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Doctoral thesis

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A plan is only as good as the experience it builds on

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Summary

This research was initiated to establish mitigations of the performance gap in well construction. Expert representatives from each discipline spend on average 4,000 to 6,000 manhours of planning for each offshore well, resulting in 15 to 20% non-productive time. The largest source of saving, however, was identified in field trials using "Drilling performance analytics" software and automated rig equipment. Significant invisible lost time is concealed in the time reported as effective operations. With more than 20 years' experience from onshore and offshore drilling, completion and intervention engineering and supervisor roles, the industry practices and procedures were scrutinized to find the best fundament for a new sustainable way of working.

The work processes for planning and support of well construction and intervention is human based. I.e. engineers of different disciplines manually select input, feed software models and analyze the result before processing further to other linked models. The main product from this work is a groundbreaking new work process tying all disciplines together in a digital and automated process. An application is designed to link equipment properties, experience, engineering, etc., and produce digital programs and procedures. The application is called Well Operative System (WOS). Several other actors in the market are developing applications performing automated engineering. The WOS, however, is currently the only application designed to provide automated support for administrative tasks and to establish digital programs and procedures. Engineering comprises ~15% of the workload and administration is minimum 70%. I.e. the WOS will free up significantly more manhours and provide programs and procedures of the highest quality because no other application is designed to apply experience and best practices as fundament when deriving methods and operational parameters for programs and detailed procedures. The estimated total saving using the WOS with modern engineering modules is between 20 to 30% of current well cost using smarter and leaner methods and designs.

The framework of the WOS is presented, but the development method for the software is not elaborated. Most of the engineering models exist in prototypes and some of the prototype engineering applications are covered in 6 of the 13 papers produced. The focus in this thesis is the new, fully automated and digital workflow for planning. The WOS has 2 loops, where the first produces a framework for the digital program and the second perform iterations that tune and optimize operational parameters. WOS loop 1 is programmed, but loop 2 is prepared only with few checks of functions. The first prototype of the WOS is therefore about 20% complete.

A key enabler for the dynamic abilities and fully digital platform is a universal language describing all tools, activities, services and processes. The given name is "report language" since it builds on codes and reporting format used in daily rig activity worldwide. Operators use reporting systems typically designed to describe all events and measure time consumption for efficiency. This research developed the reporting system further by adding some features to enhance the codes and connected engineering, logistics, contracts, etc. The format of the report language represents a familiar interface to industry professionals who can use the WOS with minimal training. Requiring no programming ability, the WOS is designed with a fully dynamic planning platform where the user is in complete control. Digital experience is designed to use the report language and has the same format as programs. Their appearance may be thought of as miniature procedures that are readable for man and applied by the WOS in planning. It can be used to give any property to any formation, equipment or describe methods as sequences of desired operational steps.

Once operational, the application for fully automated activity planning and support can be a game changer providing safer and more cost-effective operations for rigs with and without automated equipment. Further development of the WOS needs support and funding of resources.

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Acknowledgments

The author wants to acknowledge the supervising Professor S. Sangesland for the opportunity to investigate the ideas discussed in this PhD. Thank you for your time and efforts – you are always there, when questions pile up - and you always find a good answer.

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The author wishes to express thanks and acknowledgment to the many students contributing to the research over the years. With so many brilliant minds involved, the research has developed with a broader and better perspective.

To my dear friend who supported me through many tasks and challenges – Jesus De Andrade, thank you. Andreas Teigland deserves recognition for his great help and inspiration sharing insight and knowledge.

Lastly and most importantly, I would like to thank my beautiful and loving wife and my children for their patience and understanding. Thank you for letting me pursue these ideas and for standing by me through the busy times!

Thank you

Bjorn A. Brechan

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Nomenclature

Latin

A	=	Area
A_i	=	area of inside wall of pipe
a_N	=	maximum depth of a crack-like imperfection
A_x	=	area of pipe's steel cross section
b	=	Buoyancy factor [-]
c	=	Model Parameter
D	=	Outer Diameter
d_i	=	pipe's inner diameter (ID)
DLS	=	Dog leg severity
d_o	=	pipe's outer diameter (OD)
E	=	Young's Modulus
E	=	Elastic modulus [Pa]
E''	=	Derated Young's Modulus
ec	=	Eccentricity
F_1	=	Axial force on the upper part of the segment [N]
F_2	=	Axial force on the lower part of the segment [N]
F_a	=	Axial tension in the drill string [N]
F_a	=	Axial Force
Fa	=	axial force
fac	=	Factor Used in Tamano Equation
$f_{compression}$	=	Compression Factor
F_{eff}	=	Effective Axial Force
F_N	=	Normal force per unit length from the drill pipe on the casing wall [N/m]
$f_{ovality}$	=	Ovality Factor
f_{umn}	=	minimum tensile strength
F_{UTS}	=	ultimate tensile strength
f_{wear}	=	Wear Factor
H_e	=	Decrement Function for Elastic Collapse
h_n	=	Stress-Strain Curve Characteristic Correction Factor
H_t	=	Decrement Function for Transition Collapse
H_y	=	Decrement Function for Yield Collapse
I	=	Second moment of inertia [m4]
k_a	=	Burst strength factor
k_e	=	Model Bias Factor for Elastic Collapse
k_{wall}	=	pipe wall reduction factor (0.875)
k_y	=	Model Bias Factor for Yield Collapse
L	=	Length
L	=	Length

L_s	=	Sliding distance of the drill pipe against the wellbore [m]
n	=	Number of Samples
n	=	hardening index
n_R	=	hardening index for rupture
n_W	=	hardening index for wrinkling
o	=	Standard Deviation
ov	=	Ovality
$\acute{p}^*_{ref\ ave}$	=	reduced reference burst pressure
p_b	=	burst pressure
p_e	=	External Pressure
p_i	=	Internal Pressure
p_M	=	von Mises pressure
p_{MRW}	=	von Mises pressure limit for wrinkling
p_o	=	External Pressure
$p_{ref,M}$	=	von Mises failure pressure
$p_{ref,T}$	=	Tresca failure pressure
p_{RW}	=	pressure limit for wrinkling
R	=	Radius
R	=	undeformed mean radius of pipe
r_c	=	Radial clearance to the wellbore [m]
r_i	=	inner radius
r_o	=	outer radius
rs	=	Residual Stress
R_α	=	Radius of the bend in the vertical plane [m]
S_i	=	$(\sigma_a + p_i)/\ \sigma_y{}^{``}$
t	=	Wall Thickness
t	=	pipe wall thickness
t'	=	minimum wall thickness of worn patch
V	=	Volume of material removed per unit of length [m3]
v_a	=	Axial velocity [m/s]
v_t	=	Tangential velocity [m/s]
w	=	Unit weight of the drill string [N/m]
w	=	Wear Percent
W	=	Wear depth as a percentage of the thickness of the casing [-]
WF	=	Experimental wear factor [Pa-1]
WF_F	=	Wear factor in field units [10-10 psi-1]
Δp	=	Pressure Differential, p_o-p_i
Δp_{actual}	=	Actual Collapse Pressure
Δp_{ec}	=	Elastic Collapse Pressure Differential
$\Delta p_{predicted}$	=	Predicted Collapse Pressure
Δp_{tc}	=	Transition Collapse Pressure Differential
$\Delta p_{tc,o}$	=	Transition Collapse Pressure Differential of Neutral Axial Loading Δp_{yc}
Δp_{yM}	=	von Mises Yield Collapse Pressure Differential

Δp_{yT}	=	Tresca Yield Collapse Pressure Differential
$\Delta p_{yTamano}$	=	Tamano Yield Collapse

Greek

α_1	=	Inclination in survey point 1 [rad]
α_2	=	Inclination in survey point 2 [rad]
α_i	=	Inclination build rate [rad/m]
α_ϕ	=	Azimuth build rate [rad/m]
β	=	Buckling mode factor, sinusoidal: 4, helical: 8 [-]
θ	=	Absolute change in direction (Dog leg angle)[rad]
λ	=	Collapse Mode Characteristic $\Delta p_{yc}/\Delta p_{ec}$
μ	=	Friction factor [-]
ξ	=	$1/(D_{av}/t_{av}-1)$
σ_a	=	Axial Load
σ_c	=	Collapse Stress, Δp_{tc} D/2t
σ_e	=	Equivalent Yield Strength
σ_{eff}	=	Effective Axial Load
σ_θ	=	hoop / tangential stress
σ_r	=	radial stress
σ_{uts}	=	ultimate tensile strength (engineering stress)
σ_y	=	yield stress
σ_z	=	axial stress
σ_y	=	Yield Strength
σ_y'	=	Derated Yield Strength, $\sigma_y k_y$ $(1-H_y)$
φ	=	Frictional velocity angle [-]
ϕ_1	=	Azimuth in survey point 1 [rad]
ϕ_2	=	Azimuth in survey point 2 [rad]
$\bar{\alpha}$	=	Average inclination between survey points [rad]
ν	=	Poisson's Ratio

Abbreviations

AFE	=	Authority for expenditures (budget)
AFE	=	Annular Fluid Expansion
ALARP	=	As low as reasonably possible
ALE	=	Asset life extension
API	=	American Petroleum Institute
ART	=	Advanced Rig Technology
AUVSI	=	Association for Unmanned Vehicle Systems International
Avg	=	Average
BHFP	=	Bottom Flowing Pressure
CBL	=	Cement Bond Log
Cmt	=	Cement
Capex	=	Capital expenditure (the money a company spends to buy, maintain, or improve its fixed assets)
COV	=	Coefficient of Variance

CRS	=	Cold rotary straightened
CRS	=	Cold Rotary Straightened
DF	=	Design Factor
DHSV	=	Downhole safety valve
DSA	=	Drilling Systems Automation
DWM	=	Digital Well Management
FEA	=	Finite Element Analysis
FG	=	Fracture gradient
FMECA	=	Failure-mode, effects and criticality analysis
HC	=	High Collapse
HRS	=	Hot Rotary Straightened
HSI	=	Human Systems Integration
IADC ART	=	International Association of Drilling Contractors - Advanced Rig Technology
ILS	=	Industry Leading Software
ISO	=	International Standardization Organization
K&T	=	Klever and Tamano
KPI	=	Key Performance Indicator
LCWIM	=	Life Cycle Well Integrity (software) Model
LOA	=	Level of Automation
LPP	=	Low Pressure Production
MAASP	=	Maximum allowable annulus surface pressure
MAOP	=	Maximum allowable operating pressure
MD	=	Measured Depth
MPD	=	Managed pressure drilling
N/A	=	Not Applicable
NOROG	=	Norsk olje og gass
NPT	=	Non-Productive Time
NTNU	=	Norwegian University of Science and Technology
OBM	=	Oil Based Mud
OCTG	=	Oil Country Tubular Goods
OD	=	Outer Diameter
OPC Found.	=	Open Connectivity Foundation
OPC UA	=	Open connectivity unified architecture
Opex	=	Operating expenditure (ongoing cost for running the business)
P&A	=	Plug and abandonment
PBE	=	Primary barrier envelope
PBR	=	Polished bore receptacle
PDF	=	Probability Density Function
PID	=	Proportional Integral Derivative
PMIT	=	Platform Multi-finger Imaging Tool
ppf	=	Pounds per Foot
psi	=	Pounds per Square Inch
Q&T	=	Quenched and Tempered
RBD	=	Reliability Based Design

RTD	=	Real time data
SBE	=	Secondary barrier envelope
SC5	=	Steering Committee 5 with API/ISO
SCP	=	Sustained casing pressure
SPE	=	Society of Petroleum Engineers
Std	=	Standard Deviation
SwRI	=	Southwest Research Institute
T	=	Tresca
T&D	=	Torque and drag
TD	=	Total depth
TH	=	Tubing hanger
TR	=	Technical Report
TVD	=	True Vertical Depth
ULS	=	Ultimate Limit Strength
USIT	=	Ultrasonic Imager Tool
VME	=	von Mises
WBM	=	Water Based Mud
WDS	=	Along with Working Stress Design
WHP	=	Wellhead pressure
WIMS	=	Well integrity management system
WIRA	=	Well integrity risk assessment
WOB	=	Weight on bit
WOS	=	Well Operative System

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1 Introduction

The techniques to recover oil and gas onshore and offshore are essentially the same. These techniques have been refined and improved over the years, but the workflows and processes from planning through construction to final plugging of wells is still human-oriented. Project teams scoped to plan construction or maintenance of wells often read and produce texts which then is shared with other disciplines vital to achieve the project objective. Examples of such disciplines are contract management group, logistics, rig crew and the organizations management who approves cost and risk. The principle in the described workflow has not changed since oil and gas became big business. The transition from pencil and paper to computers introduced electronic messages and engineering software for modelling operational limits. But the workflow has in effect the same information bottleneck. The transition from paper / text to a fully digitalized process is called “Digital Well Management” DWM in this thesis. A new important feature with DWM is the focus shift to the entire value chain of operators. Moving from discipline to value chain KPIs can bring substantial revenue and reduced cost and risk.

The product of the PhD is a framework for a software planned to automate the mentioned workflow including automated well planning, well intervention and well integrity. The framework is designed to produce a digital and readable program. It is designed so experienced engineers can easily operate it, i.e. no programming abilities are required. Once complete, it is planned to be an application controlling 3rd party. i.e. the same calculations as performed in well planning today. It is also planned to enable information management where all disciplines automatically find required information and automate administrative tasks. These three objectives are part of the DWM process. The 20% of the framework is programmed. The essence in this PhD research is therefore a theoretical method to achieve the three listed objectives. The research builds on more than 20 years of industry experience in roles from early planning (Front End Engineering Design – FEED), roles in onshore and offshore drilling, completion and intervention operations, contract development and strategy for said disciplines and as a manager of a Well Integrity group. The method described for the framework of the software in this thesis builds on this experience to achieve the listed goals. However, further programming and testing may reveal better ways to achieve these goals than the framework described in this Thesis.

Imagine a situation where the work with wells were as modern and intuitive as your phone and your social media apps. E.g. working with a software using AI techniques using relevant experiences as a fundament of the planning and automated verification of compliance with governing documentation is taken for granted. Over the last decades, downhole technology and technical solutions for hydrocarbon recovery have developed a lot, while the tools for supporting planning and construction of wells have not seen any significant change.

In the wake of declining and low oil price, many actors in the industry conducted studies to find new and more cost-effective operations. This initiated the wave of digitalization where planning and working smarter was identified as a significant potential for cost saving. Comparable capital-intensive industries such as aviation and automotive have upgraded their business and workflows with modern digital technologies.

The processes of planning activities like new wells, intervention, slot recovery, full field developments, etc. are facing considerable changes over the next decade. There are already several initiatives available in the marked, where some of the engineering is less dependent on human interaction. Over time, the need for human intervention to drive the engineering and planning cycles will be gradually replaced by intelligent software planning and following up operation automatically.

The main delivery of the conducted research is a new framework for improving workflows and automation of planning and construction of wells. Conferring with numerous colleagues employed with major operators have confirmed the need for a new generation software to support the planning process and that there are no current products on the market at the level discussed in this thesis. The investigations indicate that improved planning and accuracy in operations may potentially save more than 10% of effective operating time and up to 30% of the nonproductive time. Automation of planning and engineering during construction may also reduce manhours through automated integrity analysis and risk assessment, automated digital programs and procedures, and automation of administrative routines. Pinpointing saving potential from these elements is difficult but is likely to be considerable for the larger operators and service companies.

1.1 Background

After years of experience in various roles in the industry, the PhD initiated to work on a number of insights and realizations, some of which are:

- The industry needs a proper framework for digitalization and improved work processes
- Experience handling relies too much on people
- Engineering models and software have a clear potential for improvement

Today, planning processes are too manual and people dependent. Software for planning and follow-up of operations are supported by applications which is centered around engineering calculations. Each of the engineering models can be described as “calculators”, where the user carefully select input, feed this through to the “calculator”, which in turn provide an answer in terms of plots and tables for the user to evaluate and process. Most of the available software on the market are “closed” which prevents understanding of the underlying presumptions which again is part of the resulting safety factors. This does not promote in-depth understanding of the simulated integrity of the well construction. Consequently, the engineered results from “closed” models are often not challenged.

Engineers and projects should have the tools and capacity to evaluate the calculated results and identify areas where it is possible to save environmental and financial cost without compromising the level of safety. Parts of the conducted research was to evaluate and analyze the quality of the engineering calculations, models, and practices. The background was to understand the complexity in automating the engineering. Other important factors for selecting the right calculation for each model to were identify the saving potential, pin-pointing accuracy and understand the safety factors to establish a sustainable model. Some of the industry standard engineering calculations were found to be obsolete because more recently developed calculations provide more flexibility, which can materialize in considerable environmental and cost savings. Third and last analysis consider where the current workflow is good and where a new software can bring improvements.

Experience handling in the oil industry depends on the individual humans involved in projects. Experiences typically exist in different systems ranging from large databases to plain text-based formats. Common for all systems is the user threshold for accessing them to apply them in next operations. This leads to duplicate and overlapping experiences and a high risk for repeating failures. Engineers are often pressed with time and using experience systems where extracting information is not straight forward often contribute to hamper experience transfer. Thus, it is especially difficult to learn from other projects, i.e. experience transfer between teams. This topic was researched and concluded a significant saving potential. In a digital format readable for man and machine, planning software may automatically filter and make use of learning across projects in planning and future operations.

Another significant driver behind this PhD is available new technology. AI techniques, for instance, seems promising to improve planning and construction of wells. I strongly believe AI may significantly improve the processes in terms of how engineering models are run.

Possible improvements across all phases[1] were examined through this research. With personal industry experience from early planning through production integrity support to final plugging of wells both on and offshore, the research was conducted with a holistic view on the core elements in the value chain of operators. The goals of the research can be described as:

- Optimal work processes in all phases
- Optimal project deliveries[2]
- Cost risk reduction

Based on my experience from software for all roles in a Wells team, one perspective was to evaluate format and scope for a new software. Rigs with automated equipment are already outperforming traditional rigs in the initial field trials. However, currently no software supports engineering and development of digital plans. This is the ultimate goal of this thesis. As part of the work, improvement goals have been placed in four categories:

- Saving time, effort, environment and cost – in all phases
- Work process - enhanced support
- Tools / software tools and methods applied to achieve improvements
- Engineering

Table 1-1 exemplifies and details these categories of improvements.

Table 1-1 - Discussed improvements of well planning

	Potential improvement	Category	Comment
1	Save time planning	Save	Today, planning an offshore well takes between 4000 to 6000 manhours. The model can ultimately reduce with about 90%. Initial saving with no digital experience added, is estimated to approx. 50%.

[1] Phases in this thesis relates to planning, construction, production / intervention / integrity and final plugging of wells

[2] Planning, constructing, producing and maintenance of wells and reservoir

	Potential improvement	Category	Comment
2	Save operational time	Save	Investigations of industry NPT and effectiveness of the remaining operational time, indicates a potential saving of 30% NPT and 10% of the effective operational time.
3	Automated admin	Save	Investigations show that operators workforce spend about 70% of their time on administration. Saved time can be used on other pressing tasks
4	Compartmentalization minimized	Work process, save	KPI and conflicting interests across disciplines prolongs and complicate both planning and operations. Lack of understanding across disciplines is a significant cost for operators
5	Digital journal of the history and state of individual wells	Work process, save	Planning an operation in existing well construction requires careful investigation of historical events. Today, this is a manual job, while the model can read and plan using historical data. Engineering calculations run continuously and report integrity (real time) – through the life cycle of wells
6	Focus: more available time for planning and operations	Work process	Quality in planning and operations can be improved with less administrative tasks. Engineers can go deeper into engineering, experience, new methods, etc.
7	No programming abilities required	Work process	Working the model should be no more advanced than writing standard drilling / activity reports. Current knowledge and level of computer skill set of Wells personnel should be adequate.
8	Role of personnel	Work process	As with pilots: still flying, but in an observation and verification role (reducing manual handling significantly)
9	Focused on the core of operators' value chain	Work process	KPI set per discipline can conflict with the optimal global delivery / value chain
10	Digital contracts	Tool, Work process,	Contracts on a format readable for man and machine can contribute to automate engineering and administration
11	Digital standards / gov doc	Work process, tool	Standards and Governing documentation on a format readable for man and machine can ensure (automated) compliancy – planning and operations
12	Dynamic planning model and Management of Change	Work process, tool	Planning to be flexible according to set objective, consider contingencies and handle changes during operations.
13	Integrity <=> well control	Work process, tool	Well Control or "operational well integrity" can be fully automated.
14	Interface – modern and intuitive	Work process, tool	Apply modern techniques and designs from gaming and social media to upgrade existing interfaces
16	Digital programs and procedures	Tool	Activity programs and procedures on a format readable for man and machine can contribute to automate engineering, administration and rig equipment

	Potential improvement	Category	Comment
17	Engineering models modernized	Tool	More tailor-made constructions. Better insight in actual safety factors
	Features:		
18	Read Subsurface data	Tool	A routine in the designed framework read and provide the latest subsurface data – engineering (integrity) is re-calculated automatically once key data is changed (formation pressures, WHP, WHT, fluid densities, etc.)
19	Digital experience	Tool	Experience is a key element for quality of plans. On a format readable for man and machine, experience can be automatically embedded, by the designed framework, where relevant. A digital experience is identical to the text-based experiences written today, only in the reporting language format
20	Reporting language	Tool	The language format is identical with current drilling reports, which enables new and experienced engineer to manually manipulate programs, procedures or add experience with minimal training.
21	Model performance, industry experience	Model info	Applying the model on subsurface data with no added experience will produce a digital program which needs user intervention. A "full" set of industry experiences can enable programs and procedures requiring little or no user intervention – only verification.
22	With & without automated rig equipment	Model info	All operations use programs and procedures. For operations with automated equipment, todays operations with automated equipment need a manual change from text based to digital programs will not be required with a fully functional copy of the model
23	Phase & support (least in well intervention)	Model info	Identified challenges and required mitigations point to no hard challenges in drilling and completion, but well intervention may need some manual intervention to establish good plans and programs. The number of tools and varying objectives in each operation will require a substantial amount of experiences added for non-standard[3] operations to be planned fully automated.
24	Also for service companies	Model info	The model is to be a mutual arena with service companies, where they get access to part according to their role. Knowledge about details in operation can be provided automatically. Can go both ways, where vendor get info and provide their procedures and other information to involved operator.
	Engineering models		

[3] Solution proposed: break down each scope and then put them together in series and sequence, e.g. drifting, broaching, pull DHSV, logging, perforation, change GLV, etc. until the complete scope / objective is met. This needs more research and testing before intervention can be fully automated.

	Potential improvement	Category	Comment
25	Automated analysis of well integrity status with automated risk assessment	Engineering	Today, well integrity is a manual process with most operators. Any changes from design basis, e.g. formation pressure (reservoir or overburden) require a new tubular design.
26	Automated casing wear	Engineering	Tubular wear is causing many critical integrity incidents world-wide. In many cases of discrepancy between actual and predicted wear, the issue is faulty use of software. Automating wear prediction reduce potential for error and engineering time consumption
27	Calculator for maximum pressure test of casing to avoid cement sheath failure	Engineering	Cement is not as strong in tension as in compression, i.e. there is a limit (pressure test of pipe) before the cement cracks
28	Tubular design with the most accurate algorithms in the industry standards	Engineering	Burst: Barlow (industry standard) is not recommended => use von Mises and Lamé Collapse: API (industry standard) does not consider manufacturing process / pipe quality, which provide an unknown safety margin before adding design factor => use Klever & Tamano
29	2D model for fracturing design	Engineering	Basic insight in fracturing, i.e. a start of automated calculations for design and job execution
30	Application for drilling optimization	Engineering	Faster and more effective process by using optimal drilling parameters (RPM, WOB, etc.)
31	Application for buckling	Engineering	Application for buckling developed based on the latest input from available literature
32	Temperature model for producing wells	Engineering	Prototype application for modeling temperature in producing wells. Also prototype for injectors exists
33	Model for annular fluid expansion (AFE) and Well Head (WH) growth	Engineering	Prototype application for modeling AFE and a prototype for WH growth were developed

As indicated by Table 1-1, the conducted research covers all disciplines of a Wells team. During the process of evaluating the different engineering calculations for each modeling process (well paths, torque and drag, hydraulic, tubular design, etc.), it was decided to narrow down focus. Development of more accurate engineering is a constant process in all areas of well construction. However, for standard well designs[4], progress in engineering with possible impact to cost and environment was identified as most significant in the area of tubular design. The other standard engineering models provided with the modelling suites[5] on the market suffice for standard well designs. Therefore, efforts with engineering were concentrated around tubular design. As stated initially in this chapter, the main delivery of this research is a framework supporting improved workflow where engineering and program development is automated. The framework is designed to be independent of type of engineering calculation to facilitate new applications to be easily fitted. Thus, parts of the PhD investigate some crucial topics of software development:

[4] Typically, non-HPHT and not deeper than ~5 000 m TVD (16 400 ft TVD).
[5] Presuming these are equivalent or better than the calculations as given in the relevant API/ISO standards.

- Software development[6]: Use cases, specification(s), system architecture, and prototyping
- Investigating market situation and need
- Human – machine interaction

Communication may be added to the list above. A lifecycle digital model is a comprehensive topic spanning several aspects as overviewed by Figure 1-1. There are many lessons learned from presenting the work in conferences and informal talks with operational personnel. How people understand the topic and what makes a positive, negative or curious reaction depends on how it is presented and the audiences' background.

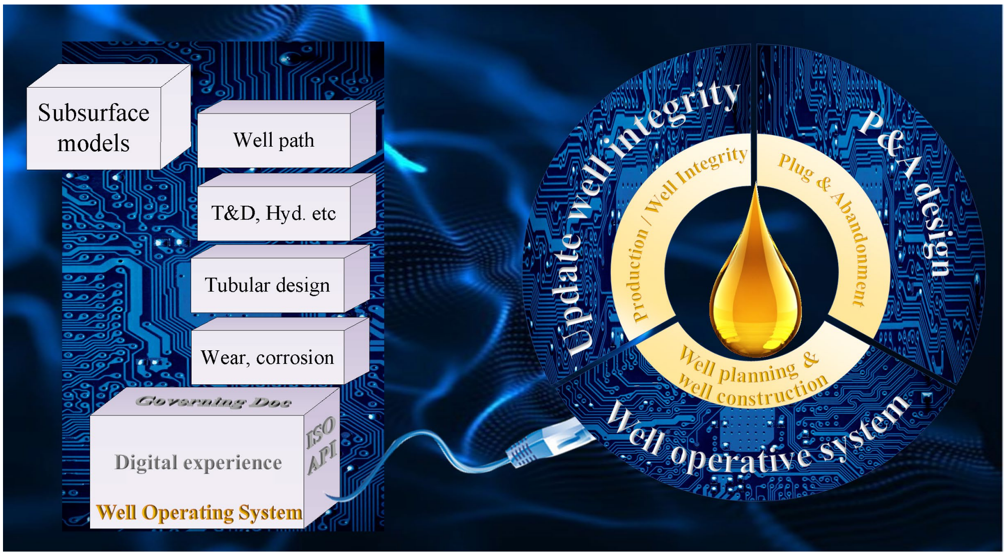

Figure 1-1 – WOS enabling a fully digital platform – Life Well Integrity Model.

