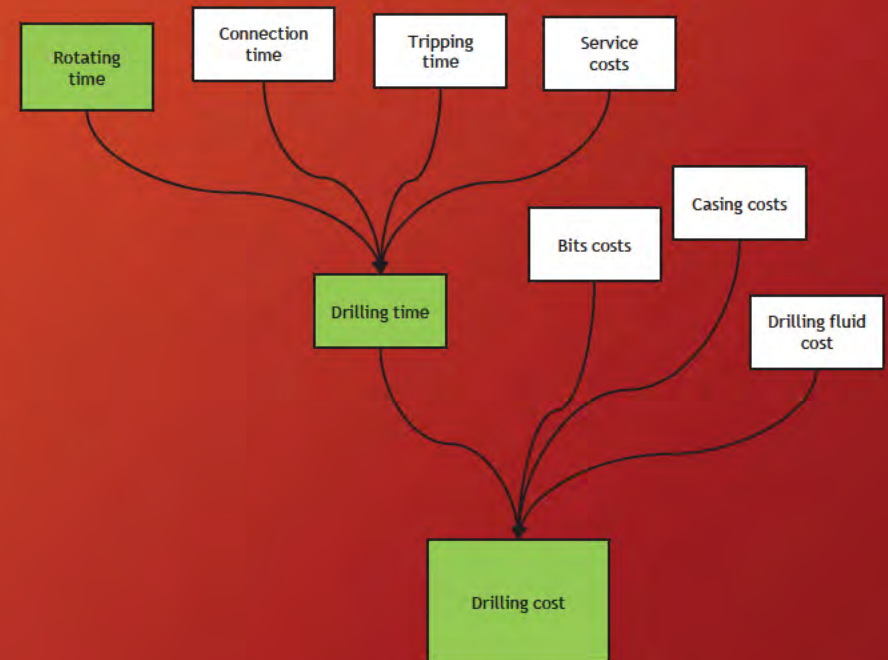
- Introduction
- Background, Literature review and Objectives
- Methodology
 - Developing a new ROP model for PDC bits
 - Bit wear function
 - Thermal effect on bit wear
 - Metaheuristic Algorithms
 - Differential Evolution Algorithm (DEA)
- Preliminary results
- Current conclusions
- Future works and potential applications



Introduction



- Increasing drilling efficiency reduces drilling cost.
- Drilling costs: rig rental, bits, casing strings, drilling fluids and service costs.
- Drilling cost increases when drilling time goes up.
- Drilling time: rotating, connection, and tripping.
- Reducing rotating time is the challenge.



Introduction



Problem (Rotating time or drilling cost) needs to be translated into a mathematical language (model).



Introduction



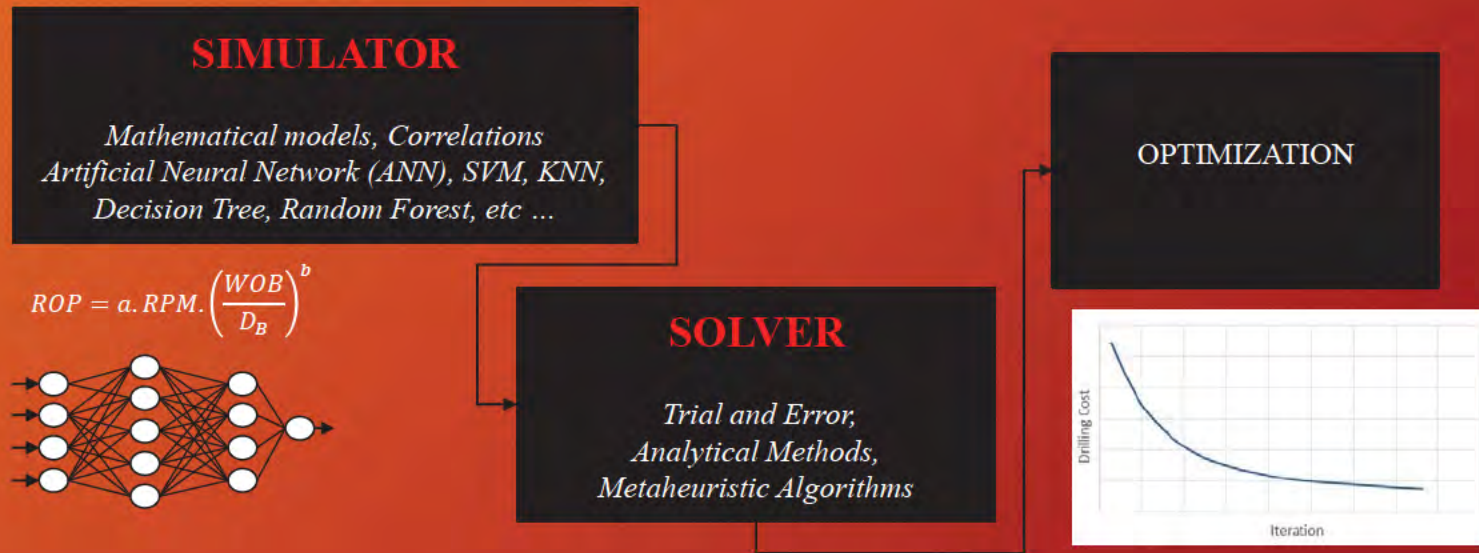
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Introduction



Problem (Rotating time or drilling cost) needs to be translated into a mathematical language (model).



Background

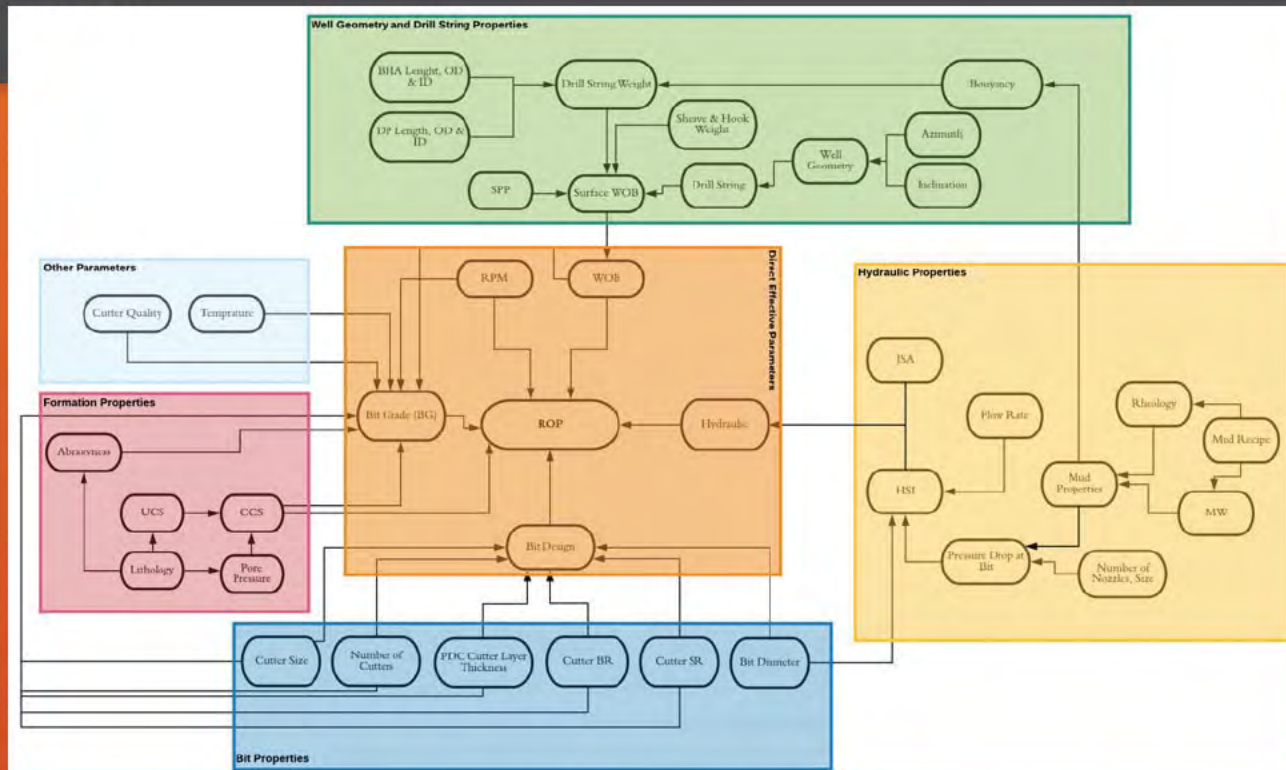


Drilling ROP is function of following parameters:

- Formation properties: lithology, abrasiveness, UCS, CCS, pore pressure
- Bit details: number of cutters, cutters diameter, BR, SR, cutter quality, bit diameter, wear flat area details
- Hydraulic: Junk slot area, HSI, pump GPM, nozzle size and selection, mud properties
- Adjusted WOB: well geometry (azimuth, inclination), BHA and DP specifications, SPP, hook load, friction, mud properties (buoyancy)
- Bit Grade: RPM, WOB, formation details, bit details, cutter quality, PDC layer thickness
- RPM

Some of these parameters have integrated effects on each other.