Figure 1-1 illustrates a concept where all data and applications are connected and work together through the life cycle of each well. The core of the model enables data extraction from initial subsurface data and communication to the different engineering applications. An important additional feature is aggregation and use of digital experiences which enable the user to promote preferred methods and the handling of events. Thus, planning engineers can effectively use the experiences as a guide when establishing the final engineering, digital program and procedures. Engineering calculation can be thought of as software components that can be fitted as required by the owner. In principle, any engineering calculation can be fitted and work within the concept to form a digital well management process.

The impact of the outlined digital well management process can be compared with developments of other industries, e.g. the aviation industry. The jobs of pilots are highly automated. However, the pilots are still responsible when life and safety are at stake, not computers and software. Similarly, in the oil and gas industry, experts will be required to verify and accept plans, programs and operations. The goals of digitalization and automation are safer and more cost-effective operations progressing production of hydrocarbons with smarter

[6] The model comprises several applications at a prototype stage. About 20% of the main application runs in writing moment.

solutions. Hopefully, this may also lead to a reduced environmental footprint. For oil and gas will still be a base commodity for the civilized world, products and items for years to come. Increased living standards in highly populated areas, e.g. Africa, south America, and Asia, is also likely to raise hydrocarbon consumption over the coming years.
Comparable industries such as automotive and aviation have established smarter processes in manufacturing using tools of the 4th industrial revolution. In many ways, the oil and gas industry have taken a back seat in this development. However, this seems about to change. I believe it is just a matter of time before operations with automated equipment becomes standard for rigs working on high cost developments. In my experience, however, these operations still rely on manual planning performed in text-based systems for programs, procedures and experience. My goal is to contribute to a digital well management process as a sustainable work process using modern computer science and technology.

Note that in some examples this thesis uses field units for practical reasons.

1.2 Some definitions

Some fundamental terms and concepts need clarification. Digitization vs digitization and an overview of levels of support in planning.

1.2.1 Digitization and digitalization

There are published many definitions of the two terms digitization and digitalization (Bloomberg, 2018). Below follows a frequently used definition.

Digitization is the process of converting information such as text, pictures, or sound from paper or another analog format into a digital one. Digitization is the process of digital enablement.
When the digital technologies such as AI are used in business models it is called digitalization.

1.2.2 Digital excellence

Today, several software packages for well planning and operations are available on the market. However, no clear definitions of support level exist. To illustrate the current and future software situation in my view, Figure 1-2 classifies support level of planning and operation modeling software per phase through the life cycle of wells. As seen, the classification scheme defines three levels to reflect that many software providers and operators typically target and develop specific areas. However, the support level of a software package depends on the workflow and situation specific for each operator. To exemplify, a specific software package may provide *support level 3* (human-driven) in planning though it supports *level 2* in operations.

In my view, support and functionality provided by available software models are mostly "human-driven" according to Figure 1-2. Referring to industry need as depicted by Table 1-1 and Table 1-4, automated operations will be increasingly more common and the operations need a higher support level than what is available on the market today. Thus, the goal of this thesis is to strive for "digital excellence" according to Figure 1-2. This means to provide a fully digital process where software executes planning, keeps track of operational history, experience and integrity in all activities through the life cycle of wells.
The DWM strives for "digital excellence.

1.2.3 Automation, digitalization and optimization

Clarification of central terms and their connection

Table 1-2 - Definition of central terms.

#	Term	Definitions	Comment
A	automation	Independent of human manipulation	In the context of the conducted research, this means a) well planning with development of a digital program and administrative tasks (invoicing, logistics, etc.) b) rigs with equipment fully controlled by software
B	digitalization	Format usable for software for planning and modelling of integrity.	All info related to wells are available (input to engineering and integrity) linked to relevant engineering and available for planning through the lifecycle of the well. Integrate with software for operations with automated rig equipment
C	optimization	Best practice / method, highest efficiency	Least use of resources and time to reach objective.

Table 1-3 - Differences and connections of central terms.

Terms	Automation	Digitalization	Optimization
Automation	-	Need digitalized info to enable automation	Automation is optimization of time and effort by humans. It also includes digital experience, i.e. smartest way to objective.
Digitalization	Need digitalized info to enable automation	-	A digital process is needed to enable automation which is an optimization over current process
Optimization	Automation is optimization of time and effort by humans. It also includes digital experience, i.e. smartest way to accomplish objective.	A digital process is needed to enable automation which is an optimization over current process	-

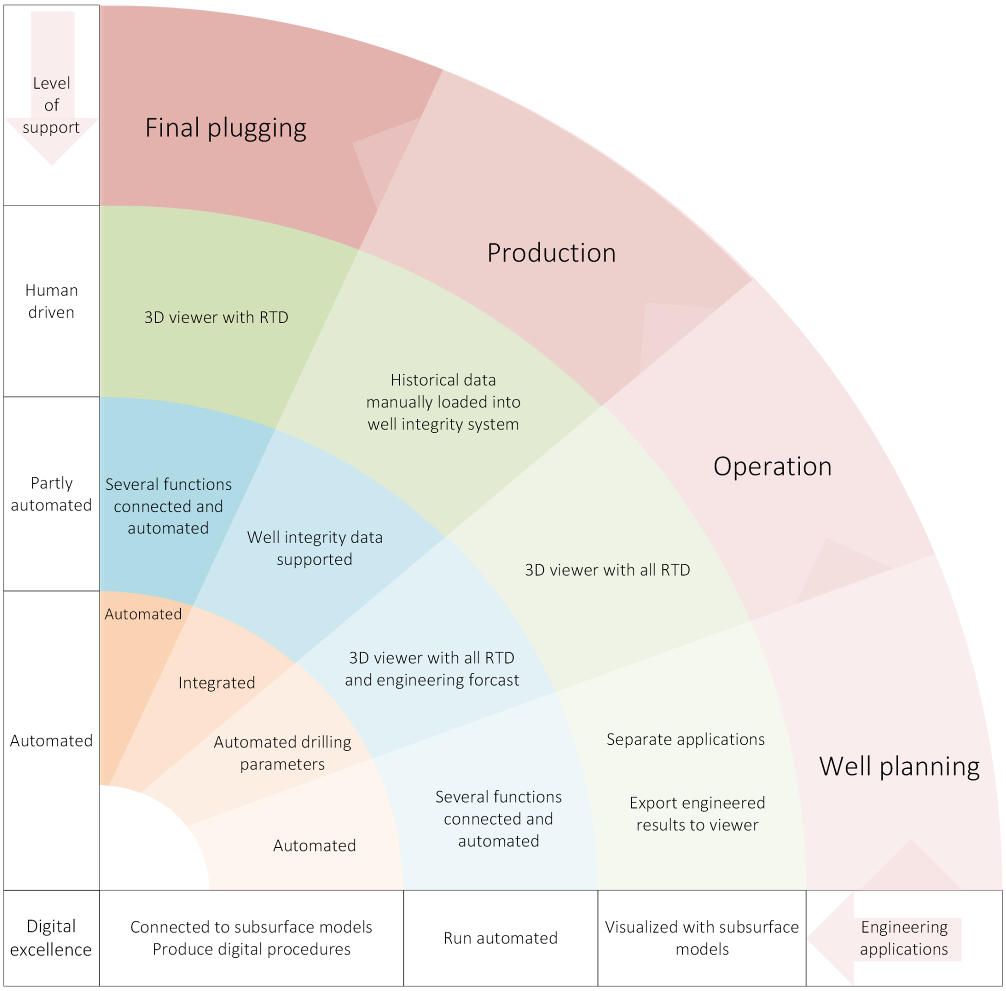

Figure 1-2 - Levels of software support.

1.3 Development of software for planning wells

The software support for planning wells has not developed much over the last decades. In turn, this means that the planning process has not changed much.

1.3.1 Brief history

One of the first software packages on the marked was produced by Maurer engineering, see Figure 1-3. It seems difficult to pinpoint the exact time when the Galaxy software suite was launched. However, a “casing design manual” from 1996 has been acquired, which indicates the software suite to be older.

Figure 1-3 - Galaxy, one of the first well planning software packages on the market.

In early 2000s, 3D viewers displaying data from different disciplines emerged and impacted the planning process significantly. Examples of 3D viewers in planning tools on the market can be seen in Figure 1-4.

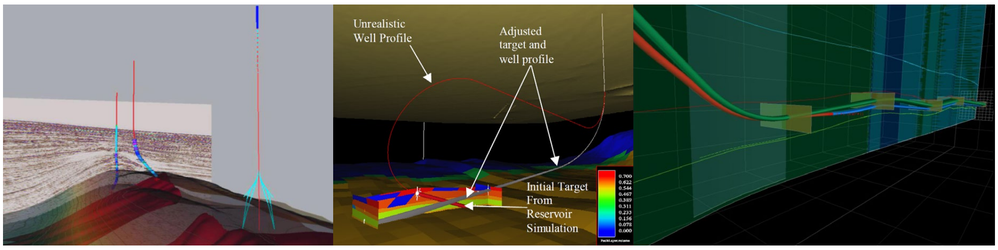

Figure 1-4 - 3D visualization tools
Left: Halliburton (Pathy, 2016), middle: Roxar (Cayeux, 2001) and right: Paradigm (Akbar, 2014).

The 3D viewers integrate geoscience, subsurface data and trajectories, allowing the users to see the results from shifting well paths and targets in real time. These 3D visualization tools have contributed to reduce the number of iterations and planning time with their provision of graphical representation. The 3D visualization tools also support real time data and play an important role during operations. Typically, all disciplines are present to analyze and verify how Real Time Data (RTD) materialize in relation to the planned parameters. This process is often referred to as "Integrated Operations" (IO). IO is a powerful tool but for less experienced teams, there are dangers such as landing out in the wrong formation should the depth change be inaccurate.

Note that there is no 3D viewer which offers a full planning interface. Their purpose is simply to visualize data. For planning wells and operations, anything made in a 3D visualization software needs to be established again in another model. From one perspective, it could be said that the 3D viewers did not change the planning workflow or process which remained equally people dependent. It only reduced duration of the planning. For operation on the other hand, IO has been an important tool for especially operation involving geosteering.

1.3.2 Future well planning

There are several drivers of considerable importance for improving the well planning process. One of the best documented is found with a road map made to align rig automation into common terminologies and standards (de Wardt, 2016). It was made by industry professionals affiliated with SPE DSATS, IADC ART, and other organizations. Table 1-4 summarizes the 2025 vision for support of automated rigs (de Wardt, 2016a).

Table 1-4 - 2025 vision: automated well planning supporting rig with automated equipment.

"System Needs" or "Whats"			System Architecture	Communications	Sensor instrumentation	Drilling machines	Control systems	Simulations & Modelling	Human factors	Certification & Standards
"2025 Vision"	**Epics**	**User Story - "As a person I want/can/am able to/need to/ do x so that some reason"**								
"**well plans are uploaded into an interoperable drilling system that automatically delivers a quality wellbore into the best geological location,** installs the casing and zonal isolation according to plan, installs the completion system according to the program and updates remote operators and experts in real time to changes in the situation, and identifies potential paths for success for the experts to input control. Deep, complex wells will rely more heavily centers of excellence onsite and remote to provide real time and near real time updates. Routine multiple wells will rely on remote operations centers to monitor progress and react to alarms."	well plans are uploaded into an interoperable drilling system	As a well engineer I am able to upload a baseline well plan to be executed to drilling system	●	●					■	●
		As a reservoir engineer I am able to visualize and download the well plan to export into other software								
		etc...								
	System automatically delivers a quality wellbore into the best geological location	As a Driller I want to automatically Trip in so that I SAFELY reach planned depth within minimum time	■	■			●	▲	■	▲
		As a Driller I can automatically drill a Stand so that the Slip to Slip time is minimal	■	■	■	●	●	●		
		As geologist I need a quality wellbore so that logging data are good quality								
		As a reservoir engineer I want to maximize the trajectory inside the target reservoirs to maximize reservoir exposure								
		etc...								
	System automatically installs the casing and zonal isolation according to plan									
	System automatically installs the completion system according to the program									

● Strong Interrelationship
■ Medium Interrelationship
▲ Weak Interrelationship

Compared to the 2025 vision in Table 1-4, this research has expanded the scope for support. As indicated in Figure 1-2, the DWM process runs life cycle and therefore include support for the production and P&A phases.

1.4 Motivation and scope of the DWM model

The main application discussed in this thesis is the "Well Operative System" (WOS). It moves data and parameters when and where appropriate. This process is called "Digital Well Management" (DWM) and the platform has the working title "Life Cycle Well Integrity Model" (LCWIM). The origin of the name is two-fold: life cycle relates to the aspect of the model running and performing active support from planning to final plugging, and that the involved engineering calculation are fundamental to the integrity of the well and the field it is in.

1.4.1 Why "Life Cycle"?

Below, three reasons are picked out to explain why the scope of software support is set to span the entire life cycle of wells.

1) Integrity support (information management)
2) Different KPI – avoid suboptimal compartmentalization
3) Revisions, proprietary systems and ownership

The "work process" or workflow is a 4th important reason discussed separately below, see section 1.4.2.

1.4.1.1 Integrity support (information management)

Figure 1-5 lists an overview of integrity issues of wells. Literature on integrity covers risk and safety matters, but not so much the fact that these wells are not producing the full potential of the recoverable reserves. In some cases, this results in drilling new wells, which is both an environmental and financial cost. As seen in Figure 1-5, tubulars and tubular design is the area of most frequent failures. Software support of all aspects in well integrity is the ultimate approach to systematic reduction in failures. Well integrity software on the market today typically focus on reporting parameters and values such as annular pressures, manually edited integrity statements, manually made risk assessments, manually made barrier diagrams (made in Visio, e.g. templates from Wellbarrier) and other analysis by integrity personnel. The engineering calculations such as tubular design is fundamental for the integrity of a well, yet no well integrity software consider this topic. For most operators, the tubular design is performed only during initial planning.

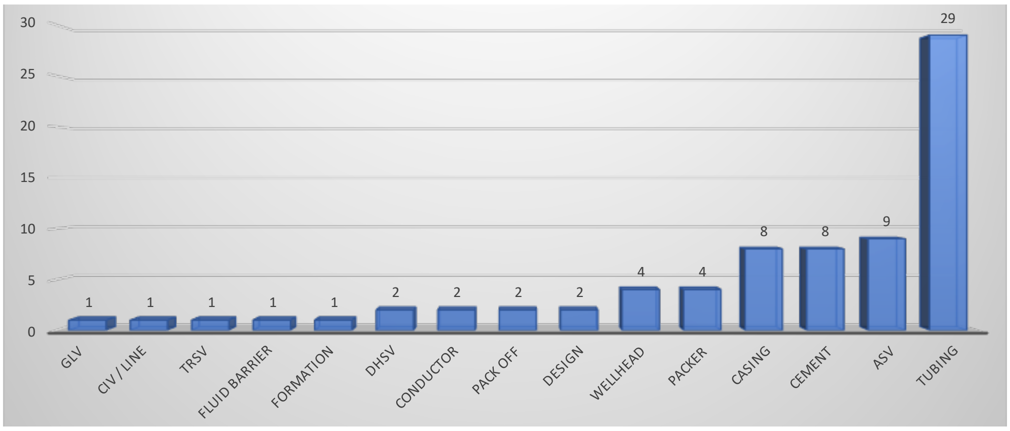

Figure 1-5 – Well Integrity issues for 75 of 406 investigated wells (Vignes, 2008).

Some oil and gas professionals feel the numbers in Figure 1-5 signifies that the industry should put more focus on integrity modeling and tubular design. 18% of the wells investigated were shut, which represents a safety issue, a significant loss in revenue and a potential for considerable expense.

The DWM process is designed to extract key data from planning, operations and to update the well integrity model with tubular design calculations continuously. Well integrity is a relatively young discipline with a lot of potential to grow. New technology often leads to new processes. All listed manual processes are designed to be automated by the WOS in the DWM process. Well integrity is discussed further in a separate section where learning from the ongoing work processes is the main topic, see relevant section in chapter 2.

Today, the definition of well integrity contains 3 basics elements, ref NORSOK D-010 rev 4. This thesis proposes "information management" as a 4th element. Keeping essential integrity data, knowing where to get it and applying it where required is part of basic well integrity. Many operators struggle with data, having too many overlapping systems and/or losing historical data. This is a safety issue not discussed or adhered to according to the proportion of the challenge it can be.

1.4.1.2 Different KPI – compartmentalization

Key Performance Indicators (KPI) are the key deliveries of each discipline. Often, management measure actual deliveries towards set goals for each group or discipline. This research considers this approach suboptimal. The main delivery for an operator is plans matured into producing wells, which is typically reflected in their value chain – see Figure 1-6. Splitting the main delivery into sub-deliveries has pros and cons. Typically, different disciplines would have conflicting interests which is often the case for suboptimal solutions from the perspective of the value chain. No department want to fall short of their target deliveries and strong personalities leverage their case. Most times, cases like this are solved by evaluations of cost and revenue. These evaluations would be subjected to the knowledge and experience of the involved personnel. The LCWIM offers a framework for planning supported by company experience, and governing documentation. The company best practice for well construction and hydrocarbon recovery, i.e. the core elements in the value chain, can be automatically protected and conflicting interests between disciplines reduced to a minimum.

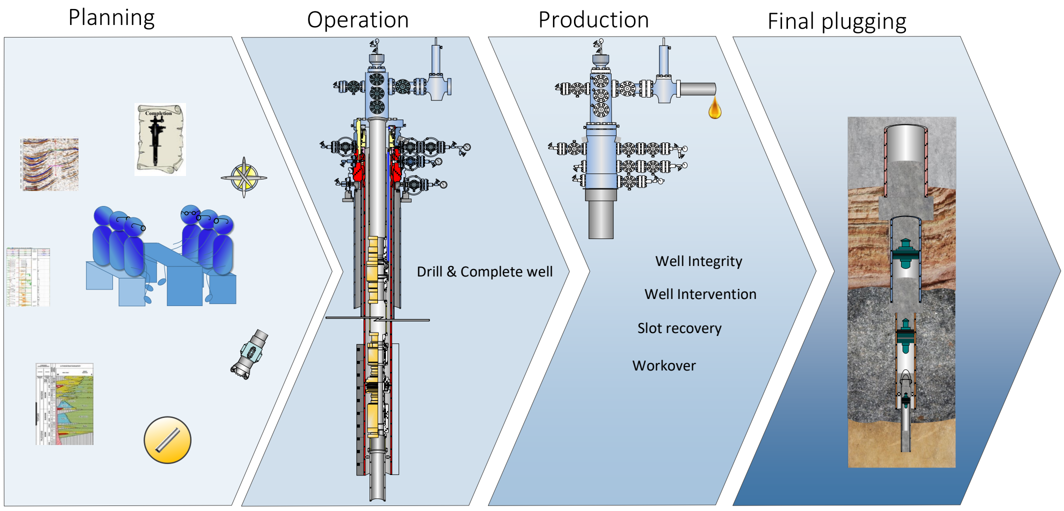

Figure 1-6 - Core of operators' value chain.

Each of the phases have a responsible team or discipline. For many operators there is a distinct separation between these disciplines and their goals. This compartmentalization has been a source of disruption for the needs of the wells or projects in many occasions. Setting the operators' best interest in focus by removing some of the walls between disciplines can bring significant value. Only when the value chain operates with a fully digital work process, the alternatives to the KPI based model will be possible.

1.4.1.3 Revisions, proprietary systems and ownership

Following the philosophy of the previous section, development of software will be driven by different needs of different departments. Exemplifying this issue using a theoretical scenario, e.g. activities in support of rig automation. With focus on operations and drilling in particular, developing software specialized for supporting automated drilling operations and later adding other activities such as logistics, invoicing would change the scope significantly. This means the new team would have to work the entrails of the initial software to fit the new additions. The same will apply for developing and adding new applications for other phases such as permanent plugging. Precising again that the case above is a theoretical example for the sole purpose to visualize the challenges with multiple interests, actors and adversaries.

An example with some relevance was the process of developing the Sony music app and player. Due to conflicting interest between departments, it was delayed, and Apple took the majority of the market because effective competition was established too late. The structure in Apple was ideal for developing products with its' small research department. A large company with a large developing team can sometimes be less beneficial, it typically also brings conflicting interests between strong personalities. Should a software be developed by a major company, it is often to promote their products, values and often made in a proprietary format. This means that other companies are not able to further develop or link other apps to the software, and the operator has to stay with the one initial vendor. These perspectives are an extension of the software and services in the industry today, in the view of this Thesis.

1.4.2 Work process and workflow

In my experience, engineers in planning and operations are working manually using text-based documents. Comparable industries have modernized their workflow and improved manufacturing efficiency and quality. Establishing a fully digital workflow has the same potential for the oil and gas industry as for most of the comparable industries. Figure 1-7 illustrates an analysis of the workload for engineers according to my experience. The work can be divided in two groups: engineering and administration. Engineering can be divided into modeling and method selection. Modelling is very much tied to the engineering platforms whereas method selection is often driven by experience with given parameters such as formation properties, etc.

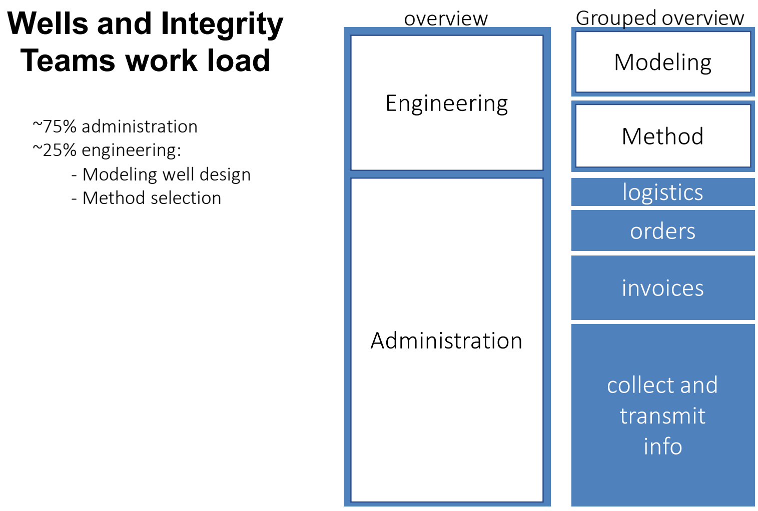

Figure 1-7 - Generic overview of workload for Wells Teams.

The distribution between engineering and administration has been discussed with several disciplines in Wells Teams with different operators. Given the grouping in Figure 1-7, consensus is that 75% administration is likely to be on the low side. Automating administrative tasks can therefore free up considerable resources which can e.g. focus on engineering. Figure 1-8 illustrates possible change in workload with a digital workflow. Administration and engineering can be automated, so engineers largely assume a supervisory role.

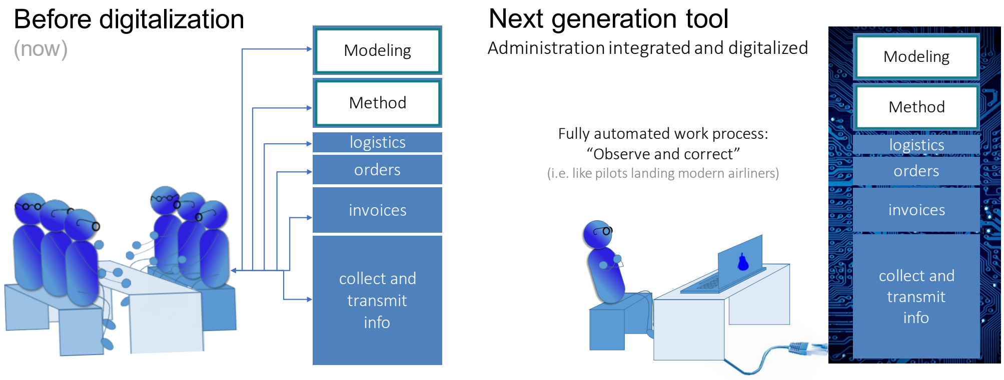

Figure 1-8 – Automation and streamlining the work processes to free up vital resources for planning.

Figure 1-8 illustrates the change from a human-oriented to a software-oriented workflow. Many in the oil and gas industry have experienced new and upgraded software to support the human role in different administrative and technical areas over the last decade. Typically, the software and workflow become more complex as requirements for added functionality, reporting and information sharing routines are accommodated into the software. Often, engineers and operative personnel are required to manually enter input and re-work the data to fulfill the added functionality. In effect, the fraction of administrative workload is increasing. As seen to the right in Figure 1-8, a fully digital model allows all added functionality to be extracted and manipulated using software only.

1.4.2.1 Impact on quality of plans

A plan is as good as the experience it builds on. The tasks in planning and operations in Figure 1-8 split engineering into modelling and method selection. Breaking down these terms brings elements important for the quality in planning.

Modelling

There are three aspects to modelling discussed here:

1) The quality of the calculation (real safety factor / black box)
2) Understanding of the calculations and their presented results
3) Operating the model (input interface, limitations, logic and adjustments)

<u>Quality of calculations</u>

It is important for engineers to fully understand the calculation methods to interpret the presented result and the contribution to well integrity in represents. Most software platforms do not show presumptions used in the calculation methods, i.e. the safety factors before adding any design factors are not clear. A way to compensate for any conflict with proprietary technology is to add more calculation methods in the same category, e.g. multiple torque and drag calculations. Comparing the results and also adding experience from similar operations can support the validity of the simulated result.

<u>Modelled results</u>

Not being able to see the details in the calculations and their presumptions prevents engineers from knowing strengths and weaknesses of models. In a way, closed modelling prevents engineers from digging into the different calculations to understand them in detail. The safety factor in the final well integrity is not well understood in closed models. Operators and

responsible engineers have to rely on experience. The latest issue of API/ISO 10400 (2018) presents rather dramatic news, disqualifying the calculation used to limit burst loads in the industry the last two centuries. Following this fact, questions are raised towards the triaxial safety factor which has been determined and set so it mates up with burst at 0 axial stress. In all the different designs performed in well construction, the calculations are not often challenged. Engineering collapse is even more revealing. The industry standard API calculations do not consider the pipe's manufacturing process and considers only pipe from the manufacturing process with the weakest performance and adds an unknown safety factor on top. In addition, the standard procedure is to add a design factor. In the end, e.g. intermediate casing in regular wells (ref. footnote #5) often end up with an effective safety factor of 35 to 40%, when the software presents the user with a safety factor of 10 – 15%.
Theory for engineering worn pipe builds on the discussed traditional calculations, which are obsolete according to the view of this Thesis.