Background



<https://www.youtube.com/watch?v=MdFzJGd54IQ&feature=youtu.be>
<http://rpubs.com/Atashnezhad/378363>

Literature review



Models:

- Bingham ROP model (1964)
- Hareland and Rampersad ROP model (1994)
- Motahhari et al. ROP model (2008)
- Kerkar et al. model for PDC bits (2014)

Optimization:

- Hareland et al. (Pason Drilling Simulator, Optimizer)
- Self et al. 2016 (PSO)

Literature review



Models

Literature review-Models



Bingham ROP model (1964)

$$ROP = a \cdot RPM \cdot \left(\frac{WOB}{D_B} \right)^b$$

WOB is weight on bit
RPM is revolution per min
Db is bit diameter
a, b formation drillability

Formation properties
Bit details
Hydraulic
Adjusted WOB
Bit grade
RPM

Literature review-Models



Hareland and Rampersad ROP model (1994)

$$ROP = W_f \times COR \times \frac{14.14 N_c RPM A_v}{D_B}$$

Formation properties

Bit details (wear flat area details, both STUD and PDC layer)

Hydraulic

Adjusted WOB

Bit grade (cutter orientation, Stud & PDC layer quality)

RPM

A_v is the area ahead of a cutter - f (BR, SR, dc, WOB, RS, N_c)

BR is back rake

SR is side rake

dc is cutter size

WOB is weight on bit

RS is rock strength

N_c is the number of cutters

D_B is bit diameter

RPM in revolution per min

COR is correction factor - f (lithology, RPM and WOB)

W_f is wear function

Literature review-Models



Motahhari et al. ROP model (2008)

$$ROP = W_f \cdot \left(\frac{G \cdot RPM^\gamma \cdot WOB^\alpha}{D_B \cdot S} \right)$$

$$W_f = K_{wf} \cdot \left(\frac{WOB}{N_c} \right)^\rho \cdot \frac{1}{S^\tau \cdot A_w^{\rho+1}}$$

Formation properties (abrasiveness)

Bit details (wear flat area details, both STUD and PDC layer)

Hydraulic

Adjusted WOB

Bit Grade (cutter orientation, Stud & PDC layer quality)

RPM

BR is back rake

SR is side rake

dc is cutter size

WOB is weight on Bit

RPM in revolution per min

D_B is bit diameter

S is confined compressive strength

α and γ are ROP model exponents, dimensionless

W_f is wear function, dimensionless

N_c is the number of cutters on bit face

W_f is non dimensional wear function

G is f (bit geometry, cutter BR and SR, cutter-rock friction)

A_w is wear flat area is f (depth of cut, PDC layer thickness)

k_{wf} , ρ and τ are numerical values

Literature review-Models



Kerkar et al. model for PDC bits (2014)

$$ROP = \left[\frac{K1 \cdot WOB^{a1} \cdot RPM^{b1} \cdot \cos(SR)}{CCS^{c1} \cdot D_{Bit} \cdot \tan(BR)} \right] \cdot W_f \cdot h(x) \cdot b(x)$$

WOB is weight on Bit
RPM in revolution per min
CCS is confined compressive strength
BR is back rake
SR is side rake
 D_B is bit diameter
 W_f is wear function, dimensionless
 $h(x)$ is hydraulic function
 $b(x)$ is effect of number of blades

Formation properties

Bit details (wear flat area details, cutter size and number, PDC cutter layer thickness)

Hydraulic

Adjusted WOB

Bit grade (cutter orientation, Stud & PDC layer quality)

RPM

Literature review

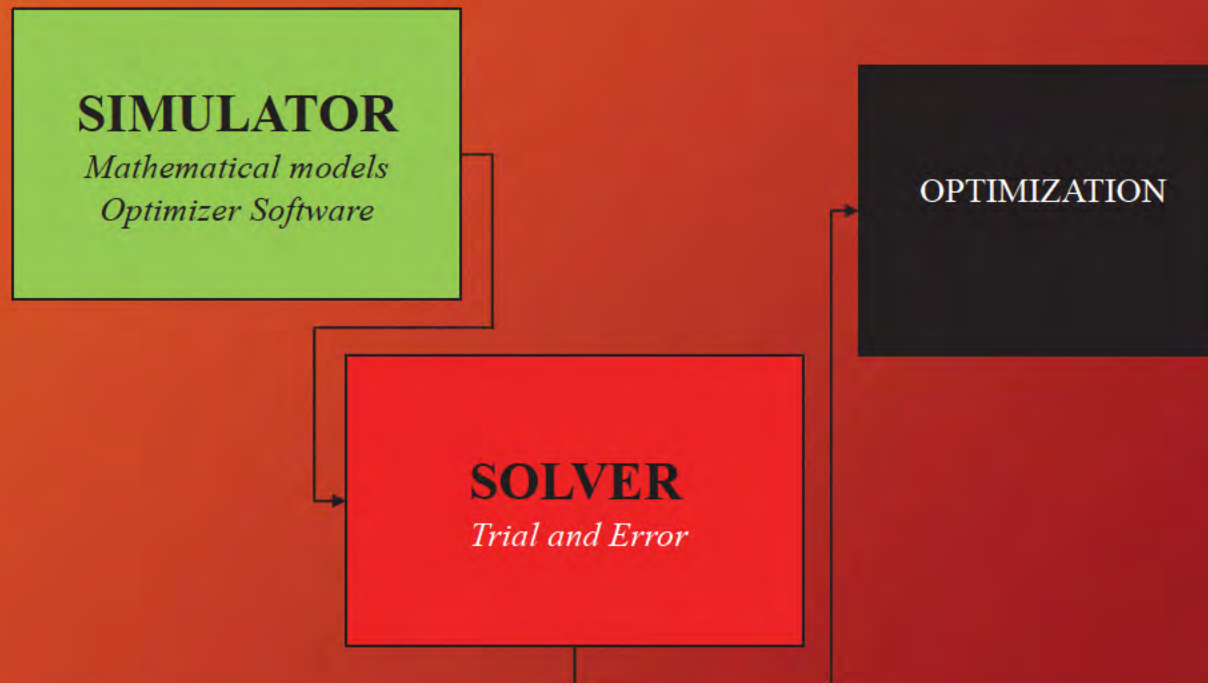


Optimization

Literature review-Optimization



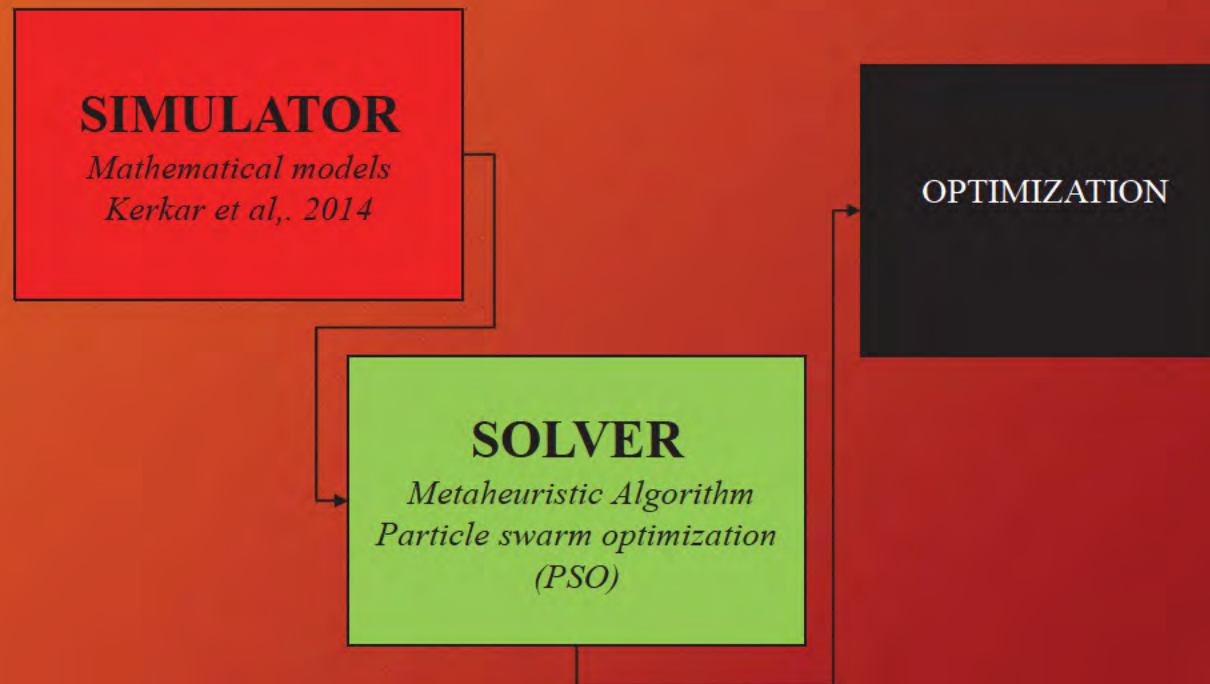
Hareland et al. 2008 (Pason Drilling Simulator, Optimizer)



Literature review-Optimization



Self et al. (2016)



Objectives



Objectives

Objectives

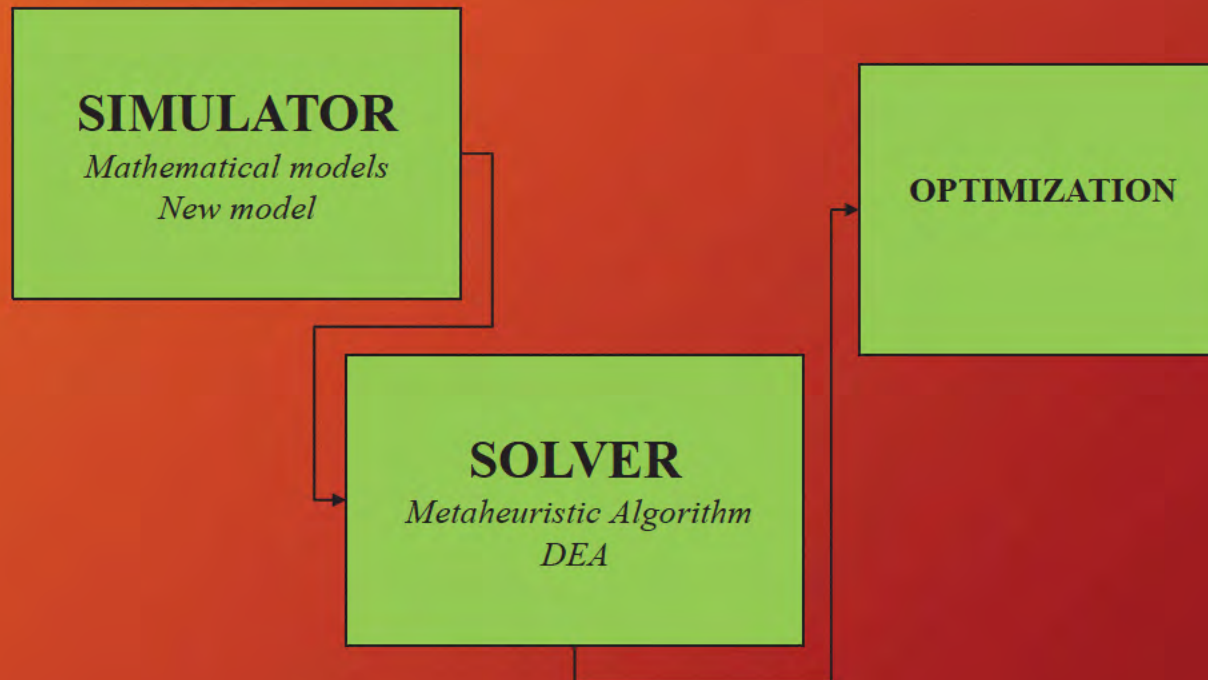


- Developing a new rate of penetration model for PDC bits by taking the cutter geometry details.
 - The new model includes the PDC layer and stud material wearing coefficients in the bit wear function.
 - The new model includes the efficiency of stud wearflat area in the ROP estimation model.
- Developing a general drilling cost objective function for optimization.
- Proposing a new approach for drilling time optimization by incorporating a new ROP model and Metaheuristic Algorithm (DEA)

Objectives



Current Work



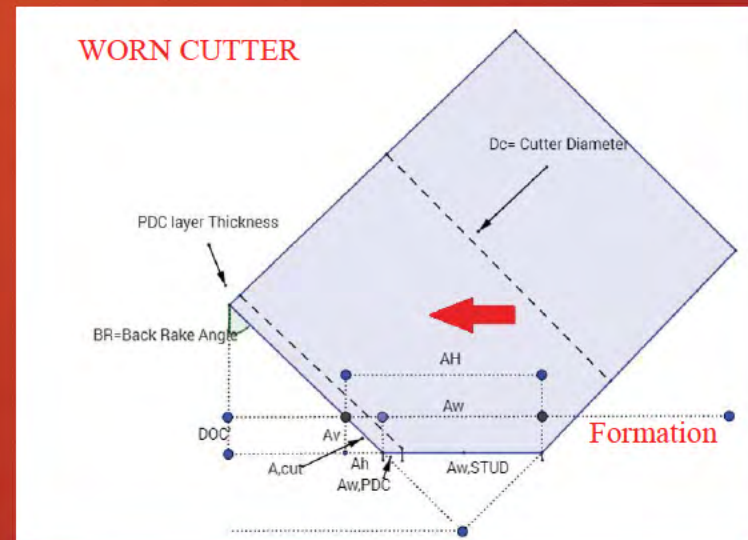
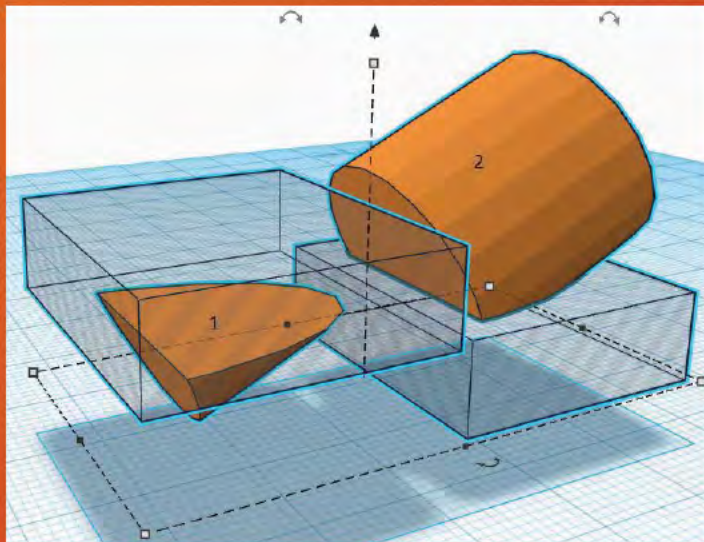


Cutter Schematic

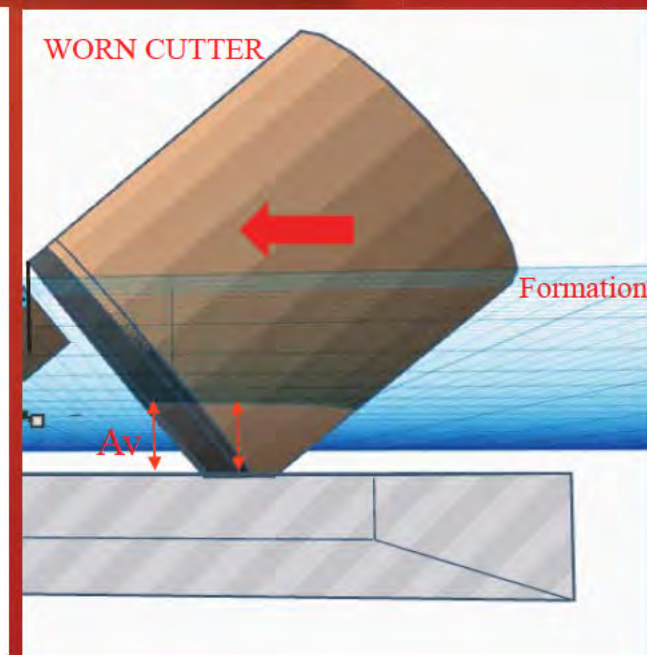
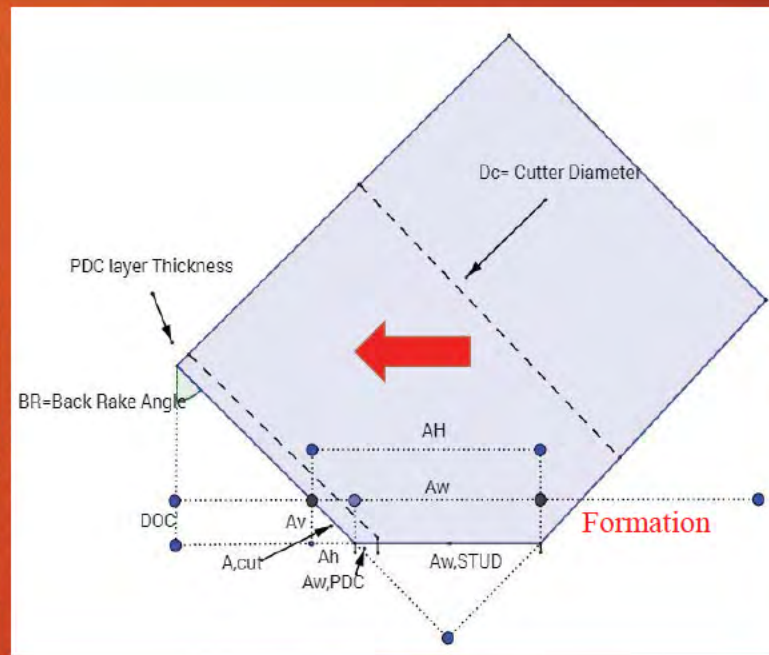
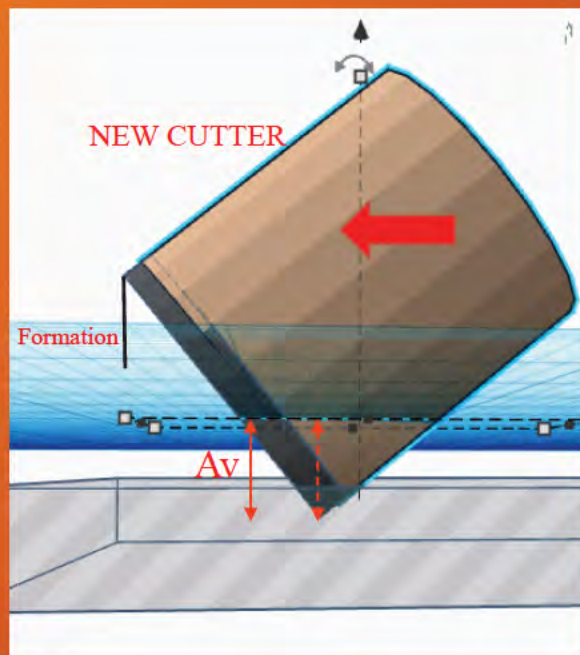
Methodology – Cutter Schematic