Model interface
Most software made to model well construction is using input from other models. Where possible, the different models should be interlinked, i.e. save users for entering the same input over again. The most advanced models on the market still require quite a lot of effort from the user before they produce any meaningful results. An important quality feature for modelling software is the balance between default settings and possible adjustments to reproduce simulated conditions. A number of parameters need to be available for the user to create realistic conditions. But these should not represent a large job where they are not relevant. This said, the software on the market today is made by engineers for engineers. Glancing over to other software like games and social media, the quality and interfaces are much more developed. Making a virtual model / digital twin of a well can be made as professional and entertaining as a game.

Method selection
Method selection is often worked out based on experience. Where conditions are benign and successful operation can be repeated, the responsible engineers call for a meeting with relevant personnel and involved service providers. Where the subsurface conditions are more complex, or the conditions are new to the planning personnel, governing documentation and special advisors often help. A less used option is to search for help in "lessons learned" data bases. Experiences are often written towards single events and stored in large complex systems. A search with a common key word would often result in a huge number of results, leaving the user with a difficult and sometimes impossible task. Experience is in effect a personal and people dependent issue. This is reflected in the way method selection is carried out in the industry. A software with capacity to apply experience from across all assets and support method selection can improve operational performance and level of safety.
Risk evaluation is connected to method selection and often carried out in a similar way as method selection – through meetings with experienced personnel. Risk evaluation can also be fully automated for all operations (Brechan(1), 2018), (Brechan(3), 2018), (Brechan(5), 2018).

1.4.3 Summary of objectives

The objectives of this thesis can be summarized as follows:

1) Life cycle support including administrative tasks
2) Support all physical well activities in all phases
3) Fully automated: engineering, administration, digital programs and digital procedures
4) Program and procedure format to interlink with software for automated rig equipment

5) Fully digital processing through the life cycle
6) Automated well integrity calculations updated and running through the life cycle
7) Automated well history (enabled by the digital format)
8) Embed and activate experiences
9) Embed and activate governing documentation, standards and practices
10) Build on current work-process and improve it into a new sustainable process
11) Enable experienced personnel to utilize their capacity, i.e. no programming abilities required
12) Facilitate familiar and user-friendly software which builds on existing practice and drilling report system
13) Any suppliers of engineering calculations can be added / used
14) Open engineering: full insight in calculations to enable tracking of effective safety factors
15) Mutual arena with service companies: project, well and equipment technical information shared

2 Learning from current planning and operational processes

This section builds on experience from some operators in the areas of early field development and planning of single well development. The operative experience behind the considerations in this section ranges from well construction, intervention, integrity and plugging. The proposed improvements were identified applying a critical view of the different processes related to on and offshore activities. Table 1-1 lists some of the highlights from the conducted research. Some key points have been selected for further elaboration.

1. Developments in performance improvement work – Key Performance Indicators (KPI)
2. The learning process – capturing and applying experience
3. Operations: software support – past and future
4. Engineering applications: calculations and accuracy
   - Engineering quality
   - Engineering hours per project

2.1 Performance improvement work – KPI advances

Working smarter and better to deliver more for less cost has been an ongoing battle as old as the oil and gas industry itself. Numerus of projects and campaigns to reduce "non-productive time" (NPT) have been initiated. For most projects, the effects have been short term. Sustained learning from campaigns decreases with increasing complexity levels of the well (York, 2009). History shows NPT has stayed in an average of 10 – 15% for many decades, depending on the complexity of the project. This is based on analysis of performance for more than 450 wells (Pritchard, 2012). Despite the efforts to change methods, improve tools and other means, the NPT has remained constant over time. This means that 85 to 90% is effective time, i.e. progress is made to meet the objective of the activity. Many projects have acknowledged the importance of making the best out of this time and developed "Technical Limit[7]" projects (Marshall, 2001). The effect of these efforts has also had limited impact. The technique addresses time consumption and it is followed up as an administrative task on top of operations. Typically, the project identifies what the fastest and most effective way each activity in a well construction or well intervention operation can be done. One of the reasons for limited success is the manual reporting by humans, which are inaccurate and have limitations in use (Thonhauser, 2004).

In 2000, a software for automated operations recognition system utilizing rig sensor data to recognize drilling operations were funded. The software interprets and make accurate real time analysis of the activities. An interesting feature is the software's ability to report the activities in the same way daily drilling reports are done manually with rig projects today. The software is called ProNova though my impression is that few operators are using the software actively in operations apart from KPI measurements. By itself, the software can identify time thieves and areas of improvement. Several rig projects have changed their way of working to mitigate these and improved their performance (Duffy, 2017) (Al-Ghunaim, 2017).

One of the most significant performance improvements thus far, is reported from field trials with automated rigs. Rig automation is a technique applied where one of the main goals is to avoid failures frequently leading to NPT. The field trials reported more effective drilling with higher Rate of Penetration (ROP), less tool failures and stuck pipe incidents due to improved control over drilling parameters, but it also reveals Invisible Lost Time (ILT) (Abrahamsen, 2015) (Larsen, 2010). ILT is a term following automated rigs. Although designed for protection of personnel (much less exposure), equipment and the well the performance changed the definition of "Technical limit" for

[7] There are several different terms for this method, e.g. Shell Expro use "Drilling the Limit" (Marshall, 2001).

several activities. Many tasks were performed faster than before, giving rise to the name "invisible lost time".
As documented, an important learning is that increased involvement of computer control leads to improved HSE and performance. However, one important piece is missing. A paper pointed out 30 years ago that the cost of a well may not be the lowest even if it is done according to "Technical limit" (Marshall, 2001). The well or project has to be planned in the best and smartest way. Planning activities such as field development, well construction, intervention or P&A is performed manually with partly connected software support, i.e. humans have to select input data, process in a software model, interpret and extract result and finally spread the information in a way that ensures it is applied where relevant for the activities. Digital well planning and digital well management are terms and technology in their infancy, but they can bring significant value to the industry.
Exemplifying the saving potential from the DWM or similar process using figures from a typical Permian well produces numbers as shown in Table 2-1.

Table 2-1 - Exemplified performance of a typical Permian well.

Current:		Improved:	saved time	Improved times	
4,5	NPT (15%)	Reduce NPT with 30%	1,35	3,15	NPT
25,5	Effective time	10% more effective ops.	2,55	22,95	Effective days per well
30	Average time per well	Total saved	3,9	26,1	Average time per well

Typical time is set to 30 days per well, which may be high for some areas in the Permian. This is 12 wells per year, not allowing for rig move. Reducing the effective time with 4 days, means every rig can drill 1,8 wells extra per year. There are 400 rigs drilling in the Permian at current. With the numbers above, it means about 60 extra wells per month. The example is likely modest. The estimate yields a saving of ~13% of the total time. Note that the majority of this comes from more effective operations and not from reducing the NPT.

2.2 Learning processes

This thesis limits the meaning of "learning process" to experience, i.e. how the industry learns from mistakes and apply this learning in subsequent planning and operations. The afore mentioned road map for rig automation describes the current work process as "driven by humans" (de Wardt, 2016). Figure 2-1 shows the wheel of learning.

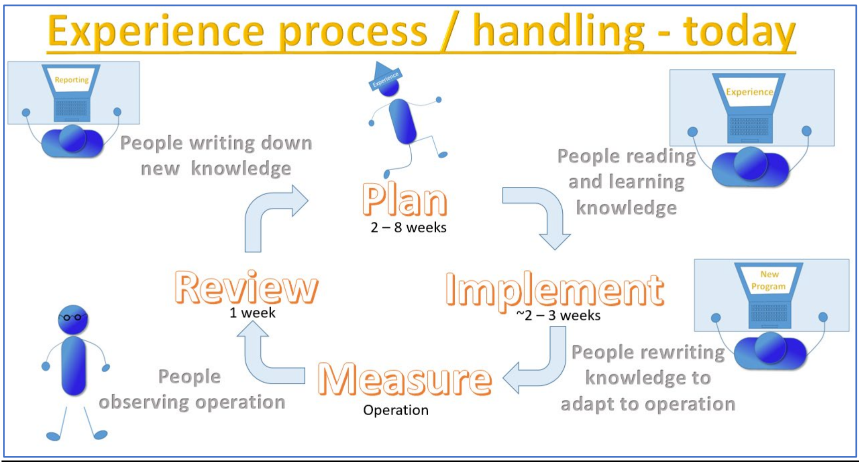

Figure 2-1 - Typical experience capturing routine – humans drive every step today.

Today, most actors in the oil industry handle experience by writing down noteworthy events in computerized systems. As illustrated in Figure 2-1, the knowledge is picked up by relevant personnel in preparation of next operation. It can therefore be argued that the wheel of experience transfer is driven by humans in every event / "corner" of the illustration in Figure 2-1.
It will vary with the workload of each project how much time is available to learn from the knowledge system. Reading experiences is prone to errors. Acquiring the right understanding of the text, recognizing the same operational pattern / event and find ways of implementing the mitigation factors are some sources of error and failure. For a database with a large quantity of text-based experience, it can be difficult to extract meaningful learning due to large quantities of search results. A computer scientist may suggest using "big data" technology on the large petroleum databases of Norwegian and British authorities to extract data. Since most "Big data" routines are not precise, and most learning must be exact to be applicable in planning and operations, it will be of good use in some areas but always needs to be verified. These solutions are offered by several actors in the market today. They represent a step forward, but the downside is the manual handling by humans. There are still requirements to the query itself, then entering input data, process the data in a software model, interpret and extract result and finally spread the information in a way that ensures it is applied where relevant for the activities. Maybe even more important is the initiative. Should the planning team "forget" to ask the experience database, the learning will not be implemented.
External text-based experience models have existed in many varieties over the last decades. Quality in planning has not changed significantly and operations still have the same range NPT. The conclusion from this research is that planning teams should not have to seek out what is relevant for their objective. As with the KPI from automated rigs shows, success is following the degree of software support replacing requirement for human-driven process. Experience should be an active part of a software and drive the planning process, see section 3.7 for details.

2.3 Organizational processes and contribution

After the Macondo accident, Professor Andrew Hopkins (Hopkins, 2012) presented interesting aspects with human nature in performance organizations working with well construction. He describes patterns how performance organizations relate to challenges. There are often a "culture of denial", which can be described by:

- It will not happen here / to us
- Dismissing failure prediction – explain indications of failure with insignificant issues
- Indications of failure are explained as "routine" and normalize the signs
- Peer thinking - disregard the weak signals / voices

It is the organization's responsibility to follow regulations and practices. Figure 2-2 lists breeches of established practice that each of them could in theory prevent the incident.

Figures

Figure 2.1 – The difference between long casing and liner: the 13⅝ in liner. 5
Figure 2.2 – First mistake, fewer barriers to gas flow. 6
Figure 3.3 – Second mistake,, fewer centralizers to evenly distribute the cement. 7
Figure 2.4 – Third mistake, a bond log was dismissed as being unnecessary. 7
Figure 2.5 – Fourth mistake, the pressure test results were misinterpreted. 8
Figure 2.6 – Fifth mistake, the mud barrier to well pressure was removed early. 9
Figure 2.7 – Sixth mistake, the blowout preventer failed to close the well. 10

Figure 2-2 - Figures in the preliminary report from the Macondo incident (Pritchard, 2011).

Figure 2-3 illustrates the current work process and the main phases. They can be thought of as separate compartments since there are separate teams handling them. The bridge between the phases and teams comprises text-based procedures, presentations and any direct communication between personnel in the different teams. The phases can be thought of as building blocks in the process, and their compartmentalization is illustrated by the concrete isolating them.

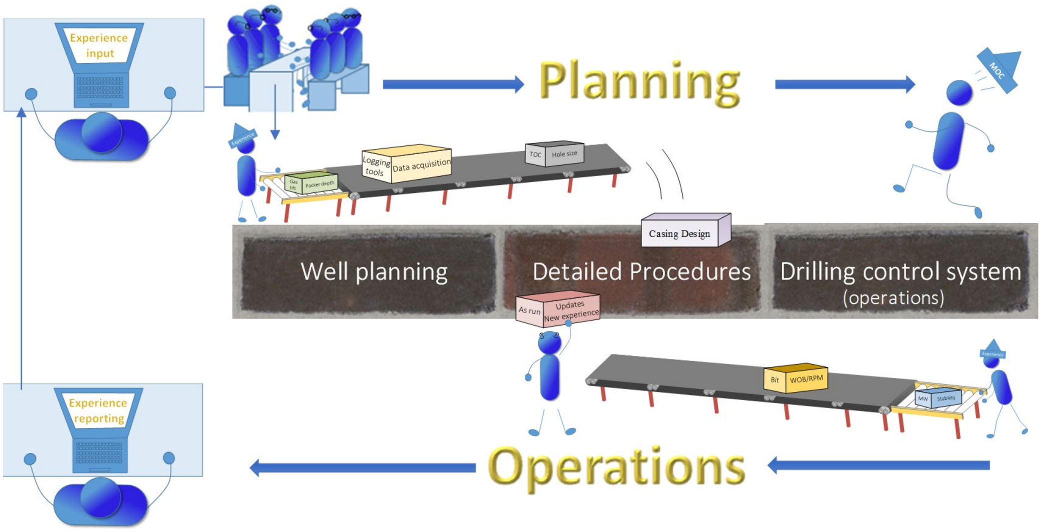

Figure 2-3 - Compartmentalized phases require manual intervention for engineering and learning to take effect.

The conducted research found studies of well control incidents relevant for how organizations act. Well control is a narrow area where involved personnel have extensive training, and it has high focus in planning and during operations. I.e. it is an area of priority by all teams. In the period 2003-2010, a total of 146 well control incidents were registered in the Norwegian Continental Shelf of which 12 have investigation reports and 21 have event reports. The conducted study by the Norwegian Petroleum Safety Authorities (PSA) also included interviews in the analysis (Lootz, 2013). The conclusion of the analysis of these incidents and interviews, points to slips (actions were not carried out as intended or planned), lapses (actions were missed) and mistakes (plans were inadequate to achieve the intended outcome), i.e. human error and organizational short comings, comprise more than 30% of the underlying and triggering causes.
The input from this Thesis is to develop a software support to replace the "weak" bridge between the phases. An interactive software can ensure a minimum standard and prevent most personal and organizational errors. A high-level support software can offer an interactive link towards governing documentation and standards[8].

2.4 Current and future software for support of planning and operations

As said, support software has a great influence on the workload and process of well planning. Available software for support of activities in the oil and gas industry is diverse and only few key vendors and their products will be discussed here. For operators, the main products are typically complete platforms supporting more or less all required engineering for planning well construction. Specialized products exist for parts of the engineering, such as HPHT, Deepwater, extreme extended reach developments (ERD). These projects are often outsourced, so external companies provide either the operational boundaries alone or in addition to the operator's engineers. The majority of simulations are prepared inhouse with traditional models according to the same workflow and type of calculations as in the vision by Maurer engineering in the 1990s, see Figure 1-3.

[8] OTC-28988 New standard for standards.

2.4.1 Available software – current work processes

Some key software used in operations are shown in Table 2-2:

Table 2-2 - Software on the market.

#	Function	Name	Comment
1	Rig equipment	NOVOS / Drillers Assist	Companies: NOV and MH Wirth Ranges from semi to fully automation of rig equipment
2	Operational boundaries	Landmark EDM, DELFI Wellplan, WellDesign, Drillers Assist (w/ DrillTronics)	Companies: Halliburton, Schlumberger, Oliasoft, Sekal Engineers safe operational boundaries in planning. Ranges from manual update to use of real time data.
3	Operational analysis	ProNova	Companies: TDE Thonhauser Data Engineering

2.4.1.1 Rig equipment

On most rigs with a modern top drive, there is software functionality like an auto-driller and few other help functions. These software packages are open for 3rd parties to interface, so e.g. drilling optimization and other software can provide their services fully automated. More and more rigs are currently being equipped with software for fully automated operations. The trend may be more evident for offshore rigs than land rigs.

2.4.1.2 Operational boundaries

Landmark EDM has had the largest market share the last decades. They assembled several software packages and established the platform many operators are still using (History of Landmark EDM). It has had some face lifts over the last years, where the changes can be summed up to improved flow of data and few improved engineering calculations. The software is highly dependent on experienced engineers selecting the right input data in the right way and interpreting the results. The simulated limits are manually transferred into text-based documents such as programs and procedures for operations. With the Landmark EDM, any updated simulations during operations require extraction of real time data, re-running the influenced calculations and finally reporting these manually over to the operational team.

DELFI is the new platform for planning wells from Schlumberger. The interface is a "SharePoint team site" variety as conveyor of the workflow for planning wells. It links together engineering simulations, text-based programs and procedures. Schlumberger cooperates with Google to enable a cloud-based solution for the software. As a tool, it offers nice interfaces and one of the smoothest workflows. Evaluation of this software is based on the web page, presentations and interviews at conferences such as OTC Asia and OTC Houston. The information presented of this software in this thesis is the view of the author and the readers are encouraged to inform themselves further.

Oliasoft is a new actor in the industry. They offer a modern planning platform and open engineering. Their software called WellDesign is still under development and has already taken a piece of the market. Evaluation of this software is based on the web page, presentations and interviews amongst others at the OTC Houston conference. The information presented of this software in this thesis is the view of the author and the readers are encouraged to inform themselves further, e.g. at their home page.

2.4.1.3 Operational analysis

The ProNova software reads of the rig sensors (pumping pressure, top drive position, etc.) and analyzes what the rig is doing. It is very powerful tool for those who applied it to analyze activities duration and effectivity. Application of this technology is much more than just measuring KPIs. E.g.

down hole problems and failure prediction and others. Further information can be found at the ProNova home page.

2.4.2 *Future software support and work processes*

Considering reports from field trials of rigs with automated equipment, future operations are likely to assume a more digital profile than provided by the software currently on the market. With an automated rig and intelligent software to control the rig equipment, intelligent software for planning is the only piece missing for a fully digitalized process. The positive learning from the field trials and the effect of operational analysis, motivation for going fully digital is clear.

The operational analysis software ProNova can register and report the most effective operations, but there is currently no software available to make sure these learnings are implemented in subsequent operations. People have to write down the experience and manually apply it in future operations. Common for all products currently on the market is the focus on easing the human role. However, there are currently no software presented with a fully digital and automated process that targets the value chain and the full life cycle of wells. A discussion of future software common in the industry, is based on what has been evaluated in the field trials of automated rigs and the conducted research. Table 2-3 shows an overview of what may be a typical software constellation for modern rigs.

Table 2-3 - Future software support.

#	Function	Name	Comment
1	Rig equipment	NOVOS / Drillers Assist	Ranges from semi to fully automation of rig equipment
2	Operational boundaries Failure prediction	DWE and similar models	Ranges from use of real time data to fully automated and digital process
3	Operational optimization	Drilling, well control, completion, intervention, well integrity, P&A	Engineers safe operational boundaries in planning and operations – fully automated
4	Operational analysis	ProNova	Full analysis of rig activities with automated KPI measurements

2.4.2.1 Introduction – modern operations

Figure 2-4 is a popular representation of the transformation of operations following automated rig equipment. The cars symbolize wells and the manual construction work being transformed into a modern automated “assembly line” with less exposure to people and a more accurate manufacturing process. In this research, another metaphor has been added to the meaning of these pictures. The cars represent the manually constructed programs for well construction and maintenance. There is another metaphor with this picture series, where the old (mechanical) cars represent todays text-based documents and the new (self-driving) cars represents the new digital (executable) programs (readable for man and machine).

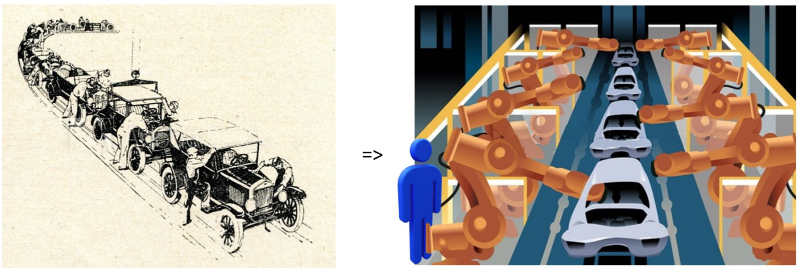

Figure 2-4 - Manufacturing processes in automotive industries went from hands on to verification.

The vision depicted in Figure 2-4 shows fewer people involved and they only observe the automated work process. A better representation would be an engineering observing each process. One of the reasons is that machines and software cannot be responsible for any process. The accountable party is the operator and key employees just as today.

2.4.2.2 Rig equipment software - NOVOS

Listed first in Table 2-3, software for automation of rig equipment is ready off the shelf and being installed on many rigs offshore Norway and will be common shortly. NOVOS is a software that performs elementary control of all rig equipment. E.g. when the signal has come to make up a new stand or to start pumping, the software initiates these sequences. There is no logic for why these basic commands should be done. Other software needs to be linked up to establish this “intelligence”.

2.4.2.3 Operational boundaries and failure prediction

Currently available software models presented earlier are interesting for their capacity to produce engineering. The calculations can be extracted and used in digital and automated processes. None of the presented companies have announced any intention of going to a DWM process, except Oliasoft. They have made efforts to provide automated planning. At current, this planning is not dynamic, i.e. the planning run through a fixed rule-based cycle.

Another fairly new actor on the market is the company Exebenus. The main scope of their software is to establish digital procedures. According to their home page and presentation material, they build a digital program that links up with software for rig automation. Their software builds on the product made by the engineers planning the well construction. Another step forward is the experience cycle, which is read by the software and used in operations. The software “Exebenus Pulse” is limited to influence and handle operational parameters in the experience cycle, but it has built in machine learning routines to recognize and predict failures

The information presented of this software in this thesis is the view of the author and the readers are encouraged to inform themselves further, e.g. at their home page.

Figure 2-5 shows an example of data flow for fully automated rig equipment processing operational boundaries and failure prediction. The latter may compose several layers from the consequence of the failure. Typically, well control incidents will have priority and scenarios posing less severe outcome will have less but overrule any drilling optimization activity. Figure 2-5 is a circle, where the left side starts with the driller, proceeds to “Optimization” where software routines can perform e.g. drilling optimization and early failure prevention techniques. “Supervisory control” represents priority actions like well control. “Feedback Control” is supervision of health of the system, i.e. verification of sensors calibrations, etc. Lastly, at the bottom are the downhole sensors like in the bottom hole assembly. Following the blue arrows on the right side to complete the circle is a stepwise back tracking of the left side. The arrows on the left represents data retrieved from sensors.

There are many aspects of safety the software is handling. First and foremost is well control, then follows hydraulic and mechanical type loads. The logic of the drilling optimization system picks its limits from the planning phase initially. But once the drilling has initiated, the simulations must be updated with real (time) data to forecast new safe operational limits. Some drilling optimizing software have these routines. Performance in automated drilling is often conducted through manipulation of drilling parameters. A study produced a prototype software for drilling optimization as part of the research of this PhD.

There are other specialized types of software available. E.g. methods for predicting emerging failures using case-based reasoning (CBR) techniques. This thesis will focus on the interface to the products and methods in the above main functions of modern operations and deliveries for less traditional operations with less technology involved.

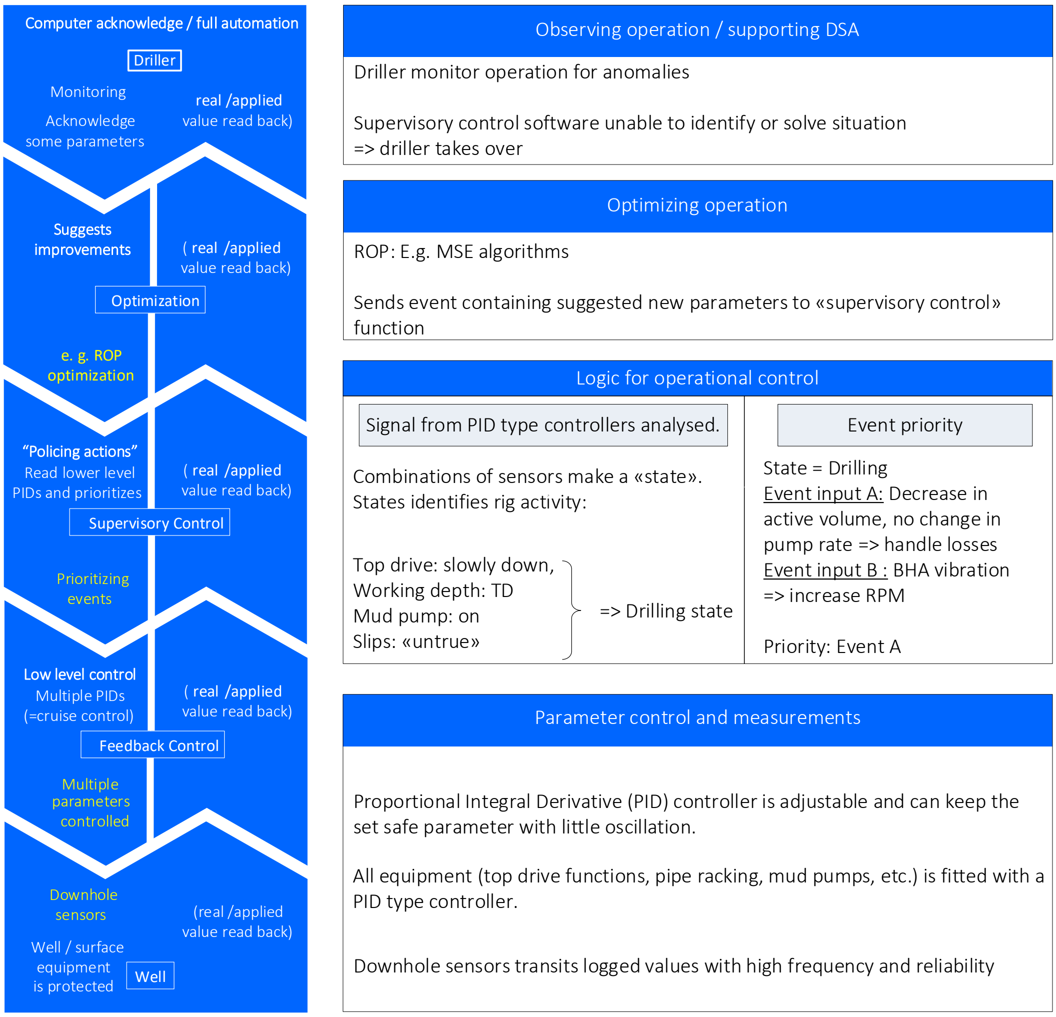

Figure 2-5 - Example of process with automated rig equipment (note blue arrow shapes).

Today, software for updating operational boundaries are typically the same as used in the planning phase. The engineering models update operational boundaries and integrity calculations with data from the operations. The PhD research has built on this process and added other phases than the well planning and construction to make the software follow the full life cycle of wells. Figure 2-6 displays an overview of the LCWIM model. There are tabs to the left indicating the integration of administrative tasks, governing documentation and standards. The red tab to the right indicates the connection to the subsurface models. The inner circular segments of the vertical circle mark the phases in the life cycle of wells, where the left 1/3 of the circle is planning and construction, the right 1/3 of the circle is production / injection and the bottom 1/3 is plugging activities. Note that the engineering listed next to the segments by phase is a visualization. The calculations are available throughout the life cycle of the well. The engineering models developed through this PhD research are discussed in Appendix B.