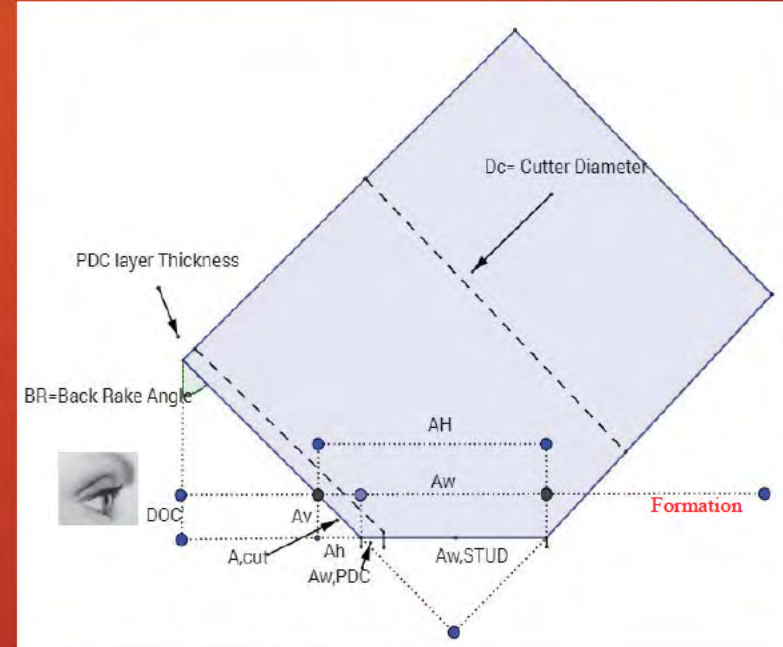
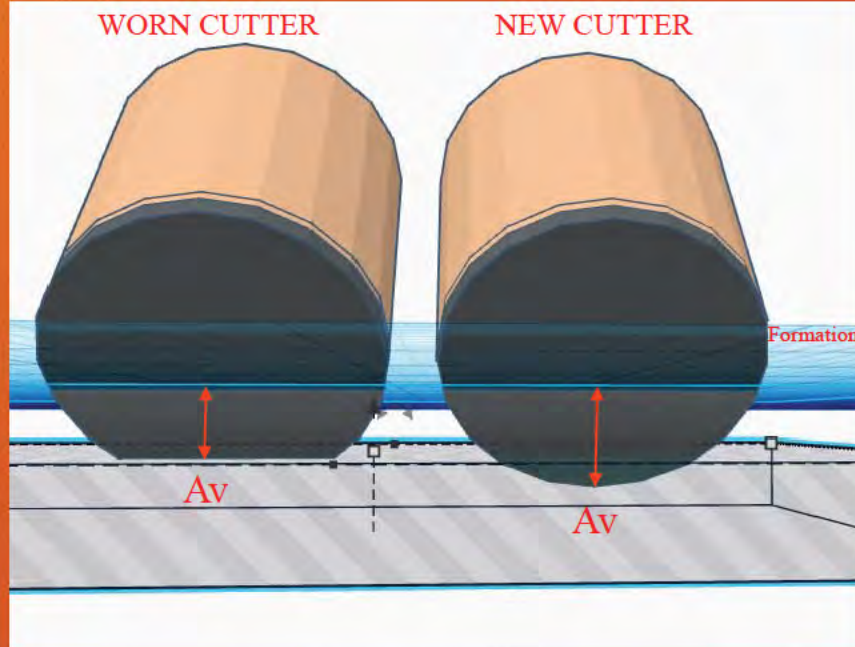
Schematic of different areas associated with the cutter penetration calculation



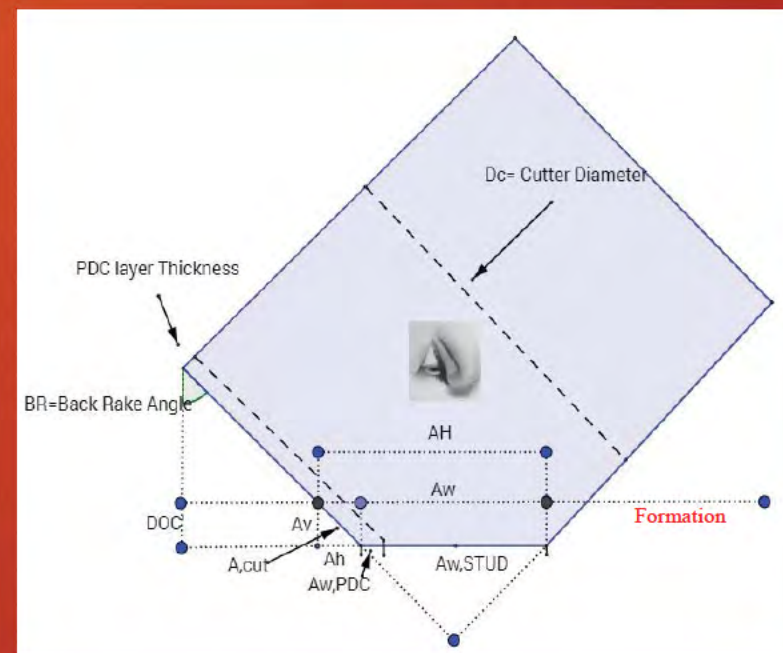
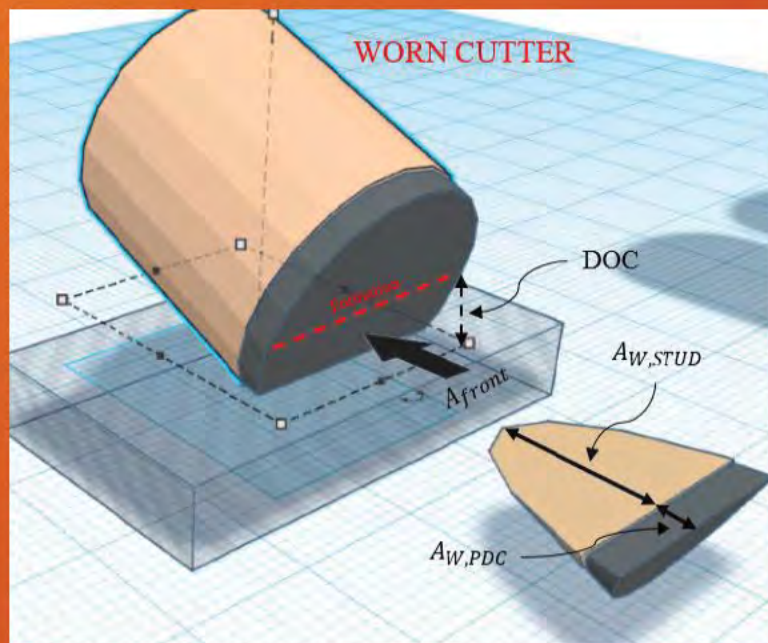
Methodology – Cutter Schematic



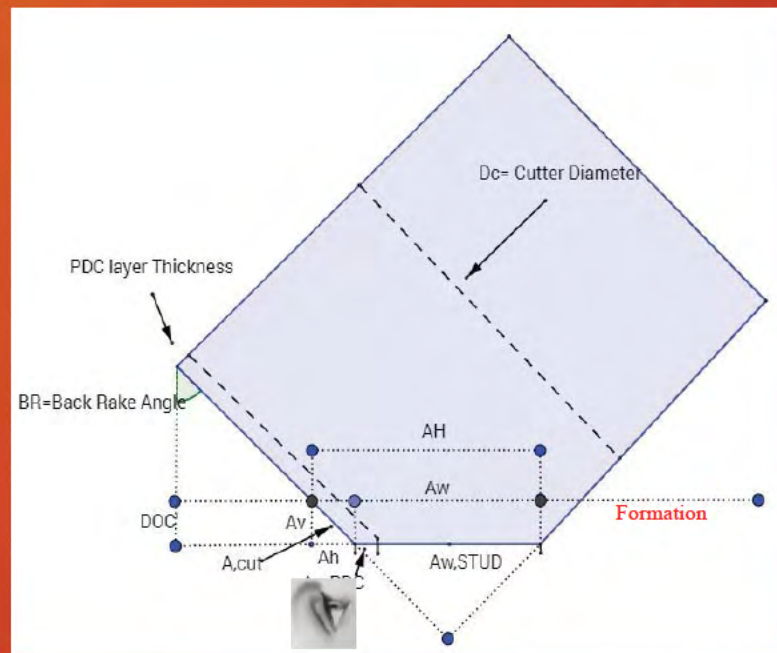
Methodology – Cutter Schematic



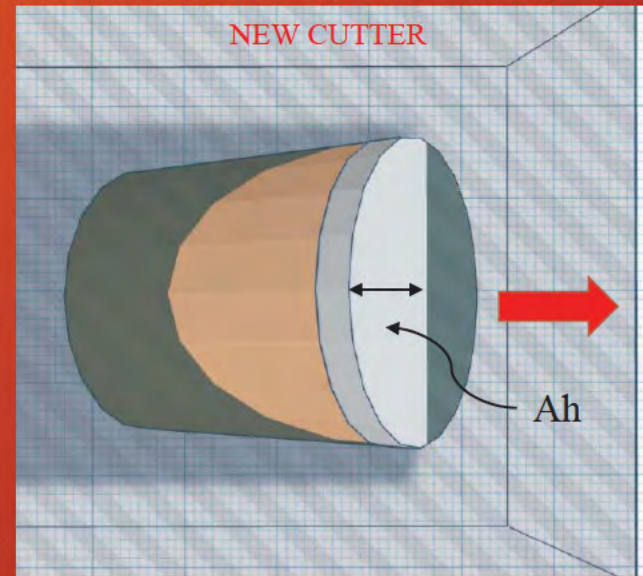
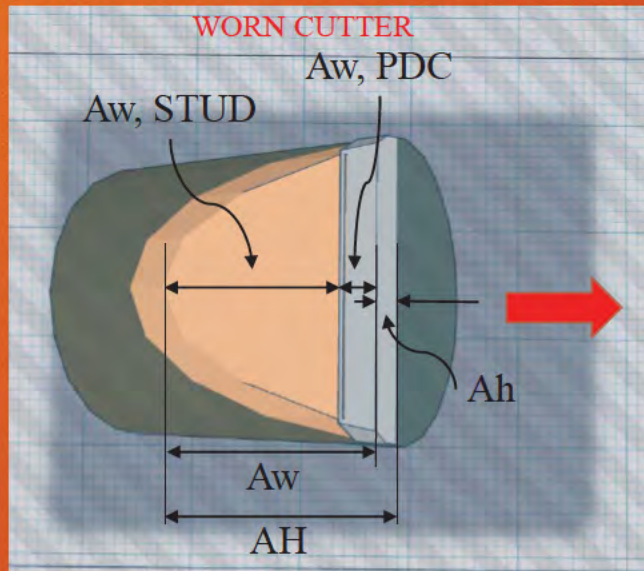
Methodology – Cutter Schematic



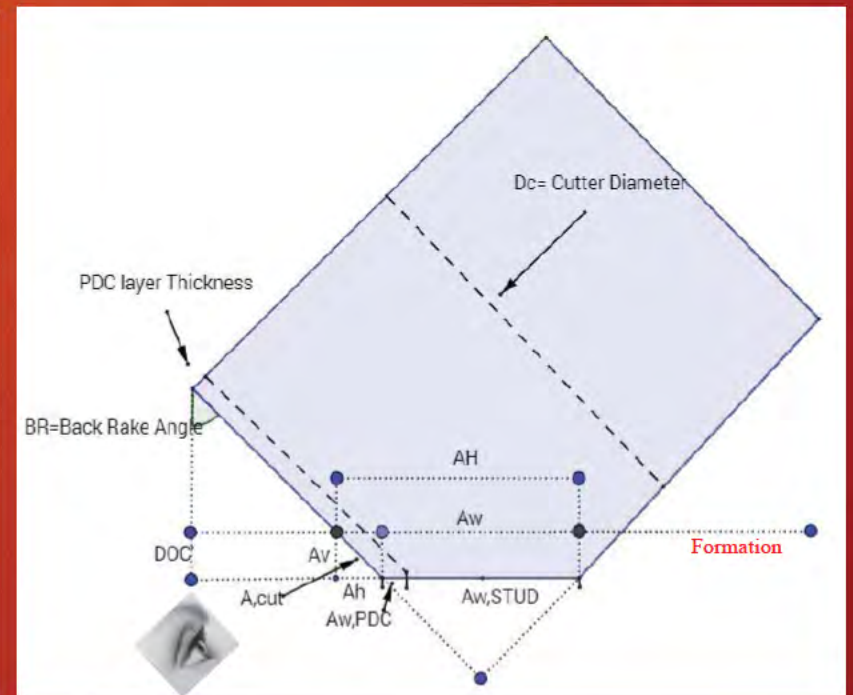
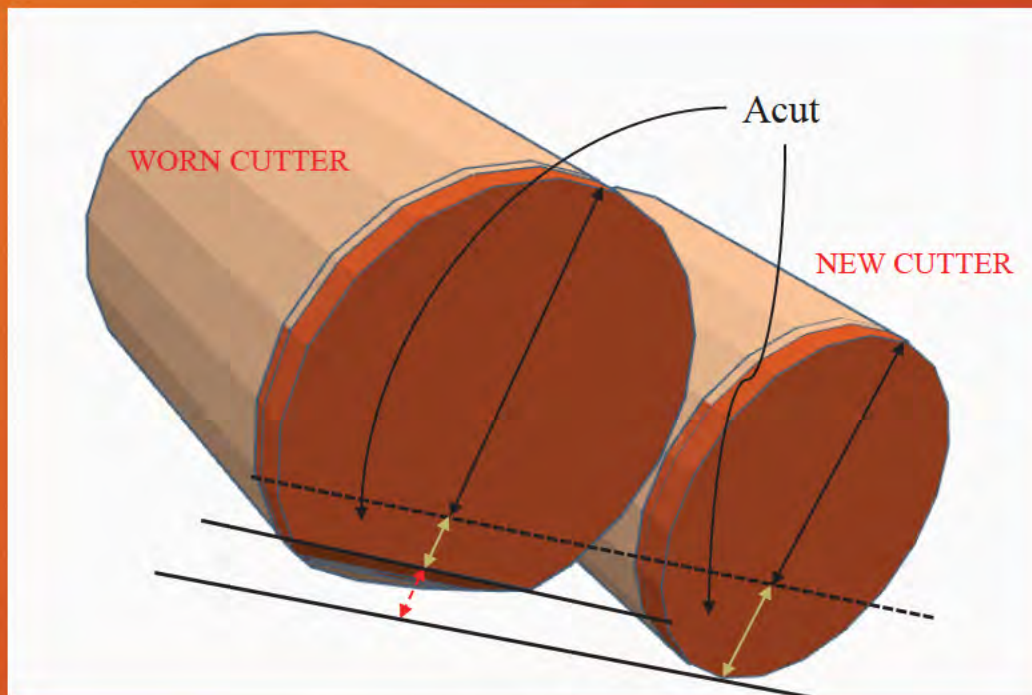
Methodology – Cutter Schematic



Methodology – Cutter Schematic



Methodology – Cutter Schematic



Methodology



New PDC ROP model

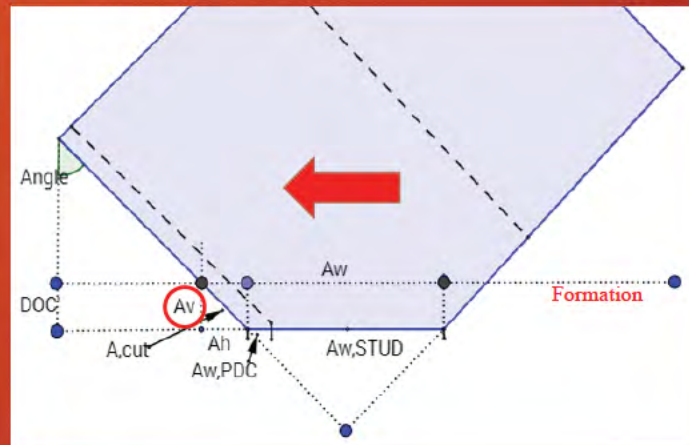
Methodology - New PDC ROP model



Developing a New PDC ROP model.

The volume of rock that is cut by the cutter at effective radius is calculated theoretically.

$$ROP = c_1 \times \left(\frac{5 \times RPM \times R_e \times C_e \times A_v}{\frac{\pi}{4} D_b^2} \right)$$



RPM in revolution per min
 R_e is equivalent radius
 C_e is cutter front area efficiency
 A_v is cutter front area
 D_b is bit diameter
 C_1 is a constant and it is function of cutter interaction and number of cutters

Methodology - Equivalent bit radius



- Equivalent bit radius: Assume an average value for R_e so that the bit face area on both sides of R_e is equal. This is based on the assumption that the amount of work required to remove the same volume of rock is the same. (Hareland and Rampersad, 1994)
- Equivalent bit radius concept is being used in the new model for assigning a BR and a SR values for a bit.



Methodology - New PDC ROP model

Developing a New PDC ROP model

$$ROP = c_1 \times \left(\frac{5 \times RPM \times R_e \times C_e \times A_v}{\frac{\pi}{4} D_b^2} \right)$$

$$A_v = \left[\left(\frac{D_c}{2} \right)^2 \cdot \cos^{-1} \left(\frac{\frac{D_c}{2} - \left(\frac{DOC'}{\cos(BR)} \right)}{\frac{D_c}{2}} \right) - \left(\frac{D_c}{2} - \left(\frac{DOC'}{\cos(BR)} \right) \right) \cdot \sqrt{2 \cdot \left(\frac{D_c}{2} \right) \cdot \left(\frac{DOC'}{\cos(BR)} \right) - \left(\frac{DOC'}{\cos(BR)} \right)^2} \right] \\ - \left[\left(\frac{D_c}{2} \right)^2 \cdot \cos^{-1} \left(\frac{\frac{D_c}{2} - \left(\frac{BG \cdot D_c}{8} \right)}{\frac{D_c}{2}} \right) - \left(\frac{D_c}{2} - \left(\frac{BG \cdot D_c}{8} \right) \right) \cdot \sqrt{2 \cdot \left(\frac{D_c}{2} \right) \cdot \left(\frac{BG \cdot D_c}{8} \right) - \left(\frac{BG \cdot D_c}{8} \right)^2} \right] \cdot \cos(BR) \cdot \cos(SR)$$

Formation properties

Bit details (wear flat area details, cutter size and Number, PDC cutter layer thickness)

Hydraulic (a hydraulic function will be added)

Adjusted WOB

Bit Grade (cutter orientation)

RPM

RPM in revolution per min

R_e is equivalent radius

C_e is cutter front area efficiency

A_v is cutter front area / $A_v = f(D_c, DOC', BR, SR, BG)$

/ $DOC' = f(WOB, N_c, CCS, D_c, BR, BG, t_c)$

D_b is bit diameter

C_1 is a constant and it is function of cutter interaction, strain

effect on RS, and number of cutters

BG is bit grade

BR is rake angle

SR is side rake

DOC' is depth of cut

Methodology - New PDC ROP model



Depth of cut calculations

A_1 is the theoretical calculated area beneath the cutter and should be satisfied to achieve force balance between weight on cutter (downward) and the rock reaction (upward) forces.