Discussion of further learning from the ongoing process follows the standard workflow in the industry: the first step is well planning, then follows well construction, production and final plugging. Note that the engineering listed next to the segments by phase is a visualization. The calculations are available throughout the life cycle of the well.

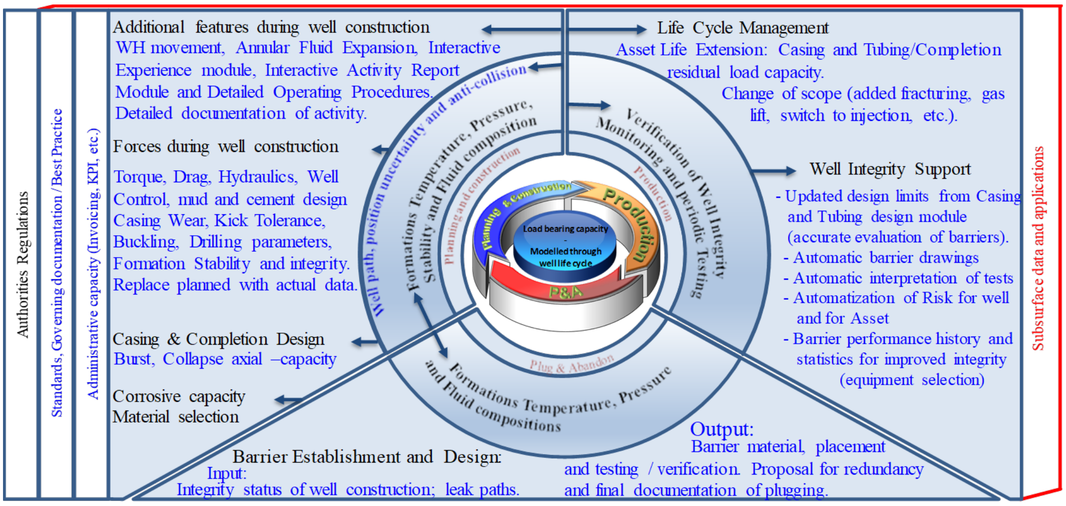

Figure 2-6 - LCWIM overview.

2.5 Workflow of current planning and operational processes

Discussion of further learning from the current planning and operational processes follows the standard workflow in the industry which spans well planning, well construction, production and final plugging. Note that this thesis will not discuss planning of field development due to the strong similarities to single well development.

2.5.1 Well planning

In the early stage, well planning is focused around tasks the Subsurface team is responsible for. The Wells team would mainly provide input to the Subsurface models, typically related to practicalities such as feasibility in operation, operational risk and cost. In many cases, the first suggested targets would represent high risk and challenges to drill. Early planning comprises many iterations where geologists and geophysicists selected new targets for the Wells team to re-assess feasibility. The workflow in legacy well planning, generalized in Figure 2-7, comprises a series of disconnected steps due to the many designs are developed in different software and depend on each other. Hence there are often many iterations and work-intensive process, see Figure 2-8. After the early phase follows a period of settling the detailed design. An important note on these designs is that they depend on the expertise of the engineer, company policies and procedures.
With the many engineering models to evaluate for a full drilling design, iteration requires time and resources since all disciplines re-run simulations in their models to evaluate the feasibility. In many occasions, there can be 10-fold(s) of iteration before all disciplines can reach consensus.

With manual calculations, i.e. input parameters have to be changed by humans, the process takes time. Iterations may take place for many reasons. Changed understanding of the reservoir may give raise to other approaches such as horizontal length, adding fracturing, etc.

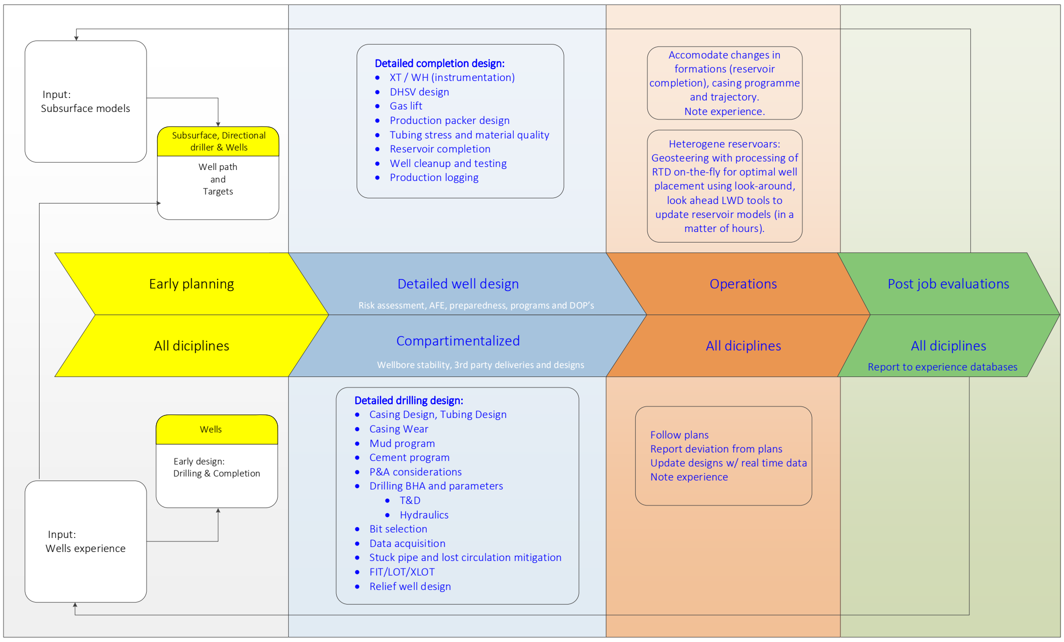

Figure 2-7 - Outline of generalized well planning process.

Well planning covers all these aspects before construction starts. Figure 2-8 shows typical engineering applications used in planning and an example how designs are developed using many parameters shared across several applications. Any design change influences the drill pipe design. Should one design calculation require a change in one of the drill pipe properties, it will trigger a recalculation of all other affected design calculations.

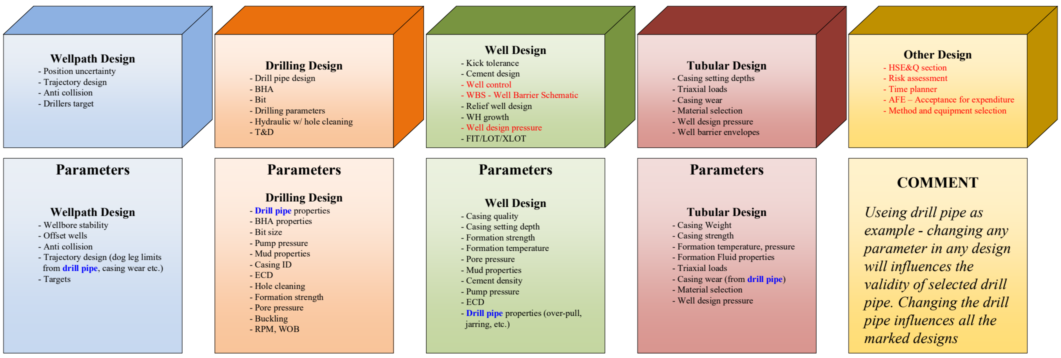

Figure 2-8 - Relationship between engineered designs.

The consequence of a dynamic planning application can change the current work flow as depicted in Figure 2-7 into the process like in Figure 2-9, which is the outlined process for the LCWIM.
The engineering sequence is the same as in the legacy workflow in Figure 2-7, i.e. experienced personnel will be familiar to the process.

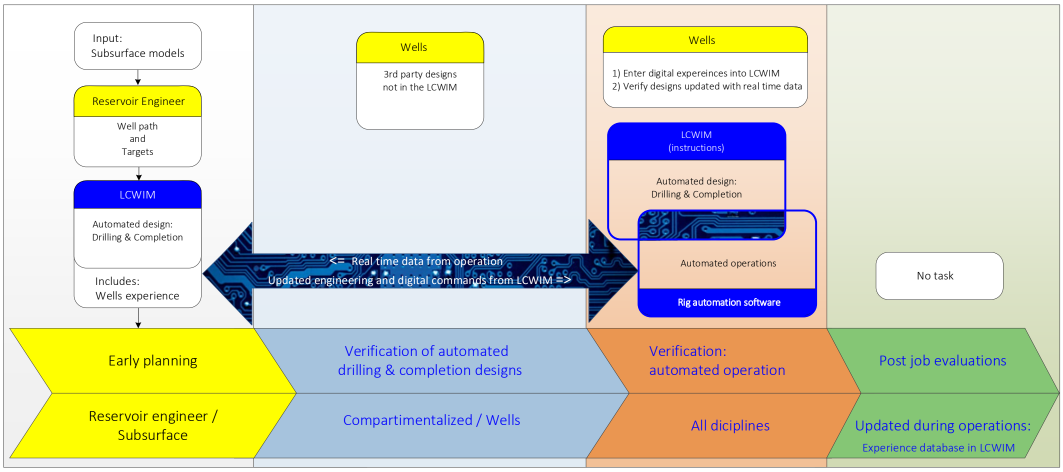

Figure 2-9 - Generalized automated well planning process.

The LCWIM is designed to run and tune the different parameters until an appropriate design is established for the set scope. This will be the initial design, made before human verification or alterations have been made. The program and designs will satisfy all the set rules or experiences in the software. The produced version may be rejected by the planning team, and the software will be re-run with some added criteria.

Some evident changes are:

- Manual calculations and designs are automated
- Iterations are not visible unless the user specifies this
- Algorithms control well path generation: subsurface can establish good plans
- Compartmentalization between disciplines and service providers is minimized
- Contracts, logistics, project planner with times and budget are created automatically
- All designs including methods are based on digital experiences
- The LCWIM can update safe operational boundaries using real time data
- Post job evaluations and reporting are fully automated
- Combining logs and events: annotation of logs no longer required
- Combining logs and events: operational history fully digital, i.e. readable for software and people

The LCWIM is planned to show the detailed engineering calculations to the planning team only when they go in to verify the detailed designs. Method selection and design verification will be the main tasks for the wells team members in future well planning process, where most administration is automated. Well construction

The next segments in Figure 2-7 and Figure 2-9 are “well construction” (e.g. drilling and completion operations) , shaded in orange. In this phase, engineers are converting plans into actions. This is done

1) Detailing operational steps into procedures and risk assessment
2) Hold meetings with involved operational roles – discuss and agree on procedure and risks
3) Any support calculations (cementing, well control, etc.)
4) Provide operational guidelines
5) Update and provide safe operational limits
6) Report experience

Currently, engineers are carrying out all these tasks manually. Often, the procedures and risk assessments are written in text editors and spread sheets. Facts are gathered from the planned program and minutes of meetings and then written into detailed operational steps in a text-based document. For operations with automated rig equipment, the key data can be written into a software such as Exebenus provides. This marks a change in work process from today, where engineers provide paper copies for the different operational roles to coordinate and ensure both safe and effective operations. Digital procedures show both man and machine the different steps, so the same operational roles can supervise the actions of the automated rig equipment.
Updating safe operational guidelines often involves extraction of operational data which replace planned parameters. Then the engineering models are run, and updated boundaries are found. Some specialized software does this automatically, e.g. the company called eDrilling and their software with the same name (home page). As with most products on the market, they target and address a specific portion of the well construction process. Combined with a software for automated rig equipment as discussed in Figure 2-5, they use logged surface data to simulate hydraulic and mechanical forces acting downhole. The results are used to update safe operational parameters. This approach is used where direct measurements of acting forces is not possible and the mentioned forces are critical. Where operations use wired pipe, another approach and software are often used. Wired pipe[9] can provide direct measurements of the acting forces in the well, which means less assumptions and safety margins since the system measures the down hole parameters directly with no lag time.

Comment to the reader:
With a combination of the software from Exebenus and eDrilling, the support of the operational phase has resemblance to future operations as predicted and designed for the planned LCWIM software. The difference is that both Exebenus and eDrilling software models rely on a traditional planning phase where humans interact and perform manual evaluations and input as today. Key data from this manual planning is then manually uploaded and the Exebenus and eDrilling models to perform operational support. The LCWIM is planned to run fully automated.

The use of wired pipe has become more frequent and is predicted to become the norm in many offshore projects. As described above, the acting forces in the well can be measured directly and automated rig equipment can operate close to the set operational boundaries. Other reasons for the introduction of wired pipe is the improved communication with the logging tools in the drilling bottom-hole assembly (BHA). In many projects, rate of penetration (ROP) has been restricted due to requirement of data acquisition. With higher bit rate, more data can be obtained per unit time and ROP may no longer be restricted for many projects.
Figure 2-10 shows a future operation as predicted using a DWM type software. At first glance, it may not seem very different than traditional operations with modern top drive.

[9] For more information about automation levels and systems for rigs with automated equipment, see (Brechan(10), 2019).

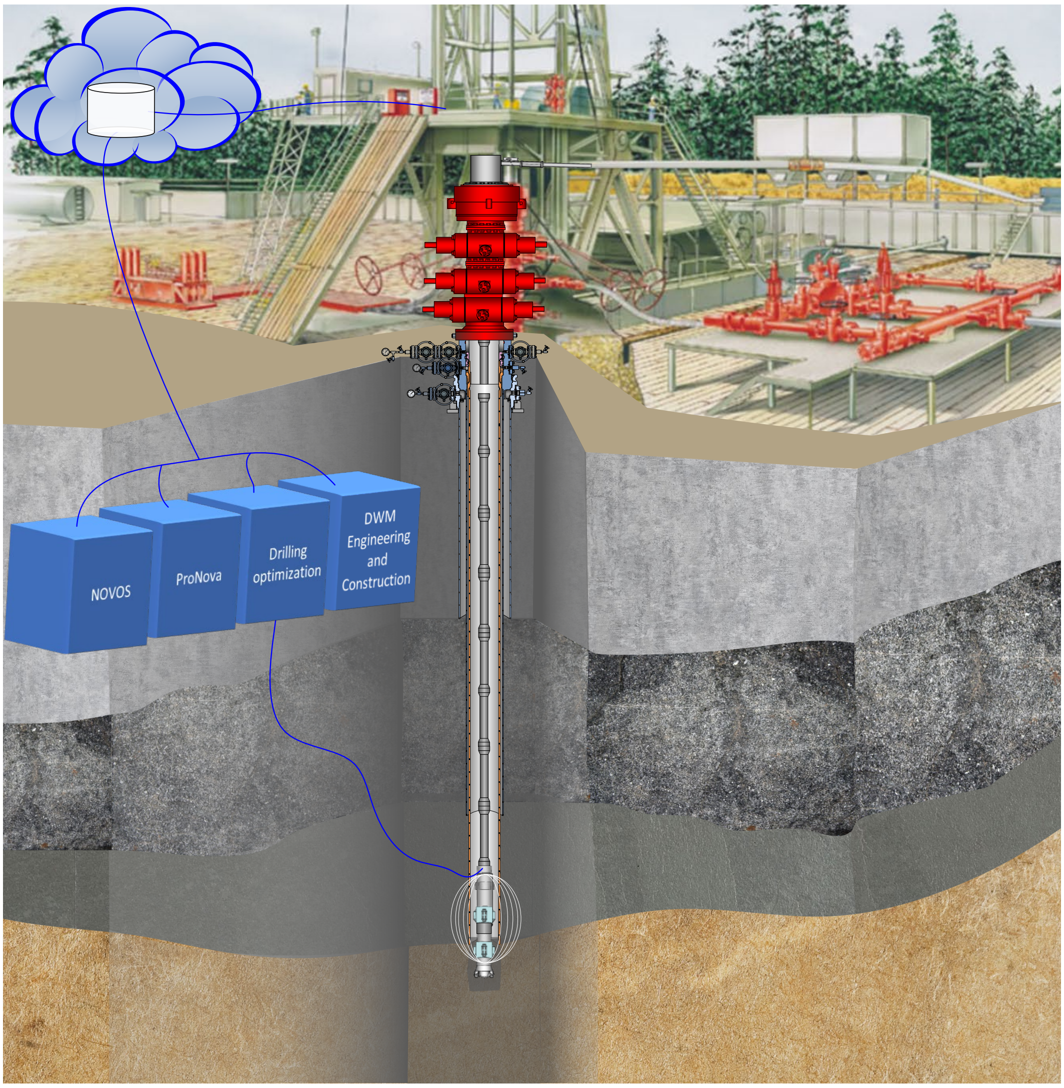

Figure 2-10 - Software support in future operations: BHA communication with wired pipe (simplified with a direct line) and internally (displayed as white stapled lines).

What separates Figure 2-10 from legacy operations are wired pipe and full utilization of the advanced operational support indicated by the four major software packages. These applications are at different stage of "readiness". E.g. the ProNova software is already established and used by many operators. Some operators are using this service continuously to collect learning and measure KPIs. Several operators are phasing in software for automating rig equipment such as NOVOS. Software for automation of rig equipment has been tested in several field trials and there are several providers to choose from. Drilling optimization is an umbrella term for several applications providing operational parameters optimized for safety and performance. Several of these applications can predict potential failures about to occur using case-based reasoning techniques. There is currently no software on the marked providing digital well management as designed for the LCWIM, indicated as the 4th application. It is possible to make queries about the other products with the mentioned vendors, which justifies more detailing of the operational support designed for the LCWM. A brief overview of the improvements following a DWM process:

1) Seamless transition from planning to digital detailed operations
2) Seamless update of safe operational parameters
3) Fully automated casing wear simulations: updated with real time data and projected ahead
4) Seamless integration between ProNova (reporting) and the activity report module (ARM) in the LCWIM
5) Standardized activity reporting: automated reporting satisfies all stakeholders
6) Digital platform: operational history preserved and available for later operations

Seamless transition from planning to digital detailed operations

Discussed earlier, the base scope of the WOS is to establish digital programs and procedures which can communicate directly with a software like NOVOS. The "report language" enables a fully digital process, which enables an automatic conversion process of each of the planned activities into meaningful commands for the rig automation software.

Today, all procedures are manual, i.e. in text-based documents. The rig crews are responsible for following them while monitoring and maintaining safe and effective operational parameters. Safety and performance are likely to improve when the same personnel shift to a verification role, which free up time due to less administrative routines. This is possible since the WOS is designed to establish procedures in the "reporting language", which means they are is readable for the personnel too. More about digital programs and detailed operational procedures can be found in the chapter dedicated for DWM. The 3D viewer often used in operations and planning as an IO interface feature is discussed only in a produced conference paper (Brechan(7), 2019).

Note to reader:

In the coming decade, major changes are expected in operational support and operational safety and performance[10]. Most literature discussing future operations involve automated rig operations. Not all rigs will see this, but they can still benefit from 3 of the 4 applications.

Completion and intervention operations are not often discussed in literature on rig automation. It is possible to establish the same digital process and support operations as described for drilling.

Points 4 through 6 interfaces with the subsequent chapters and are discussed there.

2.5.2 Production / Injection phase

The purpose of wells is to be a conduit for fluids going from or to the reservoir. Wells have voids designed to monitor containment. Typically, these annuli are carefully designed and monitored for pressure changes. The industry standard is to collect the pressure data in a control room, where an electronic system gives alarms according to set limits for high or low pressure. According to integrity standards, wells should have two independent barrier envelopes. And the same standards recommend testing of the different elements in each envelope. When wells start to deviate from recommended leak rates, integrity engineers evaluate the risk posed by the deviation and any possible escalation. Integrity work prevents major disasters from occurring.

In my experience, the work process of integrity engineers is essentially manual with limited software support and lack of automated solutions. Thus, the work is repetitive. Typical examples are:

a) Building safe operation limits – annuli pressure limits and others
b) Establishing an integrity map for each well
c) Barrier drawings for each well are made manually in software like Visio – for each well
d) Risk assessment for each occurring deviation is made manually
e) Investigating reported deviations in pressure or leak testing

[10] The saving potential demonstrated in the field trials of rig automation are so significant that the process of automating rigs may take place quite soon.

2.5.2.1 Building safe operation limits

Integrity engineers often rely on the pressure tests performed during well construction. They set limits as indicated in Figure 2-11, where the operations limit in orange is often set slightly below the Maximum Allowable Annular Surface Pressure (MAASP) in the following annulus. This means that a leak in the casing from A-annulus over to the B-annulus would not fracture the exposed formations in the latter. The lower limit is a practical matter. The limit is often low pressure to have something to monitor. No pressure can camouflage an active leak. Once the limits are set, they are communicated to the control room personnel and the well is opened up for active operation.

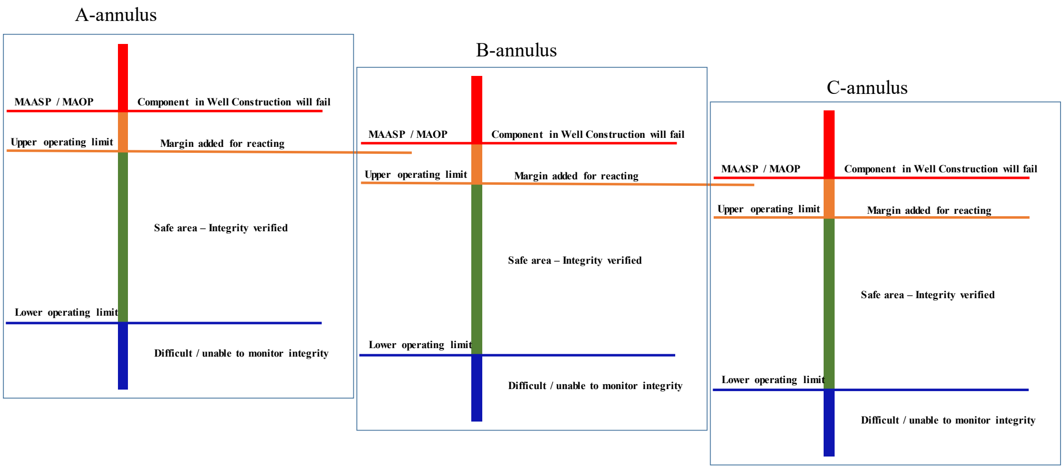

Figure 2-11 - Optimal operational limits for annuli.

2.5.2.2 Establishing an integrity map for each well

Engineers involved in planning of well integrity, P&A or intervention operations knows the efforts required to establish an overview of the history of a well. The challenges start as early as in the well construction phase due to the communication barrier between the disciplines. Typically, well integrity teams read daily drilling/activity reports to update their models with operational parameters. Examples are top of cement (TOC), cement bond logs (CBL) and leak tests and what medium the tests were conducted with (e.g. mud, clear fluid or gas). Other essential well integrity aspects and parameters are listed in Appendix E – "Well integrity aspects per phase".

Reporting as it has been conducted in the industry is not designed to provide important well integrity essentials directly. Integrity engineers often establish a file per well manually as a map. This information becomes essential in events where tests or pressures deviate from set limits and guidelines. Risk evaluation can be influenced negatively due to poor cementing parameters where CBL is not available and vice versa. There is a substantial amount of information to gather and keep track of to complete a full integrity map. In a DWM system, the reporting is automated and described integrity maps are established with humans in a verification role.

2.5.2.3 Barrier drawings for each well

Industry standards recommend Well Barrier Schematics (WBS) for each well. Typically, a drawing is made from a template and updated with current situation of barriers and any existing deviations. Each element taking part is drawn to visualize their potential as a leak and breach of integrity. E.g. all valves, control lines and electrical signals to/from the well, i.e. every part in both the primary and secondary envelopes.

It is possible to automate these drawings. The PhD research has not investigated the full potential of possible improvements in this area, but the following was identified:

- Establish well drawings following the well path with barriers marked.
- Barrier drawings to be linked to the report module to automate the task.
- Link barrier element equipment to report module and automate installation details.

2.5.2.4 Risk assessment

Risk is a topic stretching over many layers in organizations and their structure. From operator and asset level to individual wells and operations. The industry's consensus is clearly defined in standards, primary focus is safe and effective production. The essence of Well Integrity is "containment". To fully comprehend the potential of a situation where barrier elements fail to meet industry standards and requirements, it is common to perform a risk analysis. I most cases, assessments are performed manually. In many standard cases, such as noted 1 through 8 in Figure 2-12, can be a waste of personnel resources. The conducted research covers a prototype for automation of integrity risk analysis. It builds on fundamental well integrity theory, which was documented in a dedicated paper (Brechan(1), 2018).

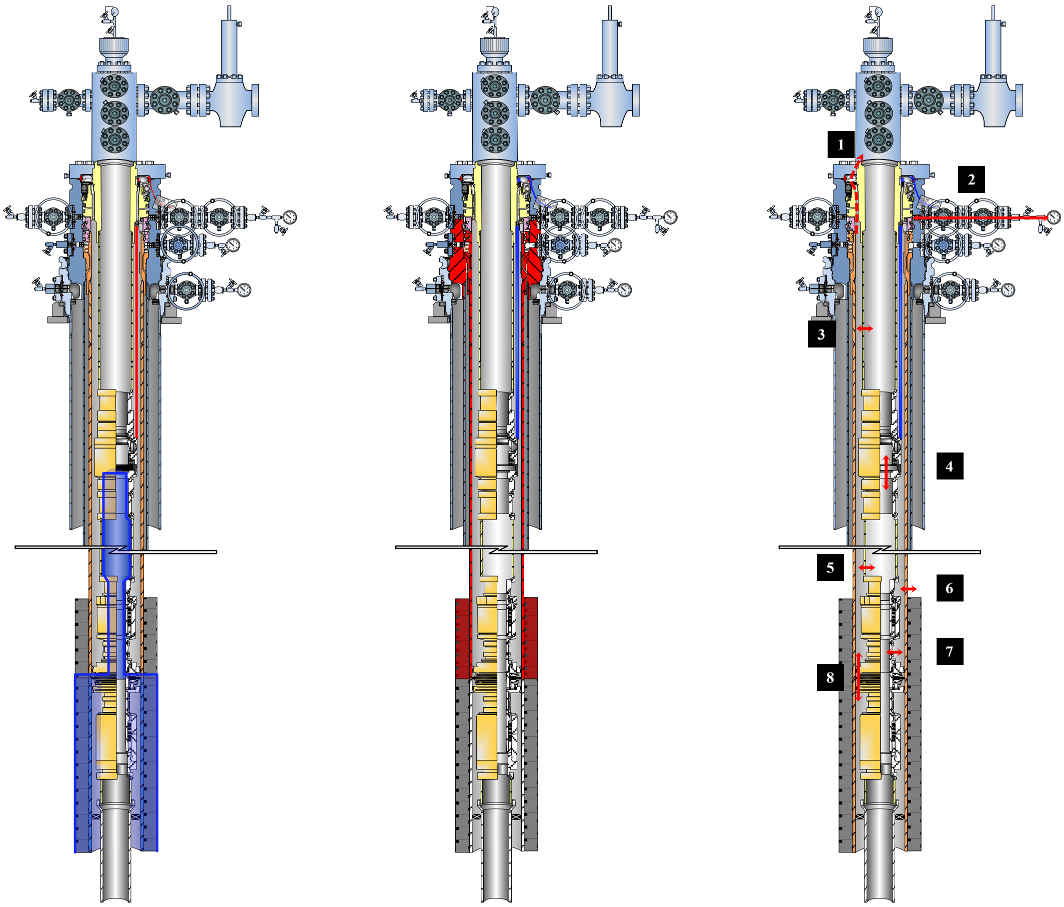

Figure 2-12 - Primary (blue), secondary (red) -envelopes and the most common leak paths indicated (1 through 8).