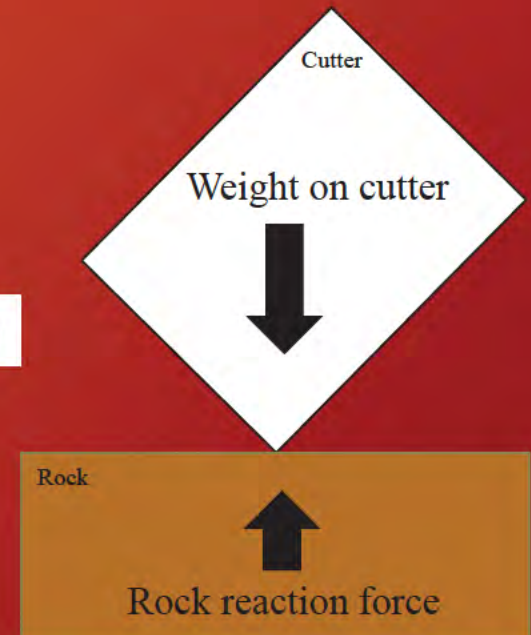
$$\frac{WOB}{\frac{N_c}{CCS}} = A_1$$

The A_w' (square inch) is the weighted wear flat area.

$$A_w' = \omega_1 \cdot A_{w,PDC} + \omega_2 \cdot A_{w,stud}$$

The A_2 is the weighted area beneath the cutter and it is achieved by adding up the weighted wear flat area (A_w') and area beneath the cutter face (A_h).

$$A_2 = A_w' + A_h$$



Methodology - New PDC ROP model



Depth of cut calculations

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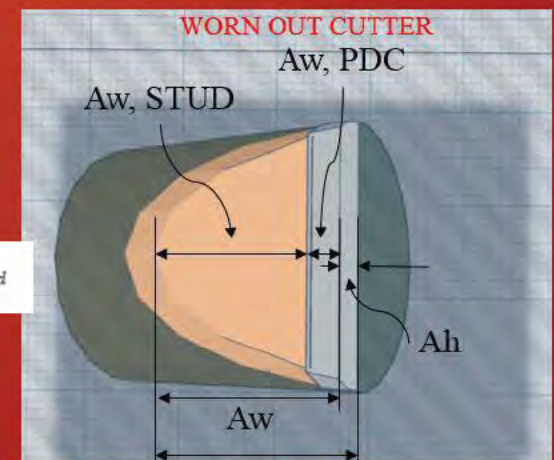
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Bit wear function

Methodology –Bit wear function



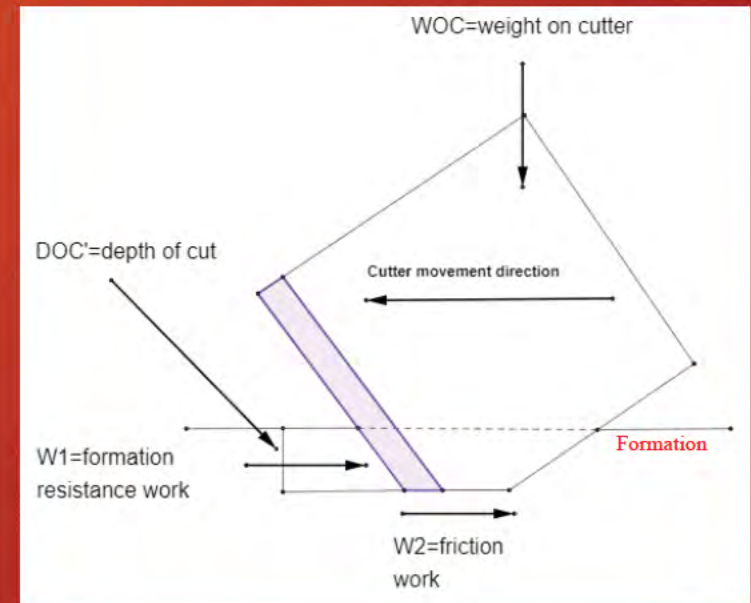
In the new ROP model, a new real time bit wear estimation model is developed by taking the physical work that is done by PDC cutter.

- W_1 = friction work
- W_2 = formation resistance work
- The total work done by cutter is calculated and is turned into the worn volume V_{worn} in cubic inch, by taking the cutter wearing constant.

$$\frac{W_1}{min} = 0.083 \times \mu_k \times WOC \times RPM \times 2\pi R_e$$

$$\frac{W_2}{min} = 0.083 \times C_e \times A_v \times CCS \times RPM \times 2\pi R_e$$

$$W_T = W_1 + W_2$$



Methodology –Bit wear function



- The wear constant (α) is the amount of work in $ft.lb_f$ that should be done to wear off unit volume of cutter in cubic inch.
- The cutter is composed of PDC and stud material with different wearing constants.
- It is assumed that the PDC layer and stud volumes that are exposed to formation is proportional to their wear flat areas.

$$\alpha_{ave} = \left(\left(\frac{A_{w,PDC}}{A_w} \right) \times \alpha_{PDC} + \left(\frac{A_{w,STUD}}{A_w} \right) \times \alpha_{stud} \right)$$

$$V_{worn} = \frac{W_T}{\alpha_{ave}}$$

$$V_{total\ worn} = - \left[\frac{\left(\frac{D_c}{2} \right)^3}{\tan(BR)} \left[\left(\frac{\left(\frac{D_c}{2} \right) - \left(\frac{BG \cdot D_c}{8} \right)}{\left(\frac{D_c}{2} \right)} \right) \times \arccos \left(\frac{\left(\frac{D_c}{2} \right) - \left(\frac{BG \cdot D_c}{8} \right)}{\left(\frac{D_c}{2} \right)} \right) - \sqrt{1 - \left(\frac{\left(\frac{D_c}{2} \right) - \left(\frac{BG \cdot D_c}{8} \right)}{\left(\frac{D_c}{2} \right)} \right)^2} \right] + \frac{\left(\frac{D_c}{2} \right)^3}{3 \tan(BR)} \left(\sqrt{1 - \left(\frac{\left(\frac{D_c}{2} \right) - \left(\frac{BG \cdot D_c}{8} \right)}{\left(\frac{D_c}{2} \right)} \right)^2} \right)^3 \right]$$



Thermal effect on bit wear

Methodology – Thermal effect on bit wear



Glowka and Stone (1985) developed an analytical model for estimating the temperature distribution in stud-mounted PDC cutters under downhole conditions.

$$\bar{T}_w = T_{f1} + \frac{K_f \times F \times V \times f}{A_w} \left[1 + \frac{3\sqrt{\pi}}{4} \times f \times K_{hf} \times \left(\frac{V}{\alpha_f \times L} \right)^{0.5} \right]^{-1}$$

$\bar{T}_w$ is mean flat area temperature of PDC cutter in Celsius,

T_{f1} is cooling fluid temperature in Celsius,

K_f is cutter-rock friction coefficient,

K_{hf} rock-formation thermal conductivity in $\frac{W}{cm}$,

F is cutter penetrating force in newton (N),

V cutting speed in $\frac{m}{s}$,

f thermal response function in $C \frac{cm^2}{W}$,

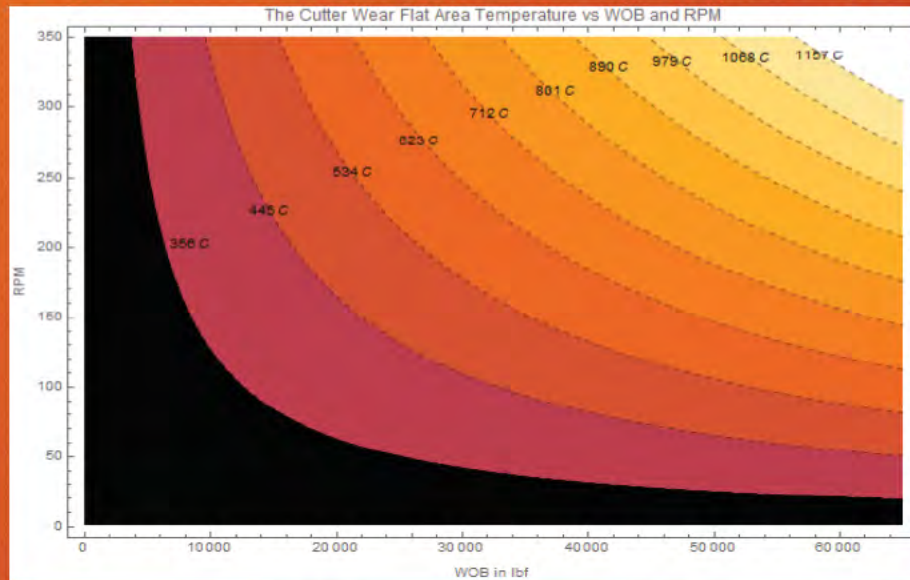
A_w cutter wear flat area in cm^2

α_f rock formation thermal diffusivity cm^2/s (in^2/s)

Methodology – Thermal effect on bit wear



Sample application of the Glowka and Stone (1985) analytical model to a 8.5" PDC bit with 0.5" cutters and bit grade of 1.5



Ref: Glowka, D.A. and Stone, C.M.: "Thermal Response of Polycrystalline Diamond Compact Cutters Under Simulated Downhole Conditions," Soc. Pet. Engr. J. (April 1985) 143-156.

Methodology



Hydraulic function

Methodology – Hydraulic function



Hydraulic function changes from 0 to 1.

- ROP is calculated as a function of hydraulics which is a function of ROP again. Initial guess and iteration.
- The new model is multiplied with the $h(x)$ to achieve the drilling ROP.

$$h(x) = a_2 \cdot \frac{(HSI \times \frac{JSA}{2D_{bit}})^{b_2}}{ROP^{c_2}}$$

HSI is Hydraulic square inches

JSA is junk slot area

D_b is bit diameter

ROP is rate of penetration

a_2, b_2, c_2 are empirical coefficients

Methodology



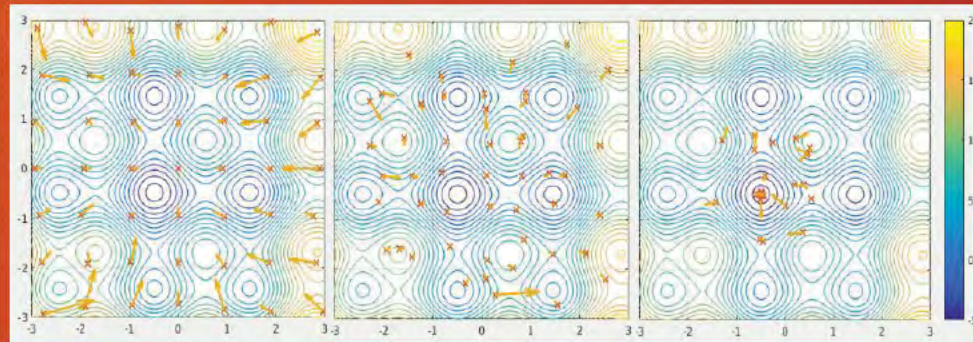
Solving Method

Methodology - Solver



Metaheuristic Algorithms

- Metaheuristic Algorithms (MAs) are procedure developed to find a sufficiently good solution to an optimization problem.
- The MAs create a set of feasible sample solutions for a problem and then try to increase the candidate's fitness iteratively.

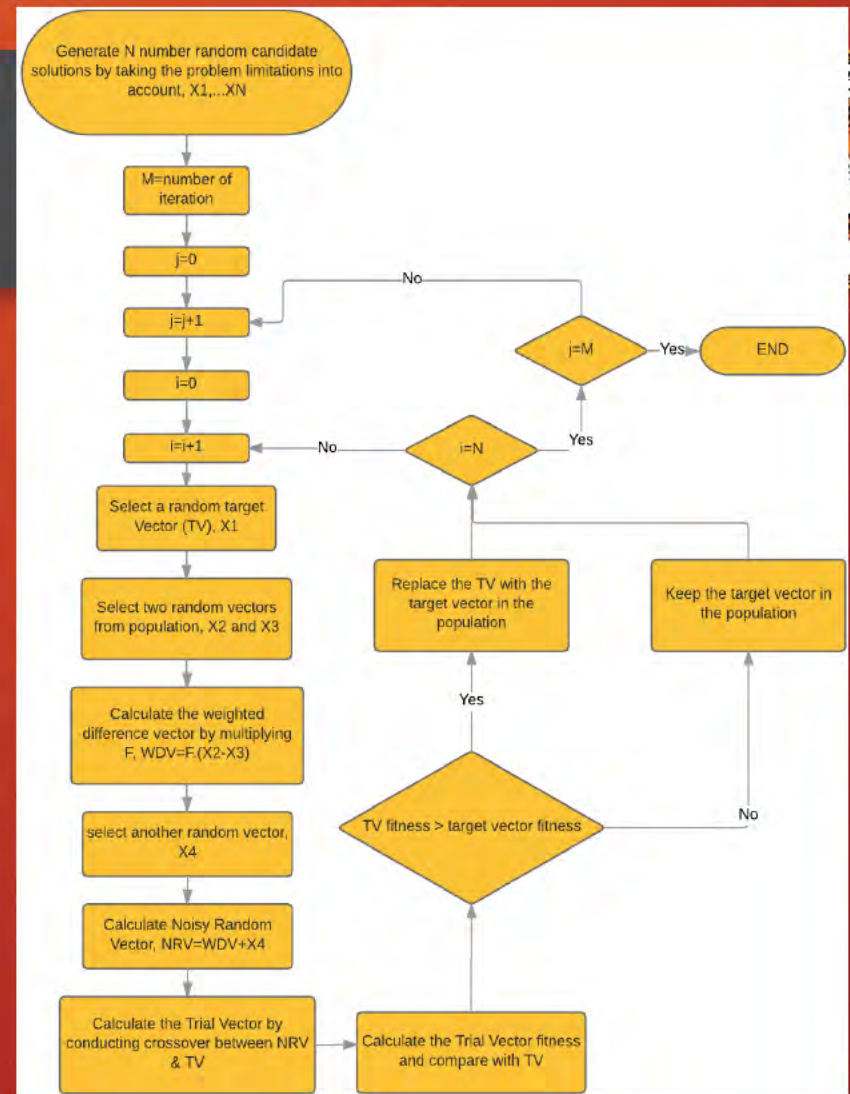


A contour of a 3D problem with PSO particles (Ephramac, 2017)

Methodology (Solver) - DEA

Differential Evolution Algorithm

- Storn and Price developed the differential algorithm in 1997 (Storn and Price, 1997).
- The Price in 1996 tested the performance of DEA on 15 benchmark functions. He found that the DEA was the fastest method for solving the 11 of them and for the remaining 4 was competitive (Price, 1996).
- The DEA improves the fitness of population using its simple mathematical equation iteratively.





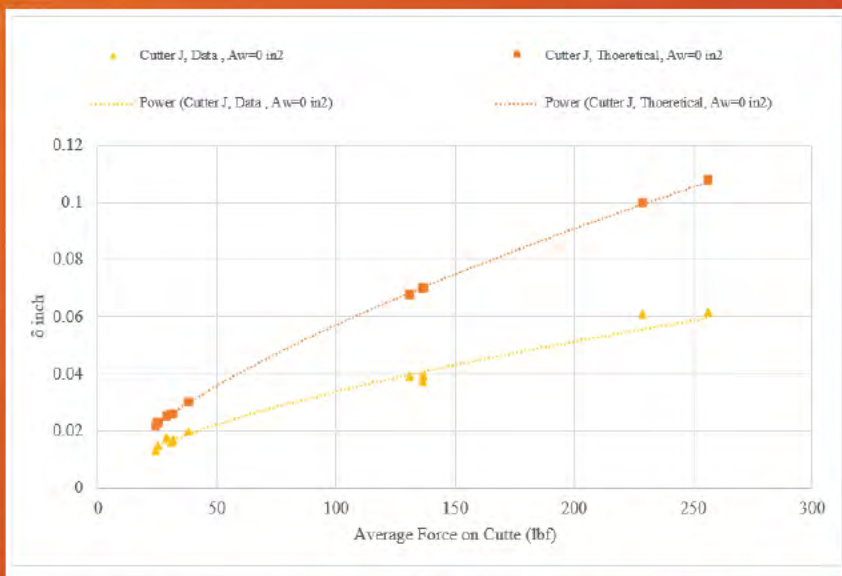
Preliminary Results

Preliminary Results

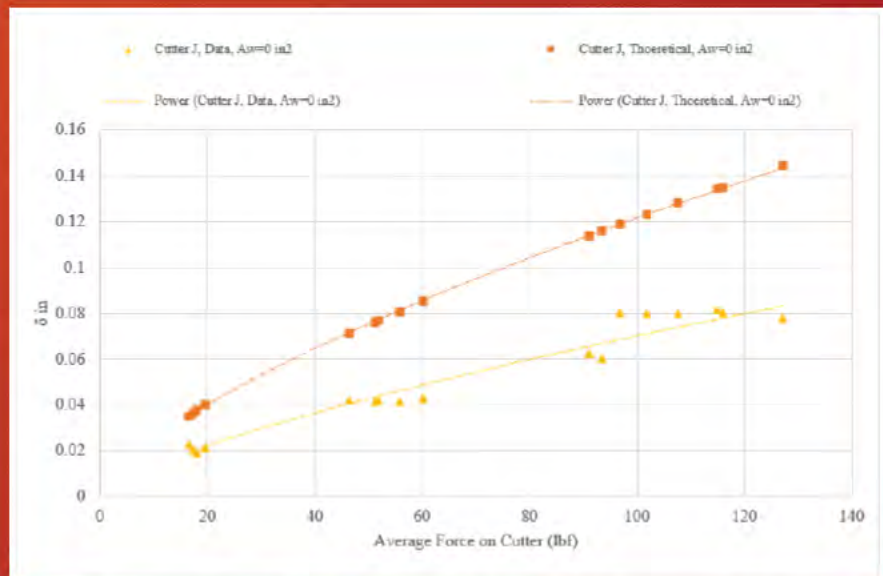


In 1998 the National Sandia Lab conducted a set of tests on PDC cutters.

- The strain rate effect is not incorporated yet.