The most common leak paths numbered from 1 through 8 in Figure 2-12, are elaborated using the same numbering reference in Table 2-4. Each case needs to be evaluated thoroughly. But much of the information required to perform the analysis and build a risk assessment can be done automatically and verified by integrity engineers.

Table 2-4 - Components most frequently involved in leaks to the A-annulus

#	Component	Source	Consequence
1	Tubing hanger seal	1 of 2: 1. High pressure in the A-annulus, e.g. temperature effect from Annular Fluid Expansion (AFE) 2. Through a component in the secondary barrier envelope (SBE)	Pressure increase in the XT cavity – sealed off with the TH neck seal and the ring gasket between the XT and the WH. No exposure to personnel, normally no external leak; but may be hard to detect since there often are no pressure measurement in the XT cavity.
2	WH valves	1 of 3: 1. High pressure in the A-annulus, e.g. temperature effect from Annular Fluid Expansion (AFE) 2. Through a component in the SBE 3. Through a component in the PBE	Dry XT: Exposing people and equipment to pressure and fluid in annulus. A leak above acceptance criteria signifies a non-functional barrier envelope.
3	Tubing leak above DHSV	Reservoir pressure and fluid	*Leak above acceptance criteria*: Production casing/liner will be exposed to high burst pressure as A-annulus assumes tubing wellhead pressure (WHP). The tubing will be exposed to highest collapse load in this scenario. Closing the DHSV mitigates the leak and A-annulus can be bled off to normalize pressure. No external exposure – the secondary barrier envelope ensures containment.
4	DHSV leaking	Reservoir pressure and fluid	Component in the primary barrier envelope has failed. No external exposure – no fluid escaping any barrier envelope.
5	Tubing leak below DHSV	Reservoir pressure and fluid	The A-annulus will contain reservoir fluids. If leak above acceptance criteria, the well needs an intervention. No external exposure – the secondary barrier envelope ensures containment.
6	Production casing leaking	Formation pressure and fluid	Communication through the production casing will expose the A-annulus to the formation pressure outside the point of penetration. Formation strength, any mobile fluids and their pressure will interact with the fluid (level) in the A-annulus. External exposure – formations exposed to the A-annulus environment. (Keywords for further investigation: FG, annulus leak paths, cemented or not, collapsed formations, mobile fluids, corrosion of well construction etc.)
7	Tubing component leaking	Reservoir pressure and fluid	The A-annulus will contain reservoir fluids. If leak exceeds acceptance criteria, the well needs intervention. No external exposure – the secondary barrier envelope ensures containment.
8	Production packer leaking	Reservoir pressure and fluid	The A-annulus will contain reservoir fluids. If leak above acceptance criteria, the well needs an intervention. No external exposure – the secondary barrier envelope ensures containment.

2.5.2.5 Investigate reported deviations

Referring to the well integrity analysis listed by Figure 1-5, out of more than 400 wells there were 75 with integrity issues. This represents more than 18% of the total wells, which means integrity engineers have a significant workload. Automation of repetitive and standard cases can help integrity experts to prioritize their efforts on complex and urgent cases.

2.5.2.6 Summary of integrity aspects:

Integrity engineers perform integrity checks daily. There are dormant cases, where pressures are either not understood or integrity issues are not detectable through standard pressure monitoring. Therefore, most operators have routines to perform frequent checks of integrity. The majority of integrity issues are registered through changes in pressure during leak testing or in annuli. The subsequent evaluations in these cases are often routine. Majority of well integrity work is manual with little automated software assistance. Some applications on the market provide visualization and organization of integrity data, e.g. Wood's iWit (home page). The proposed automation of risk assessments is a small area of improvement planned for well integrity. This area is maybe the "youngest" and least developed in the industry. The potential for improvement in this area is significant. The industry effort is often focused on improvement of drilling, which is a cost saving exercise. Refer to the investigation presented in Figure 1-5, it is a paradox that 7% of the wells are shut in. This represents a threat to the environment; the reputation and future of the operator and it is a direct loss of revenue.

Today, normally central control rooms are in charge of the integrity by monitoring annuli pressures. This is planned to be expanded with few new features adding real time data from producing wells in the DWM.

a) Similar technology as in drilling: parameter analysis to predict failure
b) Alarm setting with automated analysis, risk assessment and proposed mitigation

The engineering modules in the application can run and report well integrity and asset integrity – automated. I.e. the wells can alarm the responsible teams when there is a barrier is failing or an anomaly occurs.

2.5.3 Well intervention and final plugging

Planning intervention and final plugging of wellbores can benefit from interacting with the well integrity engineers and their integrity map. Available operational history and any other aspect related to integrity are collected and saved per well.

2.5.3.1 Well intervention

Well interventions range from simple routine to the most complex of operations. Where the work is standardized and repetitive, a DWM type software support can be established. Where there are complex and composed operational objectives, the planned software will typically produce less complete support and require more effort from engineers to arrive at a good program for intervention activities. Through tubing services have a vast number of tools and possible combinations of applying these tools. Another challenge with well intervention is the unforeseen factors such as friction, deposits in well (reduced ID), etc. Well interventions are a demanding "customer" in the sense that it is a driver for a flexible solution for operational support software. Developing intervention programs and procedures can be done by singling out each possible scope and objective. Secondarily, the sets of procedures can be assembled. The next level of optimization needs to be campaign-based priorities such as loss of revenue, cost, access to wells, availability of tools, optimization of resources (service personnel and equipment, etc.) and other constraints.
It is as important for well intervention as any other operation to develop plans based on experience, reduce administrative workload and link up governing documentation. The research conducted in the area of intervention indicate that the highly mobile units of intervention may benefit in the same range as drilling, i.e. ~13% reduced cost.

2.5.3.2 *Final plugging of wellbores*

Investigations of plugging requirements and regulations for different parts of the world in the early part of this research, see Figure 2-13. In the last decade, several new techniques were matured and introduced for establishing barriers in wells. There are a few techniques used when plugging wellbores. These can all be described digitally using the reporting language and integrated in the LCWIM. This means that all planning can be automated, based on experience, automatically verified to be compliant with governing documentation and the planned software can provide digital procedures where there is automated rig equipment. The LCWIM can provide detailed cementing calculations and perform e.g. setting of balanced cement plugs fully automated.
Efficiency and saving are estimated to be in the same range as for drilling, i.e. ~13% of current time and cost. These estimations exclude the new and exotic methods where there is no need for a rig to establish barriers.

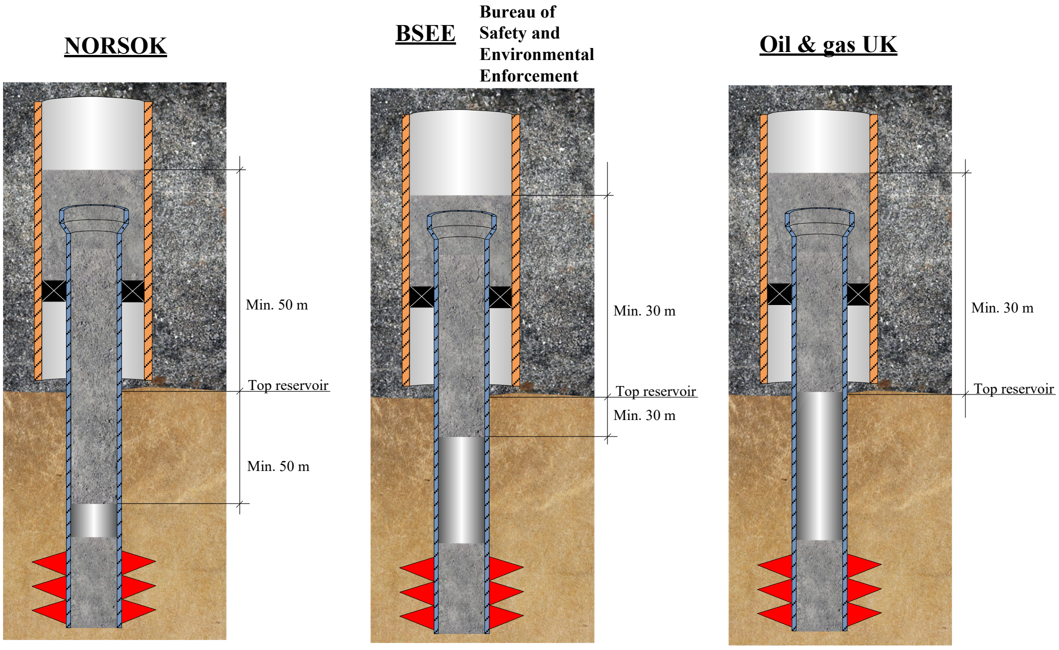

Figure 2-13 - Some governing requirements for cement plugs when abandoning wellbores.

2.5.4 *Current engineering: methods and accuracy*

Working through the best practices of engineering calculations used in well planning, several areas have been identified for improvement. This thesis will exemplify saving and improvement from modern engineering by presenting potential in tubular design. These calculations influence the full life cycle, safety / integrity and revenue of the project.

2.5.4.1 *Managing safety factors in collapse prediction*

Figure 2-14 shows the industry standard calculation (API) and real performance of a range of tubulars[11] in a particular grade. Note that the borders for the different API collapse modes are approximate. Notice the gap between minimum performance guaranteed by the manufacturer of the pipe and the minimum performance API collapse prediction. In the range of the most used tubulars, the empirical API method underpredicts the collapse resistance of the pipe with ~15 to 35%. Other methods of calculating collapse exist. ISO/TR 10400:2018 states that the Klever & Tamano (K&T) collapse model is the more appropriate choice. A model for K&T collapse was built and calibrated

[11] Pipe performance supplied by one of the major manufacturers in the industry.

with data from 115 tests without axial stress and 25 with axial stress. Section Appendix B, (Brechan(8), 2019) and (Brechan, 2020) discusses the K&T model further.

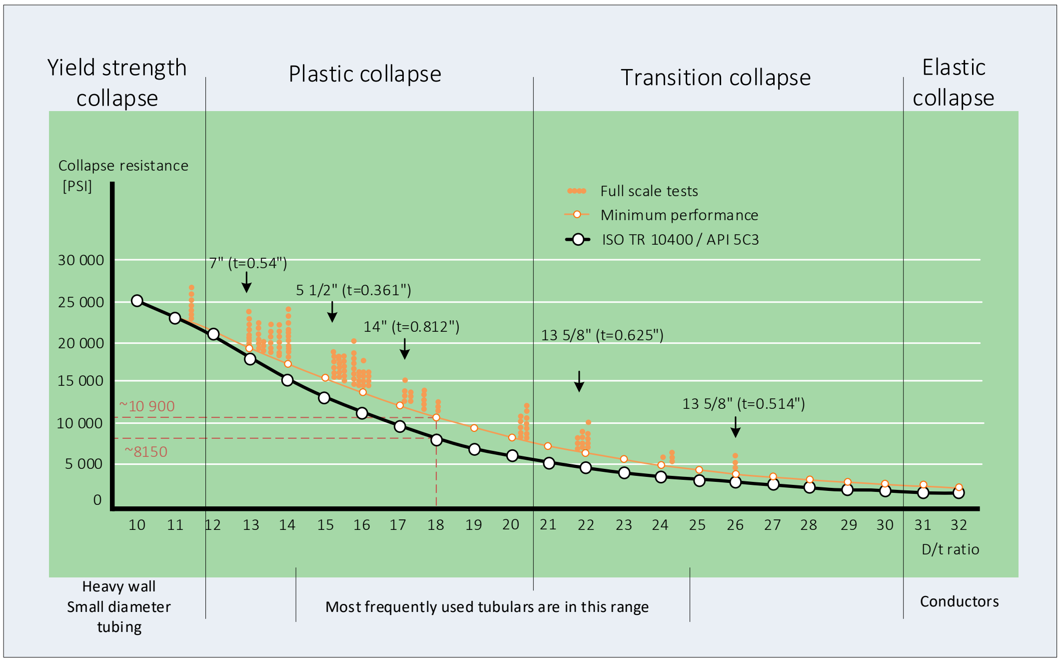

Figure 2-14 - Collapse prediction of oil field tubulars: ~15 - 35% below minimum performance for most frequently used pipe.

Given a particular grade, the performance of pipe is a "distribution" as a function of parameters such as exact wall thickness, ovality, residual stress and there may be varieties in exact yield strength between grades. The strength distribution is shown to the right in Figure 2-15, where the normal distribution in red represents API and the blue stapled line represents the actual performance.

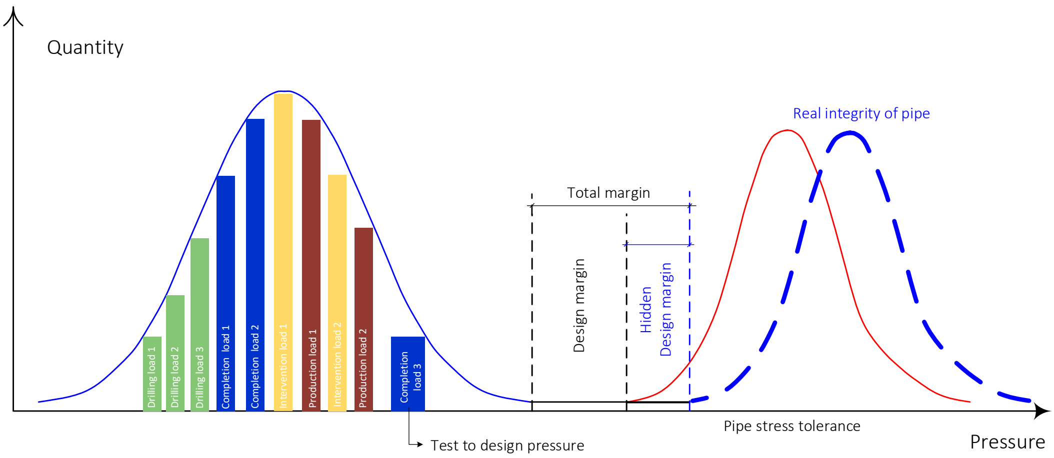

Figure 2-15 - Integrity of pipe and total margin to loads.

Design strength of tubulars are made to exceed the most severe load it will be exposed to. It is industry practice to add a design factor to create a distance between the highest load and expected minimum performance of pipes to account for insecurities in calculations, as illustrated in Figure 2-15. For collapse, standards recommend to reduce the pipe strength or increase the loads using a factor of 1.1. Applying this factor on top of the calculated collapse prediction amplifies the error seen in Figure 2-14. The hidden design margin as illustrated in Figure 2-15 is also increased 10%.

2.5.4.2 Error in burst prediction

The situation is less severe for burst. The industry standard for burst is a formula referred to as "Barlow tubular burst", see Eq (2-1).

$$P_b = 0.875\frac{2\sigma_y t}{d_o} \tag{2-1}$$

(2-2

Where:

- P_b is the burst pressure
- σ_y is the yield stress
- t is the pipe wall thickness
- d_o is the outer diameter of the pipe
- 0.875 is the manufacturing tolerance for wall thickness

The Barlow formula (Barlow, 1836) stems from before theory of elasticity were developed by Tresca, von Mises and others. In ISO-10400 (2018), there are added clauses to the Barlow tubular burst formula. The derivation of the formula violates the equilibrium condition (Adams, 2018), and it is valid only for thin walled pipes i.e. $\frac{d_o}{t} \geq 20$. Figure 2-16 shows actual wall thickness tolerance.

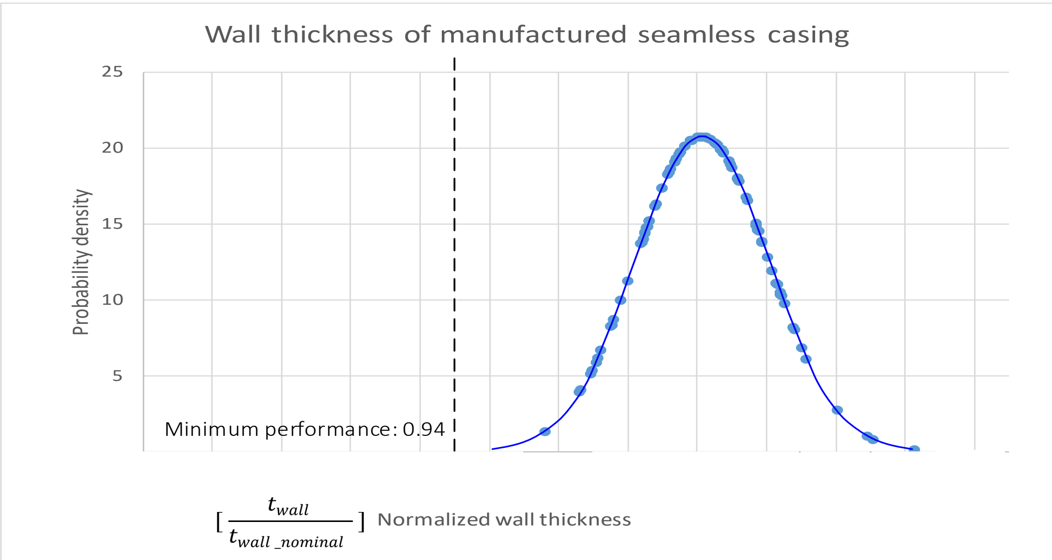

Figure 2-16: Actual manufactured wall thickness for seamless casing (source: ISO10400:2018, with permission).

The measurements of wall thickness in Figure 2-16 taken from ISO10400:2018 table B.4. The numbers behind table F.4 in the same standard have also been analyzed, which in total represents in excess of 10,000 measurement of wall thickness pointing to a minimum factor of 0.94 and not 0.875 as used in the industry.

Investigation of the origin for the manufacturing tolerance for wall thickness listed in the original standard API 5C2, identified that it was already established in 1954 (Saye, 1954). The manufacturing tolerance was added to account for difficulty in reproducing accurate wall thickness over time. However, statements from manufacturers point to a different status today. They have good control over the wall thickness (Brechan (11), 2019).

This thesis estimates error in burst calculations yields an underestimation of 6 – 7%. Again, the design factor applied would amplify this error.

Error in design interpretation

Interpreting collapse design using the API modes in Figure 2-14 as reference, yield strength collapse yields deformation due to exceeding the yield strength. This relates to the material specific behavior often seen in tensile or compressive tests. The formula used for determination of yield strength collapse was derived from the theoretical von Mises maximum distortion energy theory for yielding. This means that pipe failing due to yield will be limited to the von Mises ellipsis marked with red in Figure 2-17.

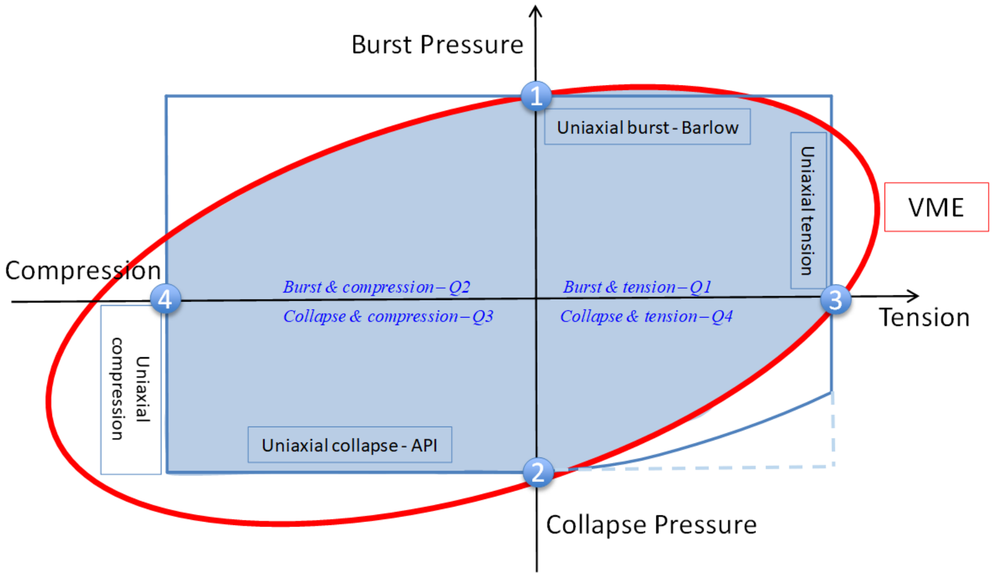

Figure 2-17 - Triaxial failure criterion.

2.5.4.3 Elastic collapse

Elastic collapse follows a failure mechanism which is predominantly governed by instability similar to what is seen with Euler columns. The formulas presented by API for prediction of yield strength collapse and elastic collapse were both derived from theory. As seen from Figure 2-14, pipe failing according to elastic collapse would typically be large diameter and be made in low yield material. Since elastic collapse is not affected by axial stress, these pipes would be limited to the horizontal line crossing point marked "2" in Figure 2-17. This includes the light blue stapled line, which is for elastic collapse only. This is a line not often seen in any standard for design interpretation.

2.5.4.4 Inelastic collapse – plastic and transition collapse

In material science, the area between yield strength and elastic collapse is one entity. API split it in two, adding the theoretical area for "transition collapse". The formulas used to derive collapse for pipe in this area are empirical. Pipe collapsing in these categories were reduced in strength using equation(2-3), which was replaced by equation(2-4)[12] in 2015. In many standards for interpretation, it is still common to use the horizontal line from point marked "2" in in Figure 2-17. This is not recommended, since the value is valid only in point marked "2", i.e. with no axial stress. There is little work published on performance of pipe subjected to inelastic collapse in quadrant 3, i.e. compression.

[12] Equation (2-4) from the 2015 API/ISO amendment to API/ISO TR 10400:2007 is an adjustment to the inaccurate calculations shown in Figure 2-14 and is in itself not very precise.

$$\sigma_{ys,\ e} = \sigma_{ys}\left[\sqrt{1-\frac{3}{4}\left(\frac{\sigma_z}{\sigma_{ys}}\right)^2} - \frac{1}{2}\left(\frac{\sigma_z}{\sigma_{ys}}\right)\right] \tag{2-3}$$

Where:

$\sigma_{ys,\ e}$ is the adjusted yield strength
σ_{ys} is the yield strength
σ_z is the axial stress

$$f_{ycom} = \left\{\left[1 - 0.75\left((\sigma_a + p_i)/f_{ymn}\right)^2\right]^{1/2} - 0.5(\sigma_a + p_i)/f_{ymn}\right\} f_{ymn} \tag{2-4}$$

Where:

f_{ycom} is the equivalent yield strength in the presence of axial stress and internal pressure
f_{ymn} is the specified minimum yield strength
σ_a is the component of axial stress not due to bending
p_i is the internal pressure

2.5.4.5 Engineers role

Engineering used in well planning and construction can be improved. One of the reasons for engineering is improving slowly is the lack of insight in calculations and the assumptions in the engineering applications available on the market.

2.5.4.6 Potential savings from accurate design

Engaged engineers with better understanding can produce innovative and creative designs. They are also likely to drive change towards modern and accurate designs. The prototype and a potential professional application will support this with "open engineering". The assumptions and the steps in calculations can be made available to the users, so the full understanding of the engineered design is easier to understand. This feature can also support training of personnel.
Standards discussing collapse performance often present a guide as Figure 2-17. The recommendation is often to keep to the area shaded blue in Figure 2-17, which leads to a practice where pipe collapsing in different categories are mixed. Consequently, the well has an overly heavy tubular design. The research conducted for an average well of ~4000 m in a reservoir at 3000 m with a 1.03 sg gradient pore pressure showed that using accurate design can save ~50 metric ton steel per well. At a cost of 10 cents/lbf for steel, this is ~$50,000USD saving potential per well. Maybe more important is the ~50 metric ton CO_2 saved per well since 1 metric ton steel produced the same approximate amount CO_2.

2.6 Other motivation – new technology

Already documented and discussed, the rig automation organizations desire a system like the DWM, see Table 1-4. But there are several other factors motivating the development of a fully digitalized process. With new technology comes new work processes. E.g. drones and robots replace people in exposed areas. Relevant for a DWM process is the development of the wireless sensors for pressure and temperature measured externally on casing and liners. Figure 2-18 shows an example of how wireless sensors can be installed to monitor formation pressure. The application of these sensors is likely to grow in the future since they can bring great revenue to many assets. E.g. controlling injectors to optimize pressure support by direct measurements in the cement and cap rock, measure contribution from each producing zone and identify sources of sustained casing pressure (SCP). These sensors can be integrated in automated integrity analysis to improve safety for the asset by knowing overburden pressures in mature fields. The history of gas migration and changes in formation pressure in the overburden can be useful for engineers planning P&A activities.

Going to a DWM process opens for expansion to full life cycle software support. Automating well integrity routines means that risk and safety of the well and asset is constantly monitored. The full integrity analysis includes tubular design, which is modelled in the software platforms for supporting planning. Many fields are extended from their original duration. There is significant revenue in both increase oil recovery (IOR) and postponing permanent P&A. Both depend on asset life extension (ALE). ALE is a change from original scope and the integrity of the relevant wells needs to be confirmed. Today, the integrity analyses are conducted manually be experienced personnel to understand the integrity of each well before it can be safe to extend production of a well or asset.

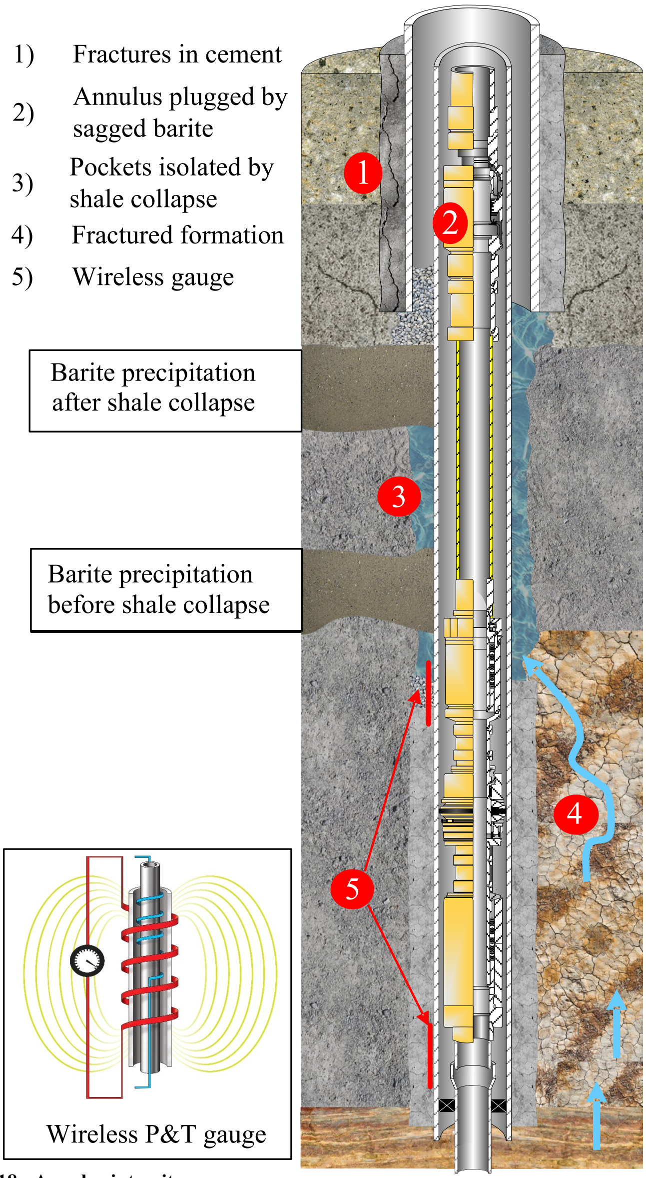

Figure 2-18 - Annulus integrity.

2.7 End note – application of DWM for traditional / manual rigs

Providing digital programs for rigs with automated equipment is a driver for digital well planning. As mentioned in section 1.3.2 "Future well planning", the affiliates of IADC ART and board of directors for SPE DSATS (de Wardt, 2016) consider digital procedures an important delivery for full utilization of rig automation, see Table 1-4 (de Wardt, 2016a). Many rigs today are manual or semi-automated. A possible future for these rigs can be outlined as in Figure 2-19 which is like Figure 2-10 without the "NOVOS" package for rig automation software and the active part of the drilling optimization[13].

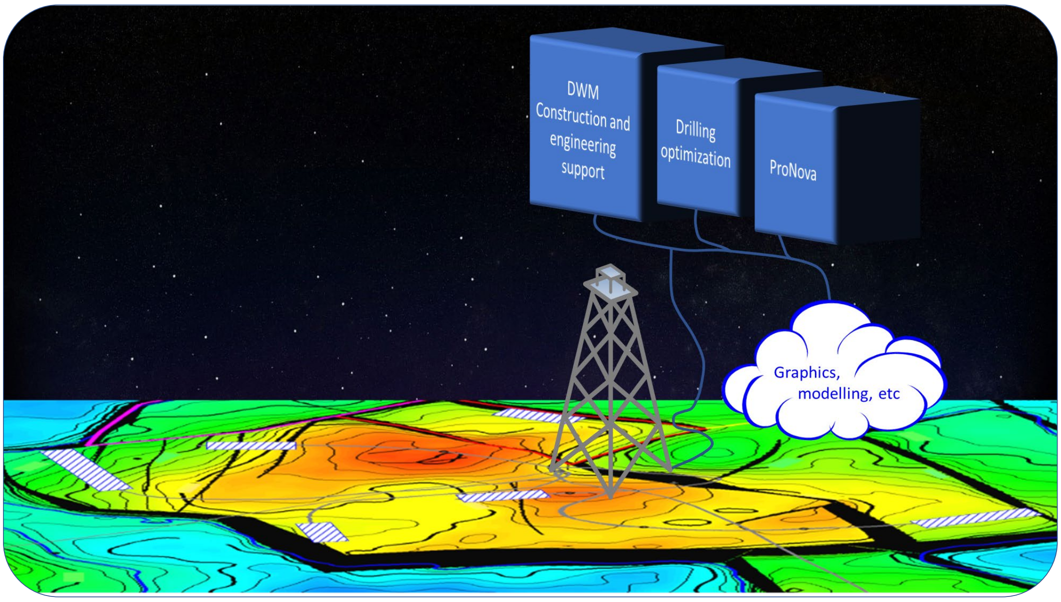

Figure 2-19 - Non-automated rigs with modern software support.

Software like ProNova can make a step change in planning and operations. Adding DWM can enhance that change and make it permanent. The detailed procedures for activity programs, e.g. for drilling, is presented on a format as shown in Figure 1-8. This is similar to the daily drilling reports used today. The codes are used to communicate with the rig automation software and other objectives, and they come with a standard descriptive text (not shown in the figure). The work process for a non-automated rig can be to follow the program as the process is today and let a software such as ProNova correct the detailed procedure into "as run". I.e., the actual performed tasks and how they were done can be detailed in a final well report directly with no requirement for direct human intervention.

[13] Drilling optimization software can still assist though the crew who ensures suggested parameters deducted from analysis of offset wells and from real time data.

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3 Digital Well Management

The framework for a new well planning software provides a new work process designed to accommodate and support planning and operations through the life cycle of wells. Clarifying key terminology in this thesis for the benefit of the reader, see Table 3-1.

Table 3-1 - Key abbreviations.

#	Abbr.	Name	Comment
1	DWM	Digital Well Management	The digital and automatic process of well construction and integrity
2	WOS	Well Operative System	The central application in the LCWIM model which enables the DWM
3	LCWIM	Life Cycle Well Integrity Model	Model for planning and constructing wells. Updates well integrity through the life cycle of the well.

Figure 3-1 displays the system architecture for intervention mode.

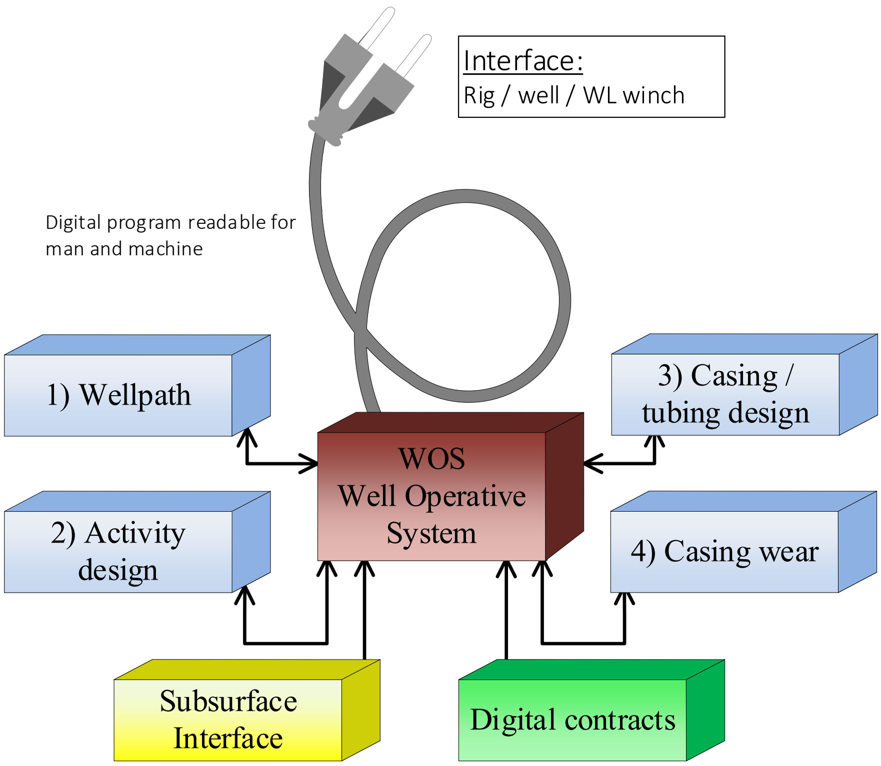


Figure 3-1 - DWM process overview.

A routine reads data from the subsurface models containing the latest key figures for modelling well construction and integrity, see yellow box in Figure 3-1. The WOS is the application controlling the data flow, i.e. which data goes where and when. A digital contract provides equipment cost and properties in addition to personnel, see the green box in Figure 3-1. The heart of the process is the WOS, which verifies and moves data where and when it should. The user can set the objective of the WOS to perform initial planning of well construction, well intervention, integrity verifications, slot recovery or final plugging of the well. The WOS is operated using the “reporting language”, i.e. a

system the engineers in well construction and intervention is familiar with today since it is very similar to the "daily drilling reports" used worldwide.
DWM can be described as a process extending beyond automated engineering of well constructions, automated digital programs, automated support of well construction, integrity, intervention and P&A. Its' core property and provision are a fluent information flow to all stakeholder through the full life cycle of the well. A fully digitalized process means less "waste"[14], as the different disciplines have their models filled with key data without queries. Data is not lost, stored or reported multiple times.
The WOS is designed to be the enabler of DWM. The application retrieves and distributes data to/from the subsurface models through the LCWIM digital well planning model, into digital activity programs compatible with software for automated rig equipment, interfacing with activity software such as ProNova[15], and finally distribute operational data to all stakeholders.
The LCWIM is the model for planning and constructing wells. At a glance, the designed looks like the current models with the addition of the WOS and the subsurface interface application. This is visualized in Figure 1-1.

Apart from a short introduction to parts of the application under development, this chapter primarily outlines how the LCWIM is planned to run.

3.1 Introduction to the DWM process

One of the corner stones of the DWM process is the ability to shape the process and model as required. The users will find the "reporting language" easy. They will use this language to build experience stored as intelligence into the planning section of the WOS. Also, the language is a tool to manipulate activity programs and procedures. The user can change any step or parameter and the WOS apply the manually entered input in the subsequent planning cycle. This process fulfills a proverb: "Computers are incredibly fast, accurate, but stupid. Humans are incredibly slow, inaccurate, but brilliant. Together they may be powerful beyond imagination". The designed process is an attempt to combine and enable the best in humans and computer technology. Following the above description of DWM and the proverb, this thesis proposes to add a 4th well integrity pillar to the *technical*, *operational* and *organizational* solutions from preventing loss of containment: "information management". Not only is communication often difficult and the industry could handle information better, but the support of software is increasing in most areas. Information should ideally be handled as in the description of DWM above, as designed for the LCWIM. Another difference from today's compartmentalized processes, where wells have stepwise discipline-based deliveries through the life cycle. The focus is changed from discipline KPIs to focus on operator's value chain, see Figure 1-6. Note that KPIs per discipline are still interesting, but they are placed in the context of and subordinated the value chain.

3.2 Introduction: fundamentals of the LCWIM

Introducing a few essentials to understand the architecture of the LCWIM.

1) Introduction to report language and digital experience
2) Background architecture and system
3) Level of detail in programs

[14] Term borrowed from "lean"
[15] Once fully developed, the prototype is designed to interact with e.g. ProNova to make detailed activity reports.

3.2.1 Introduction to report language and digital experience

There are three central functions enabled by the report language:

a) The traditional reporting – Daily Operations Report (DOR)
b) Digital program
c) Digital experience

3.2.1.1 Traditional DOR

In the center of Figure 3-2 is a snip of a DOR, reporting 3 hours of drilling 17 ½" hole. There are 7 columns of code selected by the user before describing the operation using free text in the last column. See the similarity to e.g. line marked a37 in the same figure, which is the digital program.

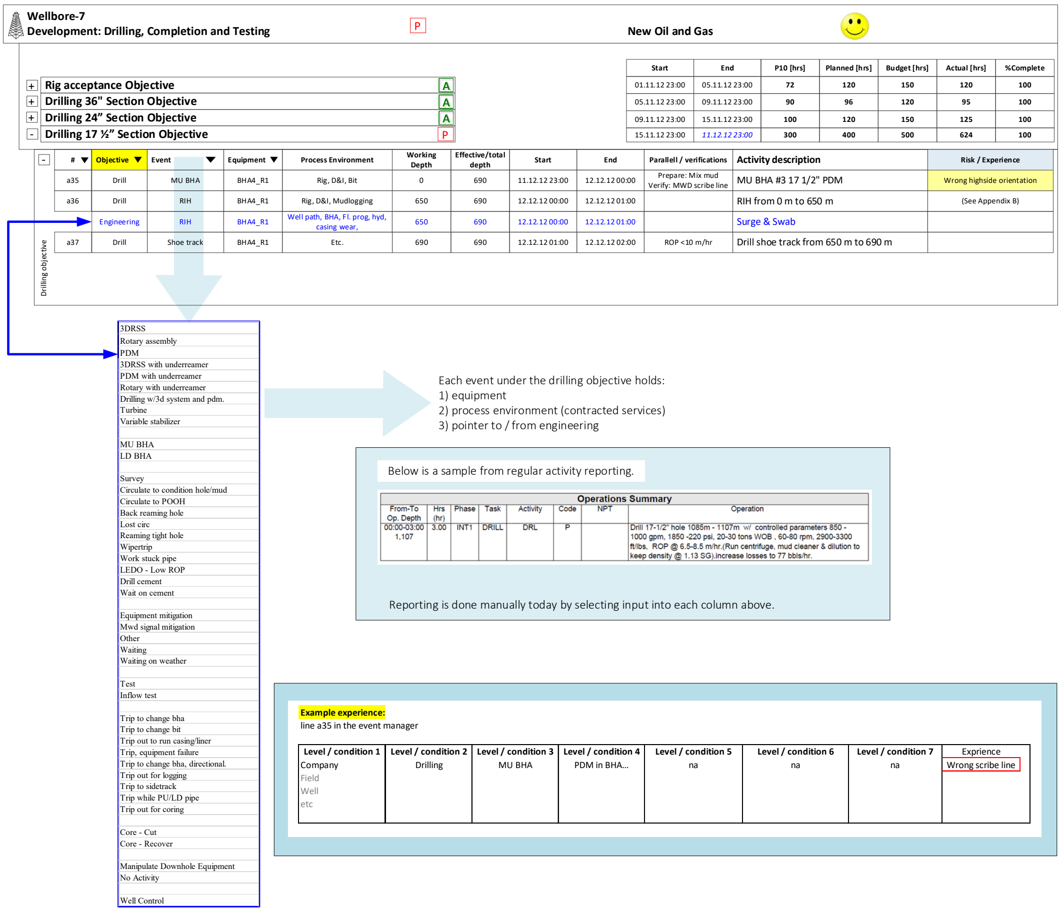


Figure 3-2 - Digital program with activity, engineering and experience.

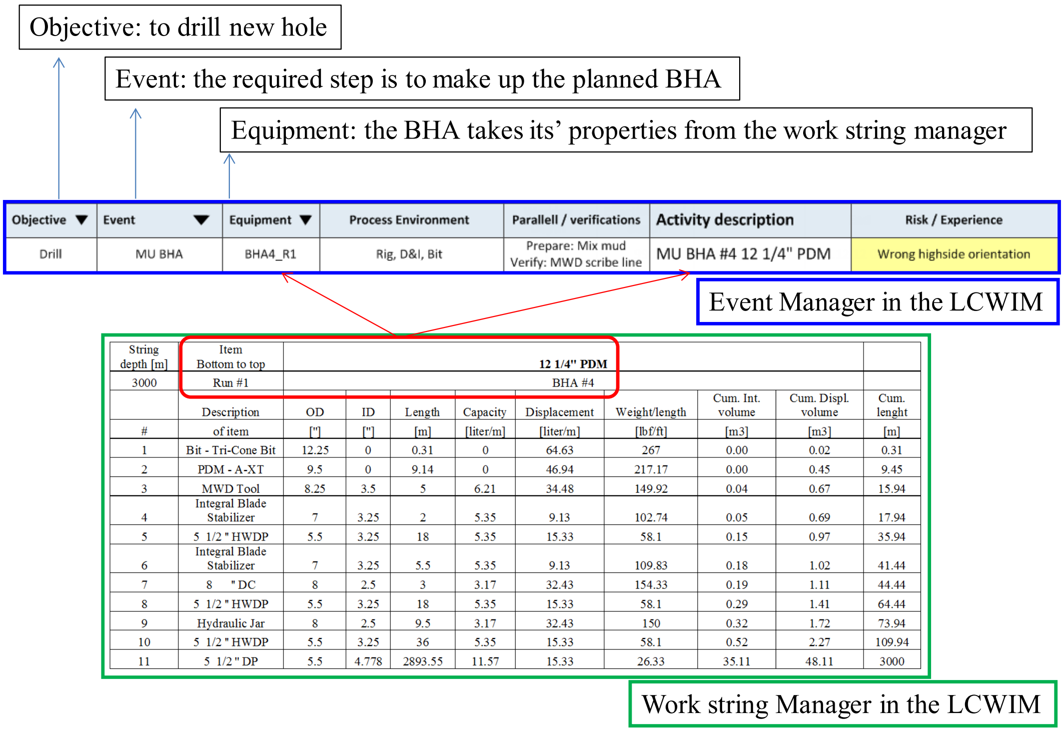
The list of "Events" marked with blue outline is further elaborated in Figure 3-6 as "methods". The figure shows a list of all activities required to perform drilling. The list has been worked out based on experience with several software models for Daily Operation Reports. A list of activities has been worked out for each type of "Objective" such as Drilling, Completion, Intervention, etc.
Current reporting programs often use drop down menus for each column. There are fixed possibilities for each of these columns, i.e. a finite selection for each of the columns, see Table 3-2.

Table 3-2 - Daily Operation Report (DOR) - columns explained.

Col #	ID	Comment
1	Time	0 to 24 hours
2	Duration	0 to 24 hours (locked to column 1)
3	Phase	E.g. Move, Prepare, Drilling, Completion, Intervention, Workover, Well Integrity, P&A, Other
4	Task	Linked to column 3 to specify which task in the "Phase" category
5	Activity	Linked to column 3 and 4 for further specification
6	Code	Boolean type field: "P" for productive time and "N" for NPT
7	NPT	Linked to column 6: in case of "N", apply code to categorize NPT
8	"Operation"	Free text to describe activities

3.2.1.2 Digital program

The digital program follows the same structure as in the worldwide reporting applications such as the Daily Operation Report sample inserted in Figure 3-2. Figure 3-3 shows an explanation to the columns in the prototype of the digital program.



Objective	Event	Equipment	Process Environment	Parallell / verifications	Activity description	Risk / Experience
Drill	MU BHA	BHA4_R1	Rig, D&I, Bit	Prepare: Mix mud Verify: MWD scribe line	MU BHA #4 12 1/4" PDM	Wrong highside orientation

String depth [m]	Item Bottom to top					12 1/4" PDM				
3000	Run #1					BHA #4				
	Description	OD	ID	Length	Capacity	Displacement	Weight/length	Cum. Int. volume	Cum. Displ. volume	Cum. lenght
#	of item	["]	["]	[m]	[liter/m]	[liter/m]	[lbf/ft]	[m3]	[m3]	[m]
1	Bit - Tri-Cone Bit	12.25	0	0.31	0	64.63	267	0.00	0.02	0.31
2	PDM - A-XT	9.5	0	9.14	0	46.94	217.17	0.00	0.45	9.45
3	MWD Tool	8.25	3.5	5	6.21	34.48	149.92	0.04	0.67	15.94
4	Integral Blade Stabilizer	7	3.25	2	5.35	9.13	102.74	0.05	0.69	17.94
5	5 1/2 " HWDP	5.5	3.25	18	5.35	15.33	58.1	0.15	0.97	35.94
6	Integral Blade Stabilizer	7	3.25	5.5	5.35	9.13	109.83	0.18	1.02	41.44
7	8 " DC	8	2.5	3	3.17	32.43	154.33	0.19	1.11	44.44
8	5 1/2 " HWDP	5.5	3.25	18	5.35	15.33	58.1	0.29	1.41	64.44
9	Hydraulic Jar	8	2.5	9.5	3.17	32.43	150	0.32	1.72	73.94
10	5 1/2 " HWDP	5.5	3.25	36	5.35	15.33	58.1	0.52	2.27	109.94
11	5 1/2 " DP	5.5	4.778	2893.55	11.57	15.33	26.33	35.11	48.11	3000

Figure 3-3 - Columns in digital program. Figure taken from (Brechan(4), 2018).

As can be understood from Figure 3-3, the digital program interface is also a key "info hub". The user can either change an activity by manipulating the codes and depending sub activities and tasks or make an addition by inserting a line where required. The LCWIM digital program has a code system available to describe any item, activity or service made for planning, construction, intervention and plugging wells. As can be seen in Figure 3-4, it is also linked to well construction engineering. The red stapled line marks the section objectives, the blue marks an expanded section objective and the green marks the text field. Green font marks detailed procedure.

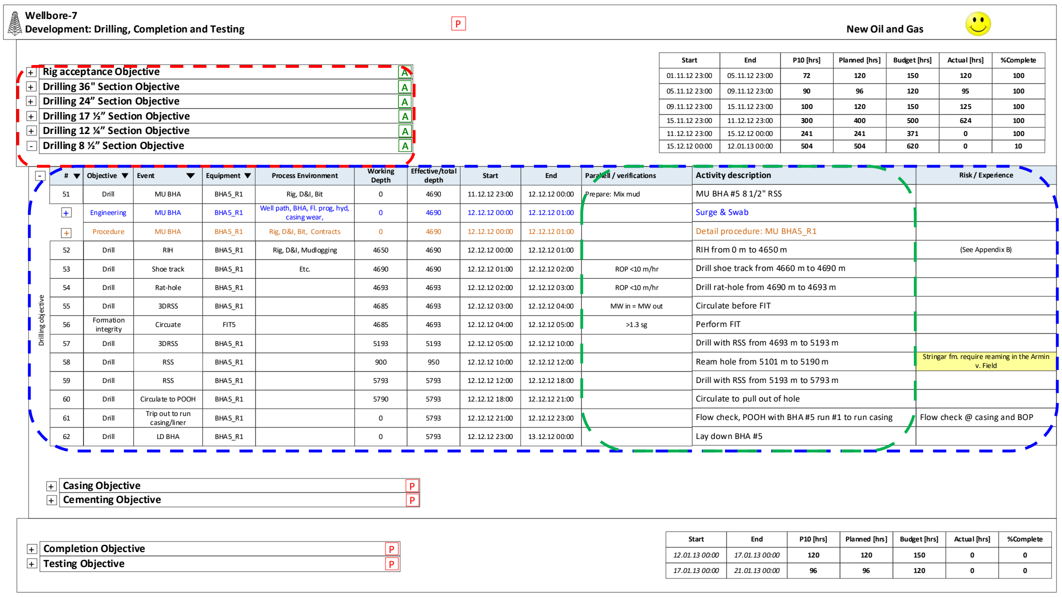


Figure 3-4 - Event manager: blue font is link to engineering.

The "Event manager" can be seen in Figure 3-18 and more details can be found in chapter 1.1.

3.2.1.3 Principal architecture of digital experiences

A central feature in the LCWIM is the ability to make plans using learning and experience automatically. An example of a digital experience can be seen in the bottom of Figure 3-2. It is automatically added due to the matching conditions in line a35. Since digital experiences are written using the same "report language" as the digital program, experiences can be made to do any physical change to the program or services. The framework is designed to recognize the code sequences and where relevant replace undesired activity sequences, methods, tools or engineering with the desired method, equipment and services.

Another use of the code sequences is to compare with regulations and standards to verify compliance. Standards and governing documentation are mostly description of experiences related to physical conditions and is therefore possible to describe using the reporting language. Both digital experiences and digital experiences are discussed more detailed in dedicated subsequent sections.

3.2.2 Background architecture and system

As said previously, the LCWIM follows the same sequence in engineering as in legacy well planning. The digital program as shown in Figure 3-2, connects information about all physical items and services while describing the main activities planned for the operation. Figure 3-3 displays some of the connected applications and functionalities. There is no new information required out of what is accessible to planning engineers today. Only a transformation of the currently existing information from the text-based form into a digital format. Moving away from dependency on individuals, their experience level and ability to convey information into actions, means that digital contracts and a digital "language" for manipulating operations and engineering is required. The language should be easy to operate for the involved engineers, so they can work with the application without requiring programming abilities. A familiar "language", engineering and planning sequence can boost and empower contribution from each engineer.

3.2.2.1 Digital copies of contracts

Contracts often have a series of documents to cover wide range of scenarios and events. What is needed to enable the WOS to run automated engineering, planning and invoicing is a more systematic approach for remuneration and technical info. For the other main documents, anything that frequently leads to a transaction needs to be listed in a digital format readable for the LCWIM. The rest of the contract documents may continue in their current text-based format.

Table 3-3 - Overview of typical contract documentation.

Col #	Main section	Subsections
1	Agreement	
2	General conditions of contract	Definitions, Contractor's general obligations, Transportation, Contractor to inform itself, Contractor to inform company, Assignments and subcontracting, Contractor personnel, Defective performance, Changes to the work, Force majeure, Suspension, Terms of payment, Insurance by contractor, Indemnities, Ownership, Consequential loss, Patents and other proprietary rights, Laws and regulations, Taxes, Confidentiality, Termination, Audit, Liens, Business ethics, General legal provisions, Resolution of disputes, Warranty, Access to locations, Health, safety, environment and the welfare of personnel, Performance management, Aggregate of liability, Continuing obligations, Anti-corruption undertakings, Special conditions
3	Scope of work	
4	Remuneration	General, Mobilization and demobilization, charge rates, Third party services, Fixed rates, Payment and invoicing provisions, Schedule of rates and charges, Volume discount, Depreciation of contractor’s tools & equipment (LIHC), Schedule of rates and charges, Contractor’s price list
5	Quality assurance	
6	HSSE	
7	Code of conduct	
8	Interpretation	
9	Technical	See example for packer in Figure 3-5- Table 3-4 lists technical info
10	Special provisions	
11	Tax provisions	

Figure 3-5 and Table 3-4 are examples of specifications of items in contracts.

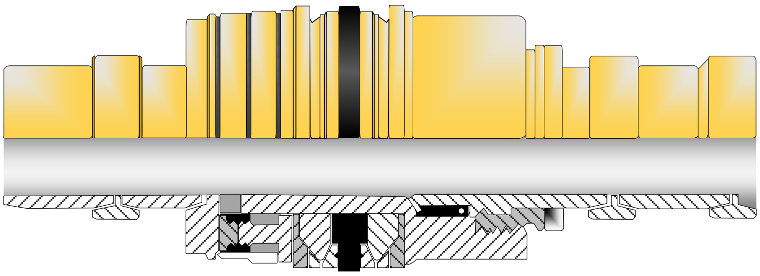


Figure 3-5 - Contracted item - production packer.

Table 3-4 - Some technical info provided with contracts – related to item in figure above: production packer.

Casing size	9 5/8”
Weight range	4047 pound/foot
Maximum OD.	8.420”
Minimum ID.	6.000”
Seal bore ID-min.	7.000”
Length	81.12”
Material	13cr 80 my
Element material	nitrile
O-ring material	Viton/aflas
O-ring back-up material	peek
Bottom thread	7 5/8-33.7 VAM top box
Latch type	7 7/8-4 ac
Temperature rating	40325 deg. F
Pressure rating	5,000 psi
Burst pressure (calc)	7,000 psi
Collapse pressure (calc)	5,000 psi
Tensile strength (calc)	339,100 pounds
Piston area	11.27 sq. Inch
Start setting pressure	1,740 psi
Setting pressure-min.	2,700 psi
Setting pressure-max.	5,850 psi

The work to standardize contracts can be minimized to sections “Technical” and “Remuneration” and all administration related to standard equipment selection for planning and engineering is covered. This is also enough to fully automate ordering of equipment and services, make proforma invoices for a detailed budget and AFE, and a coupling to the performed activities makes sure the proforma invoices are corrected and payment can be automated. “Technical” and “Remuneration” can have a digital format based on the reporting language or other formats.
In the late 1990s, SAP was introduced and became the standard for the industries’ stocking and quality systems. Every part used in a well down to the smallest O-ring currently have an SAP number, which can act as a unique identifier. This number can be used as a tracker for the WOS enabling automated picking of standard equipment (packages), identification of which item is installed in which well and other electronic services requiring electronic tracking. Only a few central properties of an item are required for engineering and automation of invoicing.