The variation of penetrating force with depth of cut for Sierra white granite for sharp cutter



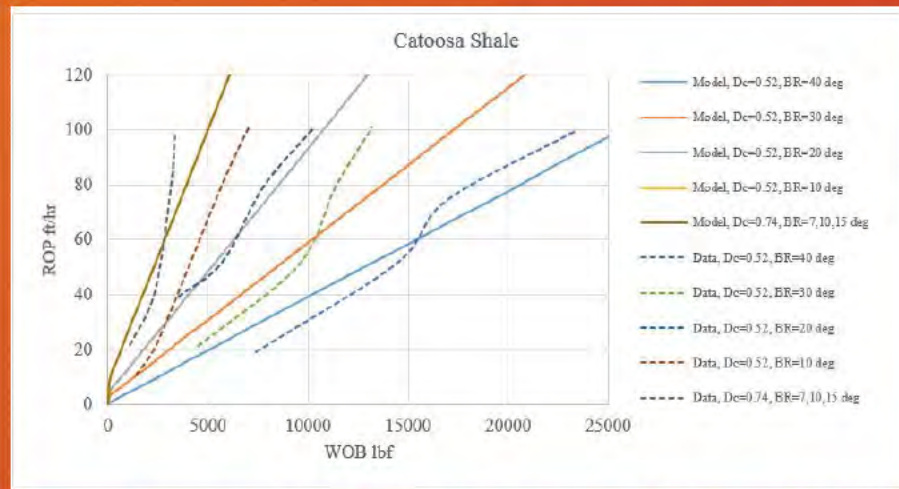
The variation of penetrating force with depth of cut for Berea sandstone for sharp cutter

Preliminary Results – BR sensitivity

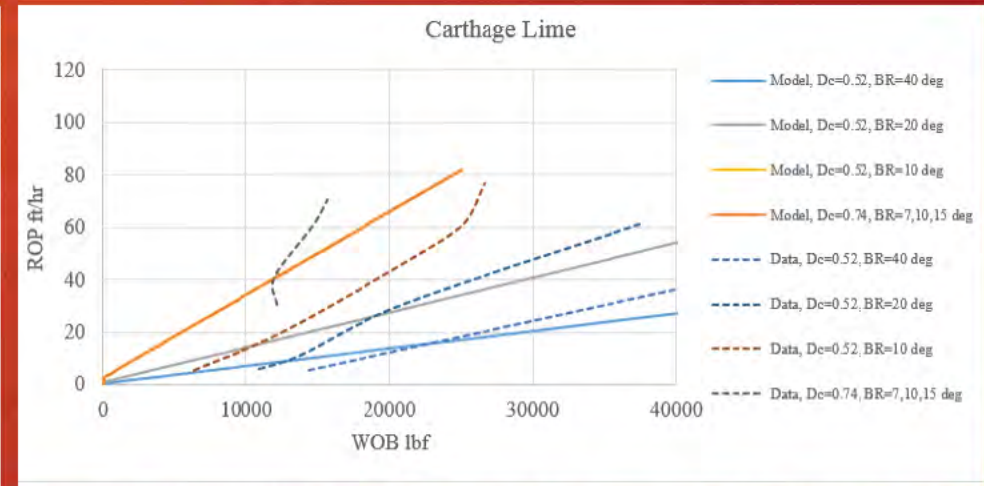


The model was used for simulating the ROP versus WOB for full hole 8.5” bits with different cutter orientations and sizes for Catoosa Shale and Carthage Lime (Sinor et al, 1998).

- The ROP model coefficient (C_1) has the geometry effect that should be taken into account.



Comparison between Data and model estimated ROP versus WOB for different bits with different cutter back rake angles and sizes



Comparison between Data and model estimated ROP versus WOB for different bits with different cutter BR angles and sizes for Carthage lime

Preliminary Results

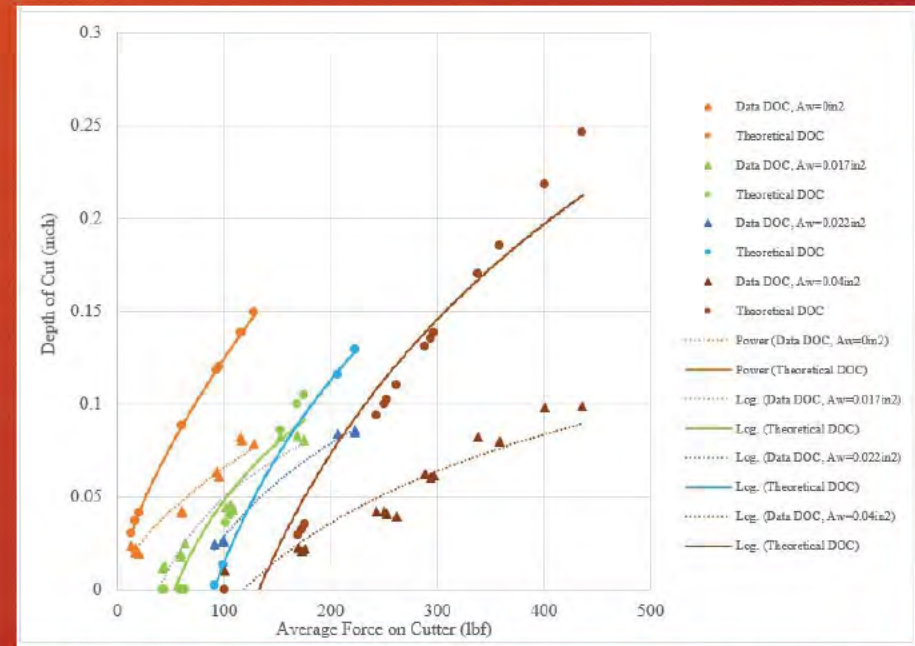


- For a cutter with different wear flat (field worn out) areas, the penetrating force versus depth of cut were simulated for Berea sandstone.
- The cutters wear flat area and size were 0.016-inch and 0.52-inch, respectively.

Preliminary Results



- The model simulated results were compared with the lab data (Glowka, 1987).
- The model overestimate the cutter depth of cut because of:
 - The effect of cutter velocity on rock strength (strain rate effect on rock strength should be taken into account in the model)
 - The stud wear flat area efficiency should be adjusted (here it was assumed 30%).



Comparison between measured penetrating stresses from data and model for constant wear flat area with 0.52-inch cutter diameter



Conclusions

Conclusions



1. A new model was developed.
 - a) The Kerkar et al. (2016) hydraulic function will be used for hydraulic concerns.
 - b) The Glowka and Stone (1985) model (potentially) will be used for cutter thermal concerns.
2. Data in the literature were used for model verifications.

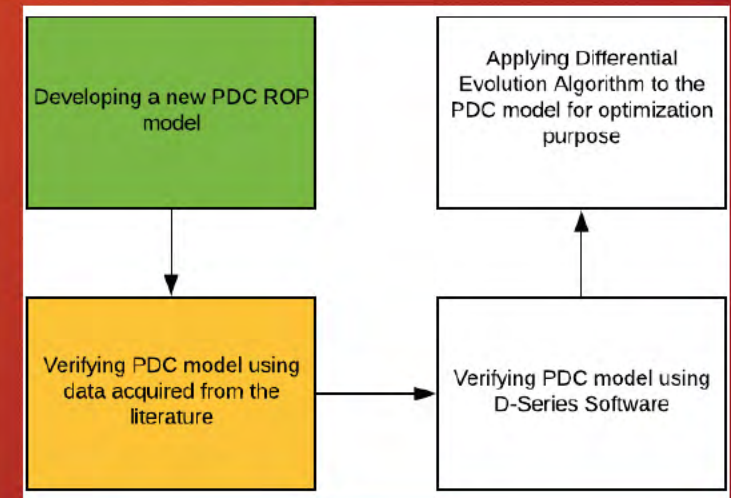


Future works

Future works - Verification



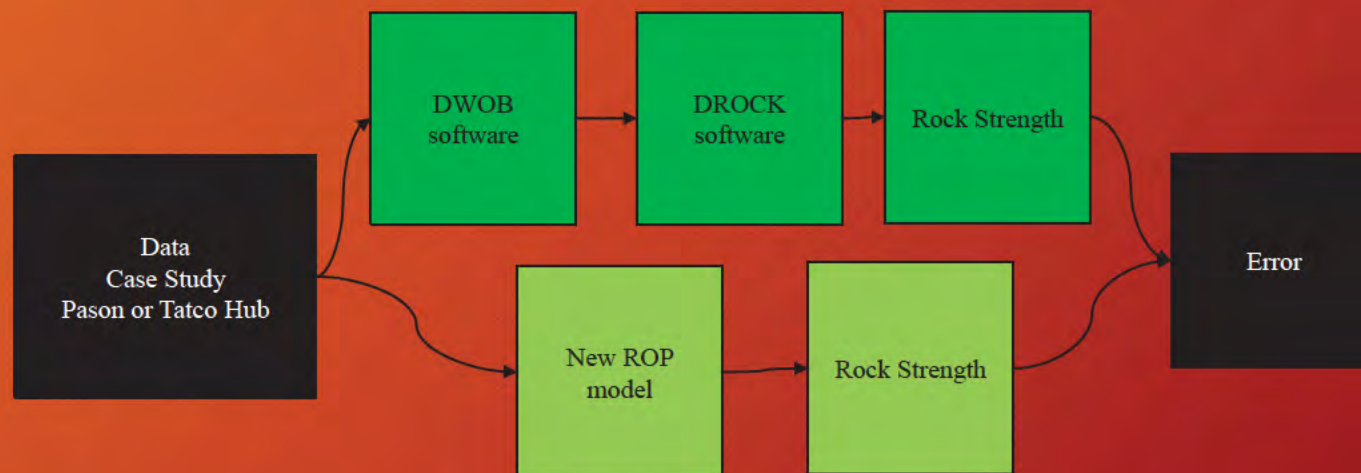
- Incorporating the effect of cutter velocity on the CCS
- Finding the accurate stud wear flat area efficiency
- Developing cutter front area efficiency model



Future works - Verification



- Verifying PDC model Using D-Series Software



Future works - Optimization



Final task in this project is to perform optimization on a field case study.

1. How many bits should be used?
2. What is the optional bit design?
3. What bit should replace a used bit?
4. What is the depth that the bit should be pulled out of the hole?
5. How should the WOB and RPM be changed along the drilling interval?

Future works - Potential applications



1. Developing or integrating into current software's for drilling optimization.
2. Autonomous drilling decision making (Artificial Intelligence, AI).
3. Real-time optimization and problem solver software (AI).
4. Designing new PDC bits for different applications (PDC Bit Designing softwares). In term of number of cutters, average BR and SR, the cutter thickness and cutter quality.



Thanks