3.2.3 Level of detail in programs

As will be seen later in this chapter, the digital program is the base for the digital detailed procedures. Programs are designed to maintain the same level of detailed as in programs used in the industry today. Procedures are also designed to describe operations in the same level of detail as the text-based procedures used today. It is possible to describe operations and equipment functionality into higher degrees of detail, but the need for this is currently not present. Procedures are made to describe the activity, i.e. how to operate rig equipment, wireline winches, etc. Therefore, the level av detail remain the same as today for both manual and automated rigs.
There are a finite number of standard equipment to be either rented or purchased. The rented equipment is often tools performing a service, while the purchased items are often part of the well construction. A rig is often standardized to come with pipe handling equipment, winches, cranes, top drive, system for mud processing, security systems for fire and gas, etc., all of which have specific functions. This equipment is used in a sequence to drill down one stand. This sequence is detailed by the NOVOS software, i.e. the detailed procedures needs to describe “drilling” and the NOVOS software will drill using the operational parameters according to the input from the LCWIM only overruled by “supervisory control” commands for safety or “optimization” commands by any 3rd party software in use, see Figure 2-5 for details.

Should other system than the rig floor equipment be automated, e. g. Wireline winches, it is possible to develop an interface towards the software controlling this equipment. However, as stated by several experienced industry professionals, there is a limit to how digital and automated operations will become. Preparing tools for drilling or holding pre-job meetings are not likely to involve automated equipment. For cases like this, the digital procedure will have a line describing the activity where only humans are active.

3.3 Software development structure

Establishing a proper architecture is crucial to software implementation. Object-oriented software design is a well-established and renowned paradigm for structuring an extensive system such as LCWIM. Object-oriented design implies the design of classes of "objects" that interact with one another to fulfill the desired functionality. Classes are powerful modeling constructs as they contain both data structures (often called attributes) and procedures (called methods), c.f. Appendix G.

The object-oriented paradigm seems very well suited for design of LCWIM-based software to cater for:

- All items having a digital description of physical properties and cost
- The need for users to set up a number of constellations of operations, equipment and services
- Automation of digital programs with user intervention and verification

Central object-oriented design is to identify attributes and methods. Figure 3-6 depicts the generalized class “Drilling” which encompasses all attributes and methods pertinent to a digital drilling program. Point marked “1” in Figure 3-6 are the necessary attributes to describe a drilling operation while point marked “2” are the methods defining relevant procedures. In the same manner, Figure 3-6 shows the generalized classes “Casing” and “Cementing” defining the relevant attributes and methods for representing casing and cementing operations.

The right half in Figure 3-6 is the Event manger (c.f. Figure 3-4) with the linked engineering and detailed procedure for activity #51 “MU BHA”. The events from #51 through #62 belong to the 8 ½” Section objective. The activities in the section may be derived from the “generic” “Drilling” class of Figure 3-6 . Should the user choose to add a bit run or change the drilling BHA to accommodate an under-reamer, lines are added which are building blocks readily prepared from the “parent” class called “Drilling”.

The general class “Drilling” forms a basis for a subsequent detailed object-oriented design. A detailed object-oriented design process may decompose the “Drilling” class to form a parent class that contains only attributes and methods that are strictly common to all drilling sections – and form one or more subclasses, e.g. “DrillingSectionObjective”, that restrict relations and aggregation of only relevant drilling objectives, equipment, and events.

The codes used in reporting of drilling activities worldwide today, can be reflected, c.f. Figure 3-6 . However, programmers may react to the use of “code”. Keywords or activity ID may be a better name or description. Secondly, reporting in “daily operations reports” (DOR) has historically been used to describe activities and their general time consumption. DOR are performed for all operations in the category construct, maintain or plug wells. Because most reporting systems are made for the purpose to report per activity and in some systems support detailed KPIs, the traditional codes in most reporting systems are insufficient for a full linking to connect items and services as seen for drilling in Figure 3-6 . This means that today, every resource is manually described multiple times for each well in multiple systems, text-based reporting, documentation and engineering software.
Figure 3-7 shows the parent / child relationship for “Completion – upper completion”, where the child is collapsed. The point to these figures is to demonstrate the link between activities and the ID-

code in reporting systems historically used worldwide. And adding more functionality to each of the ID-codes can enable a dynamic planning tool, or as a software development professional said: “object-oriented environment”. The lists of ID-codes are not exhausted in this Thesis, which will not detail the research in this area any further.

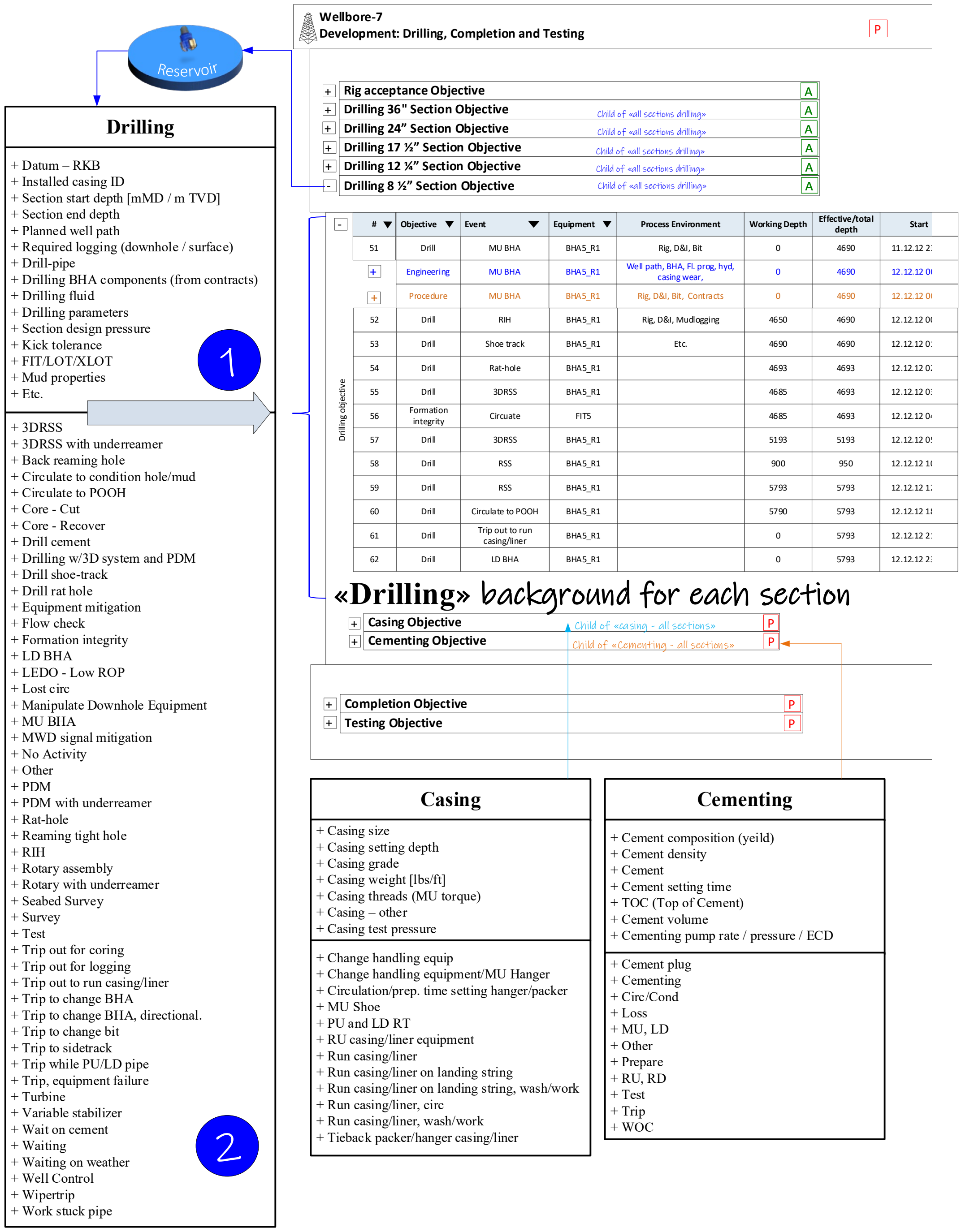


Figure 3-6 - Object oriented Programming structure applied directly on the reporting language.

Figure 3-7 shows how each ID code is linked to added functionality. When a planning engineer add a line of activity and pick from the list of "methods" (ID-codes) in the parent class, a new predefined building block is added. Each building block can be thought of as a "mini-service" as are the building blocks in Service Oriented Architecture. Figure 3-7 shows the objective of the construction, which is to install completion so production can commence.

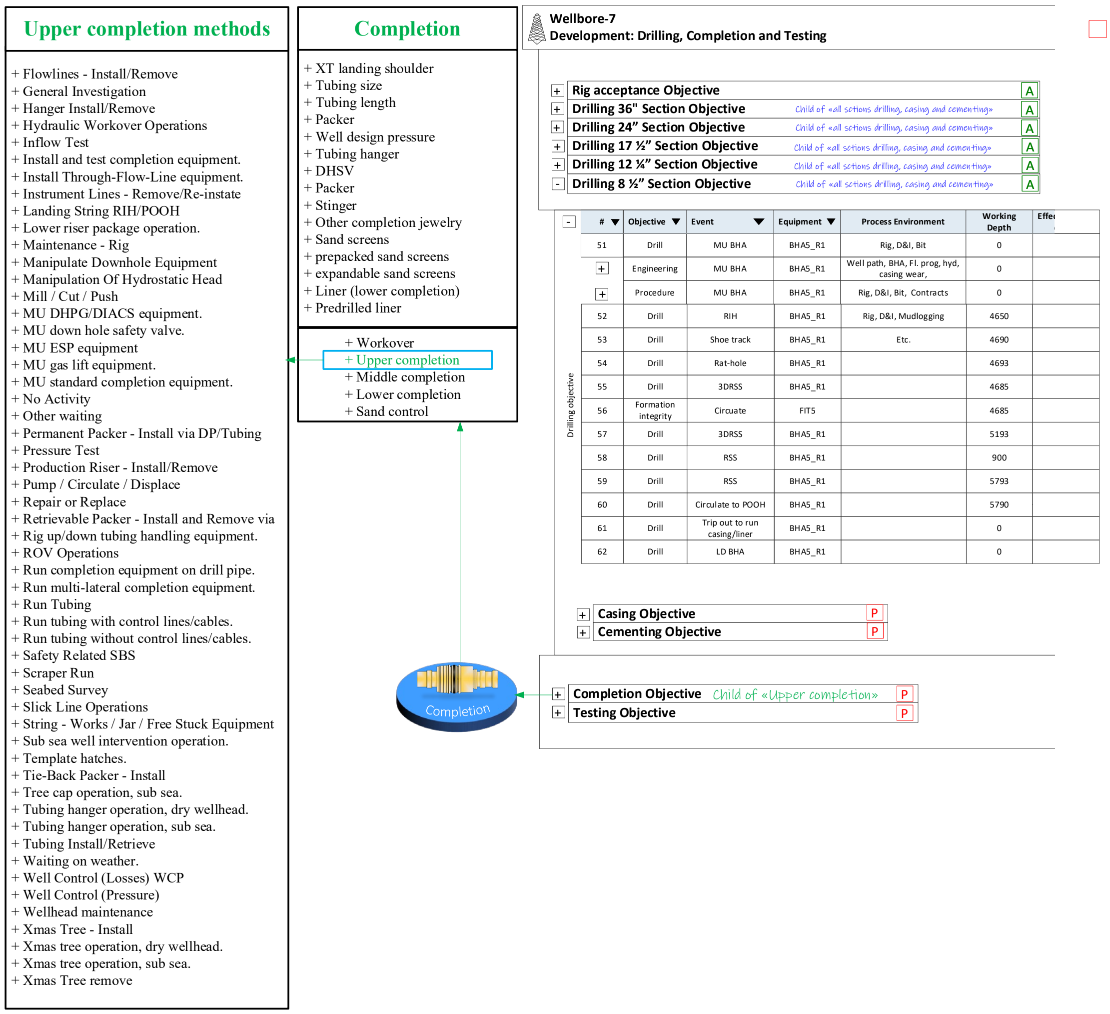


Figure 3-7 - Parent and child for Completion operations.

The Completion "parent" is used one unique way for every well. The Service Oriented Architecture is even more prominent for drilling. As can be seen in Figure 3-8, each section drilled down to final TD applies the parent "Drilling – all sections". With a relatively modest set of ID-codes, it is possible to describe the drilling sequence due to its' repetitive nature. The challenge in drilling lies within determination of optimal operational parameters. These belong in detailed procedures after the engineering cycles have been run to conclusion. As today, a set of recommended parameters and all operational boundaries needs to be determined for all operations.

Figure 3-7 shows the complexity in describing completion operations. As can be seen from the number of "methods", the complexity lies in the variety of activities and tools applied. As said earlier, well intervention are complex to describe. There is a vast number of tools and combinations of using these to meet the many objectives set for interventions. Limiting the ID-codes and intervention scope to standard operations will reduce the complexity. More complex and specialized tools and objectives can be added to the contracts and list of “Methods” later.

Figure 3-8- Each section drilled use the "parent" for every well, while completion apply the parent once.

Figure 3-9 offers an overview of the model in “drilling mode”. For petroleum professional, it can be easier to get an overview and understand the model from this figure. The data flow may need an introduction.

3.3.1 Principal data flow

Figure 3-9 shows the LCWIM picking up fundamental data from the subsurface models. This is done by the WOS, which distributes the data and initiates development of the digital program and required engineering. A structured overview of the data flow can be summarized to:

1. Pick up subsurface input
2. Make a 1st draft digital program based on these data (Name: *initial plan*)
3. Build on the previous step to detail a more accurate program (Name: *iteration sequence*)
    a. The WOS applies digital experiences to arrive at “best practice” level (method)
    b. The engineering models iterate until optimal operational parameters are determined
4. The WOS reports level of “confidence” to the user (how well the program is)

The above sequence is the outline from start to end of how the LCWIM operates. It will be useful for the reader to remember this when the different steps are detailed. Step #2 is detailed in section 3.4. The section is called “Well planning” as the sequence of how the 1st draft is established follows initial engineering of well planning. Step #3 is called “iteration sequence” and it is discussed further in section 3.5. This is a feature where the user will get notified where the LCWIM identifies planned activities with elevated risk. This step is not be discussed further here.

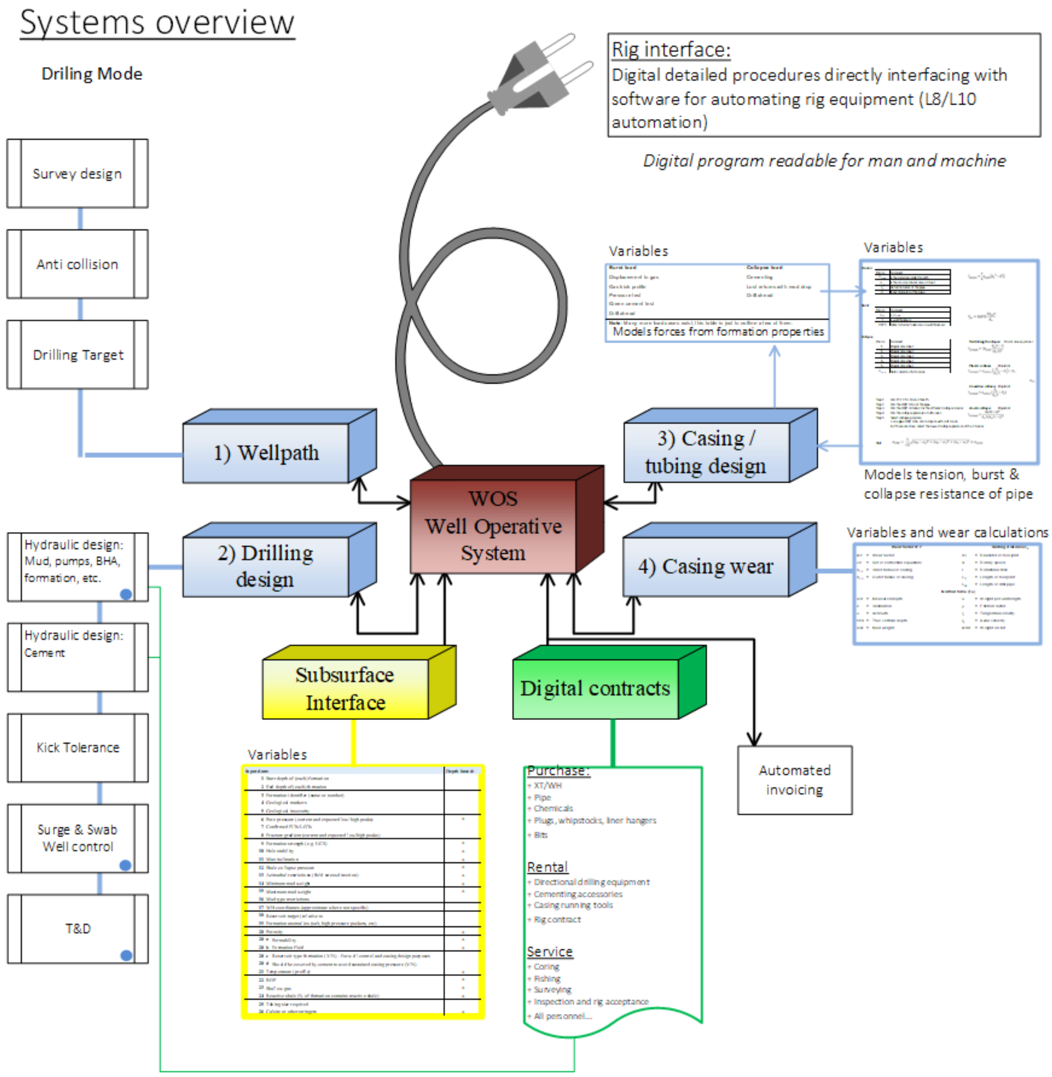
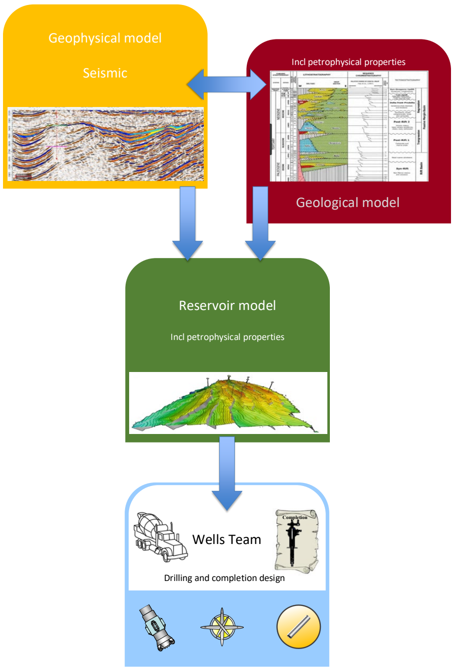


Figure 3-9 - DWM process - system overview, drilling mode.

3.4 Well planning - initial plan

The overall data flow in well planning is outlined per involved discipline in Figure 3-10. The WOS is planned with an interface to the subsurface data, subsurface interface application (SIA). With this input, the WOS can drive the engineering calculations through the required iterations until a digital program and digital detailed procedures are ready for verification by the Wells Team. The sequence of how the initial plan is derived is outlined in the flow chart to the left in Figure 3-11. The figure shows how processing of the subsurface data through Bezier algorithms in the prototype for well paths produces the first proposed well trajectory.
Note that the prototypes for engineering calculations are not the focus of this thesis, they are basic calculations made to provide simulations to demonstrate the capacity and functionality of the WOS.

A few calculations and engineering models other than the industry standard have been considered. The other designs are introduced in chapter Appendix B “Improved engineering and understanding”.



Input data:		Depth based:
1	Start depth of (each) formation	
2	End depth of (each) formation	
3	Formation identifier (name or number)	
4	Geological markers	
5	Geological insecurity	
6	Pore pressure (current and expected low/high peaks)	x
7	Confirmed FITs/LOTs	
8	Fracture gradient (current and expected low/high peaks)	
9	Formation strength (e.g. UCS)	x
10	Hole stability	x
11	Max inclination	x
12	Shale collapse pressure	x
13	Azimuthal restrictions (field stress direction)	x
14	Minimum mud weight	x
15	Maximum mud weight	x
16	Mud type restrictions	
17	WH coordiantes (approximate where not specific)	
18	Reservoir target (relative to	
19	Formation anomalies (salt, high pressure pockets, etc)	
20	Porosity	x
20 a	Permability	x
20 b	Formation fluid	x
20 c	Reservoir type formation (Y/N) - for well control and casing design purposes	
20 d	Should be covered by cement to avoid sustained casing pressure (Y/N)	
21	Temperature (profile)	x
22	ROP	x
23	Shallow gas	x
24	Reactive shale (% of formation contains reactive shale)	x
25	Tubing size required	
26	Calsite or other stringers	x

Input from Subsurface

Figure 3-10 - Left: Data in well planning per discipline. Right: Subsurface interface application (SIA), i.e. the Wells Team input.

3.4.1 Initial well-path

Typical subsurface data required for basic well planning of a well is summed up in the table to the right in Figure 3-10. The input is WH and target coordinates. The well-path is automated with few rules as guidelines.

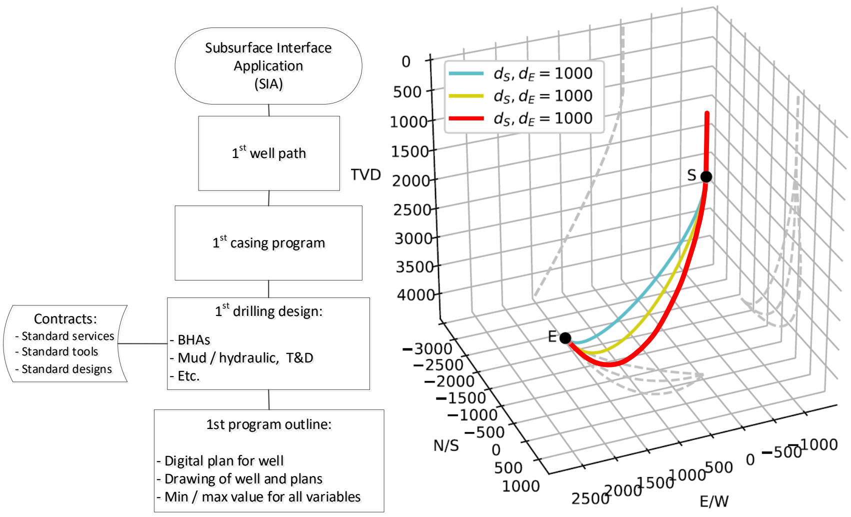


Figure 3-11 - Left: Establishing outline of well construction. Right: First well path (modified from Gravdal, 2019).

3.4.2 *Initial section design with tubular program*

The next step is a first outline of sections and casing program proposal. The logic is based on down-up analysis of pore pressure plots by defining mud weights. The automated module has been tested on a few hole stability plots with various starting mud weights, see Figure 3-12.

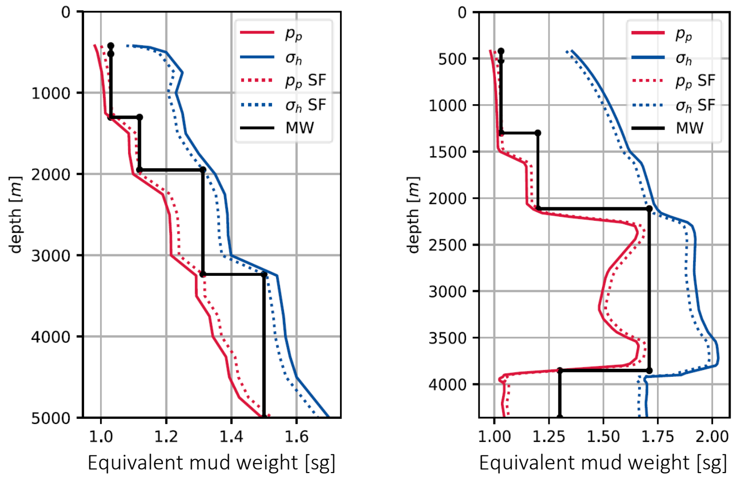


Figure 3-12 - Module for outline of sections (modified from Gravdal, 2019).

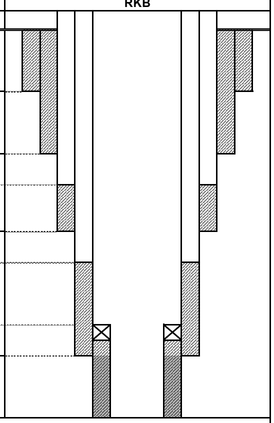
As seen in Figure 3-12, the casing program can be drafted based on the info above as input:

a) The number of sections is outlined
b) The tubing size is given from the Subsurface input

With this given input, standard tubular program is designed in the first round. The simulation in Figure 3-12 can results in a proposal as in Table 3-5. Note that several of the engineering modules are standalone and tested with different well data

Table 3-5 - Initial proposed casing program with cementing.

Well: #7			Tubing size: 7 "			
Field: ArminV			Rig: Rig 1			
HOLE		CASING		CSG. SHOE		
SIZE	TVD MD	SIZE	Grade Weight	TVD	MD	RKB
SB	300		[lb/ft]			
38 1/4"	330 330	30"	X-50 310	325	325	
26"	1200 1200	20"	J-55 133	1195	1195	
17 1/2"	2000 2000	13 3/8"	L-80 72	*1895* 1995	*1895* 1995	
12 1/4"	3200 3200	9 5/8"	P-110 53.5	*2895* 3095 3195	*2895* 3095 3195	
8 1/2"	5000 5000	7	L-80 29	4999	4999	

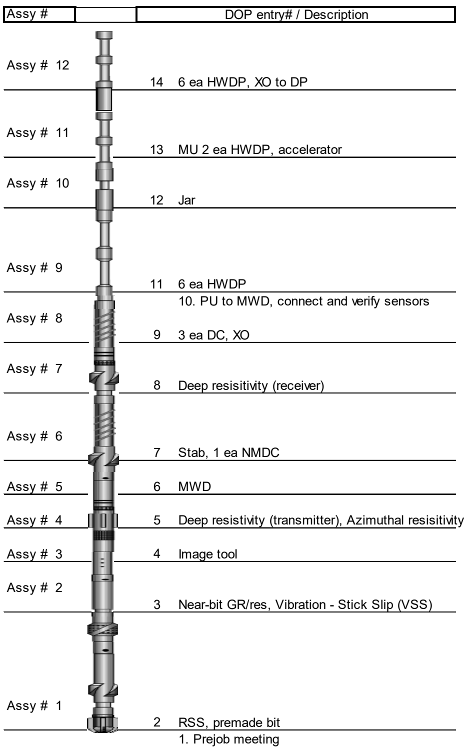


Comments:
Cement is planned according to standards and regulations for each section.

Comment to result in Table 3-5:
Casing, liner and tubing are often standardized in size due to lead time, logistics and stock keeping. The cost of stocking multiple grades and weights often exceeds the cost of standardizing on a rigid grade and weight which can be applied in most wells. What is important for an operator is to know what grade and weight per size that is able to handle the forces in the majority of fields and wells. The WOS picks tubulars from relevant contracts, where all relevant properties for engineering and costs are listed.
The proposed sizes in Table 3-5 are standard in the Norwegian sector for non-HPHT wells designed to accommodate a 7" production tubing. In fields where Subsurface often propose a smaller tubing, there may be slimmer casing programs.
Cementing details can be determined from regulations and standards. The conductor and surface casing are cemented to the top, the intermediate casing follows a practice of 100 m and the production casing has 300 m cement height for isolation on top of the 100 m liner lap. This leaves 200 m, which allows for a re-completion in case of a tubing leak. Regulations and practice vary, so the WOS is designed to allow superusers to determine the preferred cement heights to accommodate local regulations and practice.

3.4.3 Initial drilling assemblies

Knowing the casing program, hole sizes and tortuosity, it is possible to pick standard drilling bottom hole assemblies (BHA). The required logging per section is Subsurface input, so it is possible to propose a standard BHA that allow for accurate engineering. BHA components are listed with all required properties in relevant contracts, so a BHA can be proposed for each section such as exemplified for the 8 ½" section in Figure 3-13.



Assy #	Item #	Component	OD [in]	ID [in]	Bottom [in]	Top [in]	Bottom	Top	Contract ref	Length [m]
Assy # 12	18	XO	6,50	2,81	4,5	4,5	NC50	NC50	Rig acc.82	0,5
	17	HWDP	6,50	3,00	4,5	4,5	NC50	NC50	Rig acc.51	55,2
Assy # 11	16	Accelerator	6,75	3,00	5,5	5,5	FH	FH	Fish c.23	9,5
	15	HWDP	6,50	3,00	5,5	5,5	FH	FH	Rig acc.51	19,1
Assy # 10	14	Jar	6,75	2,75	4,5	4,5	NC50	NC50	Fish c.21	8
Assy # 9	13	HWDP	6,50	3,00	4,5	4,5	NC50	NC50	Rig acc. 51	55,1
Assy # 8	12	XO	6,75	3,50	4,5	4,5	NC50	NC50	Rig acc.23	1
	11	DC	6,75	2,75	4,5	4,5	NC50	NC50	Rig acc.12	28,7
Assy # 7	10	Deep Res (r)	6,75	3,00	4,5	4,5	NC50	NC50	D&I r.33	3
Assy # 6	9	Stab	8,40	4,50	4,5	4,5	NC50	NC50	D&I r.23	1,2
	8	NMDC	6,75	2,75	4,5	4,5	NC50	NC50	D&I r.25	9,5
Assy # 5	7	MWD	6,75	4,50	4,5	4,5	NC50	NC50	D&I r.15	9,6
Assy # 4	6	Deep Res (t)	6,75	3,00	4,5	4,5	NC50	NC50	D&I r.72	3
Assy # 3	5	IMG	6,75	3,00	4,5	4,5	NC50	DS50	D&I r.52	9,8
Assy # 2	4	Near-bit GR/Res	6,75	2,75	4,5	4,5	DS50	NC50	D&I r.31	5,6
	3	VSS	6,75	2,75	4,5	4,5	NC50	NC50	D&I r.72	1,5
Assy # 1	2	RSS	6,75	4,00	4,5	4,5	NC50	NC50	D&I r.83	6,1
	1	Bit	8,50	2,25	4,5		Regular		Bit A 8_12	0,3

Figure 3-13 - Drilling BHA: Generated from (offset) well conditions and contract.

3.4.4 *Initial hydraulic program*

The next step in the initial round is to outline a preliminary mud program. It can be determined based on the following established input:

- Section outline - Figure 3-12
- Proposed casing design - Table 3-5
- Proposed mud weights per section – Subsurface input (pore pressure / stability plot)
- Trajectory (stability) - Figure 3-11
- Formations exposed (reactive or benign) – Subsurface input
- Proposed drilling BHA - Figure 3-13

These parameters are input for the prototype application for derivation of hydraulic parameters, see Figure 3-14.

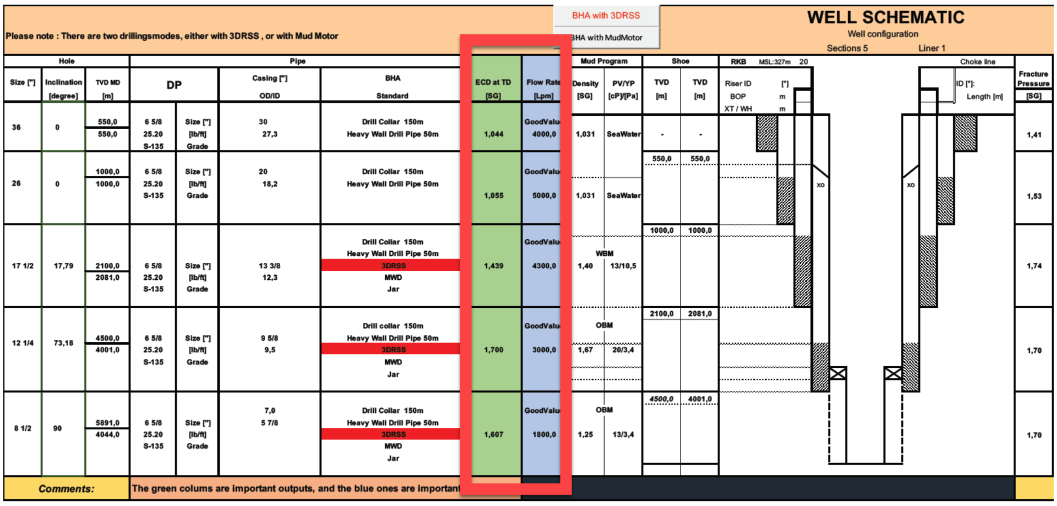


Figure 3-14 - Automated hydraulic program (modified from Al-Shami, 2019).

The application provides the following simulations:

- Bit hydraulic
- Verify / adjust proposed DP size
- BHA hydraulic (pressure loss over components)
- Mud pump design
- Flow rates (vs mud pump design)
- Equivalent circulating density
- Hole cleaning
- Proposed ROP (vs hole cleaning)

This prototype picks standardized fluid designs from contracts, or it can be defined by a superuser:

- Mud types used: Oil Based Mud (OBM) / Water Based Mud (WBM)
- Mud properties (standardized as function of exposed formations, mud weight, temperature and stability of formations)

3.4.5 *Initial T&D*

A prototype for T&D uses the soft string model (Johancsik, 1984) which provided the first computerized and most commonly used model in the industry. Figure 3-15 shows a test performed with the model.

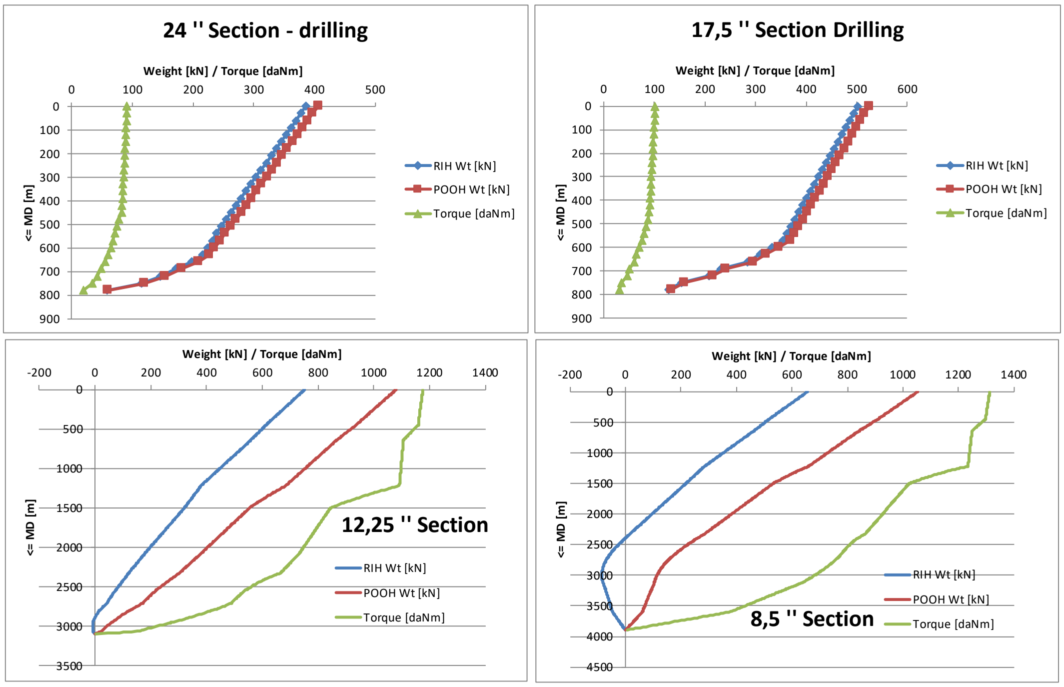


Figure 3-15 – Prototype for automated T&D.

3.4.6 *Initial kick tolerance – open hole design*

Next engineering calculation is kick tolerance, see Figure 3-16.

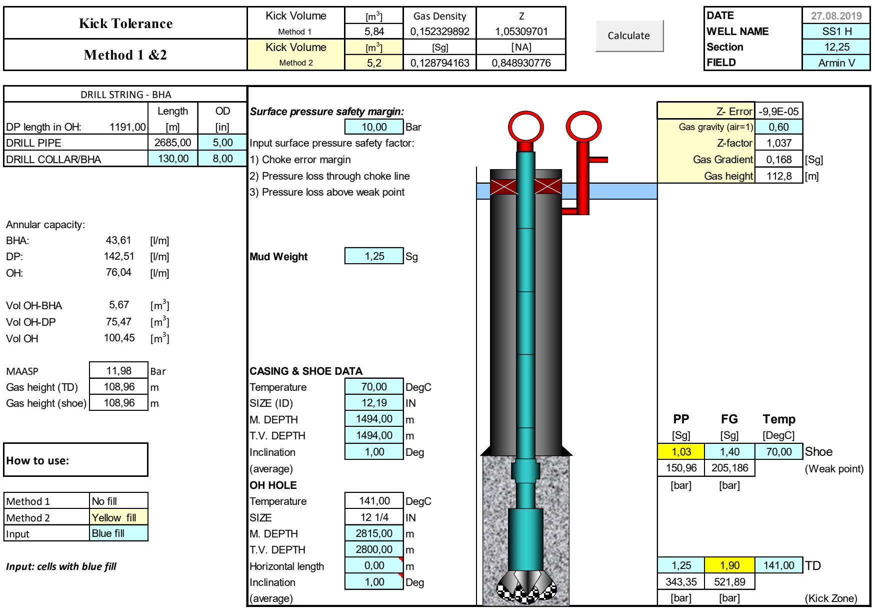


Figure 3-16 - Kick tolerance.

The application calculates and reports kick tolerance in two parallel calculations: The Redlich-Kwong and the Standing-Katz gas calculations. Both the T&D and the kick tolerance applications are giving "judgement" of the preliminary drilling design. A faulty design has consequences only in the next stage – *iteration sequence*.

3.4.7 Initial digital program - example

Once the basic engineering calculations in Figure 3-11 through Figure 3-16 and Table 3-5 are in place, the first digital program can be made. This is the event manger which was introduced in section 3.2.1.2. The target of the initial plan is to establish the basic parameters and outline a plan which can act as fundament for the development of the final program. Once the *initial plan* has been used to establish the first draft digital program in the event manger, the software is designed to start the second round – *iteration sequence*. This is step #3 in the list in section 3.3.1, which shows the overall data flow of the LCWIM.
The event manger act as a hub for the information flow and development of programs. Figure 3-17 shows how it is coupled to two blocks called Design 1 and Design 4. The final step in the *initial plan* derives a draft digital program. In the process, the WOS applies information from standards or company regulations which are the 2 top layers. The bottom layer of each box in Figure 3-17 represents engineering. The *initial plan* prepares and builds the connection between the boxes for designs, so the iteration sequence can run and develop an optimal program. As indicated by the arrows on top of box 1 in Figure 3-17, the engineering and development of programs takes place though iterations.

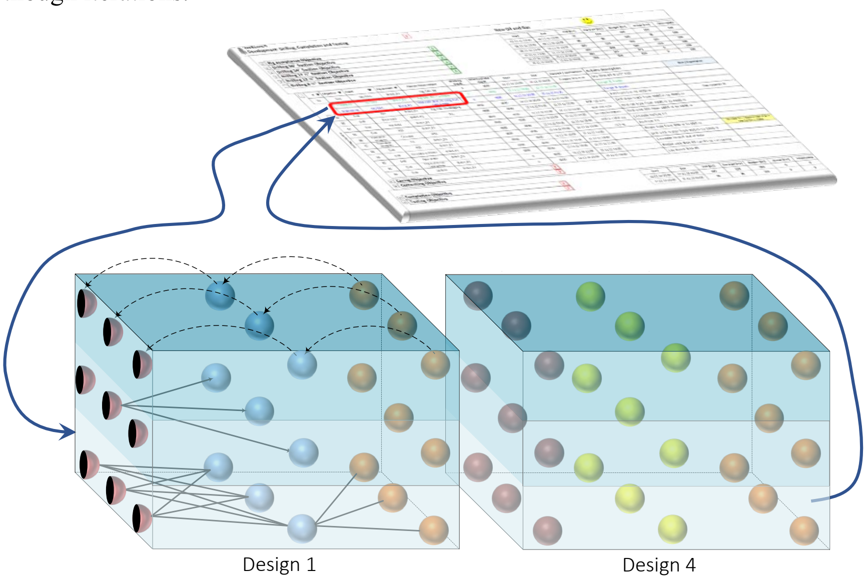


Figure 3-17 – The variables follow an iterative pattern, see section 3.9 for details.

Each ball in Figure 3-17 represents a function (engineering calculations, digital experience, method selection, governing regulations, etc.) with a set of variables. The process of managing the variables is part of the "iteration sequence" and will therefore be discussed and made clear over the subsequent chapters.

The example covering the development of the first draft digital program is based on the information in Table 3-5. The data for the example is the 8 ½" section. The fundament for the derivation of the program is therefore a "fixed" list of 7 elementary steps found in company best practice[16], which has

[16] The industry has used "best practice" as fundament for operations as a way to ensure learning is transferred from one operation to the next. The method often implies updating a planned detailed procedure with actual events taking place,

the objective of drilling described in detail for each section. The basis steps for the 8 ½” section is the list below[17]. The example will reveal the steps going from the 7 basic generic steps into more detailed sequence using designed and programmable logic. Finally, the link to detailed procedure will be shown.

1) MU BHA, optional: test casing to section design pressure
2) RIH, optional: test BHA
3) Drill shoe track and rat hole
4) Drill 5 m new formation and perform FIT/LOT
5) Drill 8 ½” section
6) Circulate hole clean and flow check
7) Pull 3 stands, flow check, POOH: flow check at casing and BOP.

3.4.7.1 MU BHA

The MU BHA method is linked to “equipment 1”: Here, the system selects BHA5_1 which is depicted in Figure 3-13.

Tools involved are:
Rig equipment is often used manually since it is often required to change size of handling equipment frequently. Most times, BHA components are pre-made from the workshop. MU BHA is a manual process, see Figure 3-45.

Procedures involved are:
Each item in the bottom hole assembly has a standard handling procedure given in best practice and by supplier. There is an option to test the casing / liner before drilling it out. These details are suited for the detailed procedure.

Engineering involved:
MU BHA links to the standard detailed procedure in Figure 3-45 and requests surge and swab calculations. This calculation will be performed once the *iteration sequence* starts.

Other (these comments are relevant but not repeated for the other methods):
“Equipment 2” links services Rig, D&I and bit. Equipment in category 1 is typically for engineering, while category 2 is mostly to enable a full digital environment where e.g. KPI and cost are fully automated. Standard detailed procedures picked from best practice are linked to each activity. Changing the linked contracts, services and engineering for each “method” is designed to be possible for superusers.

3.4.7.2 RIH

Run in hole is a method where the rig equipment transports “equipment 1”. In this case, it means BHA5_1 will be transported from surface to 3195 m. The name is from BHA #1 in section #5.

Tools involved are:
Rig equipment adds drill pipe in stands until the bit depth has reached 3195 m.

Procedures involved are:
Check float, if any, fill pipe to avoid underbalance and test BHA if required. Prepare kill sheet for drilling out shoe. If a change of mud is planned, method 1 is to circulate while drilling out shoe and

and then this updated document is used as fundament when planning the next operation. The 7 basic steps in the example is similar to the traditional approach. The best practice can be highly developed and detailed, but here it is kept simple to put focus on the method and not on the content.

[17] The section based on these steps are generic best practice. They are important for developing the event manger.

method 2 is to circulate after the integrity test. Volume control is maintained. These considerations belong in the detailed procedure.

Engineering involved:
T&D. Since the BHA is tripping in cased hole, the operation is not limited by surge and swab. Any component with a property restricting tripping speed may limit the operation.

3.4.7.3 Drill shoe track and rat hole

Drill shoe track and rat hole is a method where equipment 1 is applied to drill through shoe track and rat hole.

Tools involved are:
Rig equipment adds drill pipe in stands until the bit depth has reached 3200 m (shoe track) and 3205 m for the rat hole.

Procedure involved are:
The pump rate is limited to the same as when drilling new formation, weight on bit (WOB) is restricted to 0 – 1 ton and the string is set down on the cement in short periods of time before lifted up to circulate out cut cement. Volume control is maintained by monitoring the active volume. These considerations belong in the detailed procedure.

Engineering involved:
Hydraulic, T&D, kick tolerance, casing wear, well control, others.

3.4.7.4 Drill 5 m new formation and perform FIT/LOT

The "drill 5 m new fm." method where equipment 1 is applied with the lenient drilling parameters from the "drill shoe track" method until the stabs and other large BHA components are out of the casing (before standard drilling parameters for the 8 ½" section are commenced).

Tools involved are:
Rig equipment adds drill pipe in stands until the bit depth has reached 3210 m, i.e. 5 m new fm.

Procedure involved are:
Performing FIT/LOT is a manual process and belong in detailed procedures.

Engineering involved:
Hydraulic, T&D, kick tolerance, casing wear, well control, others.

3.4.7.5 Drill 8 ½" section

The "drill" method applies drilling parameters from give depth to set end of section.

Tools involved are:
Rig equipment adds drill pipe in stands until the bit depth has reached 5000 m. Mud pumps provide hydraulic power for hole cleaning, etc.

Procedure involved are:
Connection procedures are presumed for taking surveys, which is relevant for detailed procedures.
Drilling: apply weight up to recommended WOB for the bit unless any other component in the BHA restricts compression. Pumping and rotation while drilling as per recommendations from the hydraulic application: minimum is set by hole cleaning and maximum is either limited by equipment (pumping pressure) or fracture gradient.

Engineering involved:
Wellpath calculations, hydraulic, T&D, kick tolerance, casing wear, surge and swab, well control, others.

3.4.7.6 Circulate hole clean and flow check

The "Circulate to POOH" is a hole cleaning exercise with objective to prepare the wellbore for pulling the drilling BHA safely out of hole and prepare the wellbore for casing and cementing operations.

Tools involved are:
Rig pumps activated, rotation and oscillation of the drill string.

Procedure involved are:
Rig pumps are activated until the minimum volume of drilling fluid is pumped. This is a figure from "best practice", which may vary. Default value is three well volumes at maximum flow rate recommended by the hydraulic app in Figure 3-14.

Engineering involved:
Hydraulic, T&D, kick tolerance, casing wear, well control, surge and swab, others.

3.4.7.7 POOH

POOH is a method where equipment 1 is recovered from the well

Tools involved are:
Rig equipment retrieves drill pipe in stands until the bit depth has reached 0 m.

Procedure involved are:
Pull stands. Flow checks are performed after pulling the three initial stands, before pulling into the casing and through the BOP. Technical details in the POOH method belong in a detailed procedure.

Engineering involved:
Hydraulic (mud properties changed to "tripping quality"), T&D, kick tolerance, casing wear, surge and swab, well control, others.

3.4.7.8 Digital program after "initial plan" - summarized

Table 3-6 summarizes the linking prepared in the "initial plan". This table will be further developed in the "*iteration sequence*". Best practice detailed procedures are linked to each method. The linking takes place in the "Method manager" which is discussed in section 3.6.3. Once the code is selected, the engineering is also connected to the activity.
The kick tolerance and T&D models are examples of designs established with no impact to Table 3-6. All designs are run, and their acceptable min and max values are logged in a variable map, see Figure 3-23. This is mentioned in the flow diagram in Figure 3-11. Since it has impact to the designs made in the "iteration sequence" and does not influence the initial planning, it is discussed in the section below.
Figure 3-18 shows the event manager and Figure 3-19 shows surge and swab calc engineering. Figure 3-20 and Figure 3-21 is an early version of a fully digital procedure for drilling with RSS. It is generated from "best practice" with a generic section as seen in lines 57, p1 and 57, p2 covering safety, well status, priorities and operational steps as generated in an iteration. Line 58, S1 indicates how digital experience may automatically add activities in programs and procedures. In the design of the WOS, digital experience is incorporated after the initial iteration sequence.

Table 3-6 - Basic linking between activities, detailed procedures and engineering in the "*initial plan*".

#	Method	Linked engineering	Procedure	Comment
1	MU BHA	Surge & Swab	Figure 3-45	Figure 3-19 Initial run
2	RIH	T&D	Figure 3-19	Surge & Swab for bit trips
3	Drill shoe track	Hydraulic, T&D, kick tolerance, casing wear, well control, others	*	Standard procedure / best practice
4	Drill 5 m, FIT/LOT	As point 3 above. Add surge and swab calculations	*	* Standard procedure / best practice
5	Drill 8 ½" section	As point 3 above. Add well-path calculations	Figure 3-21	Standard procedure / best practice
6	Circulate clean	Hydraulic, T&D, kick tolerance, casing wear, well control, surge and swab, others.	*	* Standard procedure / best practice
7	POOH	As point 6 above ()	*	* Standard procedure / best practice Mud properties changed to "tripping quality" or casing running quality

* Not elaborated here

The scope of the first iteration sequence can be summarized to:

- Establish an outline of a digital program, i.e. description of activities
- Incorporate company experience
- Outline range of acceptable values for all variables:
  - Well path types (catenary, Bezier or other) with anti-collision options
  - T&D, friction factors
  - Mud weights
  - Casing setting depths
  - Kick tolerance
  - Other
- Establish basic casing program
- Basic tubing design
- Fundament for cost and risk

Wellbore-7
Development: Drilling, Completion and Testing P

New Oil and Gas

Objective	Status	Start	End	P10 [hrs]	Planned [hrs]	Budget [hrs]	Actual [hrs]	%Complete
+ Rig acceptance Objective	A	01.11.12 23:00	05.11.12 23:00	72	120	150	120	100
+ Drilling 36" Section Objective	A	05.11.12 23:00	09.11.12 23:00	90	96	120	95	100
+ Drilling 24" Section Objective	A	09.11.12 23:00	15.11.12 23:00	100	120	150	125	100
+ Drilling 17 ½" Section Objective	A	15.11.12 23:00	11.12.12 23:00	300	400	500	624	100
+ Drilling 12 ¼" Section Objective	A	11.12.12 23:00	15.12.12 00:00	241	241	371	0	100
- Drilling 8 ½" Section Objective	A	15.12.12 00:00	12.01.13 00:00	504	504	620	0	10

Drilling objective

#	Objective	Event	Equipment	Process Environment	Working Depth	Effective/total depth	Start	End	Parallell / verifications	Activity description	Risk / Experience
51	Drill	MU BHA	BHA5_R1	Rig, D&I, Bit	0	4690	11.12.12 23:00	12.12.12 00:00	Prepare: Mix mud	MU BHA #5 8 1/2" RSS	
+	Engineering	MU BHA	BHA5_R1	Well path, BHA, Fl. prog, hyd, casing wear,	0	4690	12.12.12 00:00	12.12.12 01:00		Surge & Swab	
+	Procedure	MU BHA	BHA5_R1	Rig, D&I, Bit, Contracts	0	4690	12.12.12 00:00	12.12.12 01:00		Detail procedure: MU BHA5_R1	
52	Drill	RIH	BHA5_R1	Rig, D&I, Mudlogging	4650	4690	12.12.12 00:00	12.12.12 01:00		RIH from 0 m to 4650 m	(See Appendix B)
53	Drill	Shoe track	BHA5_R1	Etc.	4690	4690	12.12.12 01:00	12.12.12 02:00	ROP <10 m/hr	Drill shoe track from 4660 m to 4690 m	
54	Drill	Rat-hole	BHA5_R1		4693	4693	12.12.12 02:00	12.12.12 03:00	ROP <10 m/hr	Drill rat-hole from 4690 m to 4693 m	
55	Drill	3DRSS	BHA5_R1		4685	4693	12.12.12 03:00	12.12.12 04:00	MW in = MW out	Circulate before FIT	
56	Formation integrity	Circuate	FIT5		4685	4693	12.12.12 04:00	12.12.12 05:00	>1.3 sg	Perform FIT	
57	Drill	3DRSS	BHA5_R1		5193	5193	12.12.12 05:00	12.12.12 10:00		Drill with RSS from 4693 m to 5193 m	
58	Drill	RSS	BHA5_R1		900	950	12.12.12 10:00	12.12.12 12:00		Ream hole from 5101 m to 5190 m	Stringar fm. require reaming in the Armin v. Field
59	Drill	RSS	BHA5_R1		5793	5793	12.12.12 12:00	12.12.12 18:00		Drill with RSS from 5193 m to 5793 m	
60	Drill	Circulate to POOH	BHA5_R1		5790	5793	12.12.12 18:00	12.12.12 21:00		Circulate to pull out of hole	
61	Drill	Trip out to run casing/liner	BHA5_R1		0	5793	12.12.12 21:00	12.12.12 23:00		Flow check, POOH with BHA #5 run #1 to run casing	Flow check @ casing and BOP
62	Drill	LD BHA	BHA5_R1		0	5793	12.12.12 23:00	13.12.12 00:00		Lay down BHA #5	

+ Casing Objective P
+ Cementing Objective P

Objective	Status	Start	End	P10 [hrs]	Planned [hrs]	Budget [hrs]	Actual [hrs]	%Complete
+ Completion Objective	P	12.01.13 00:00	17.01.13 00:00	120	120	150	0	0
+ Testing Objective	P	17.01.13 00:00	21.01.13 00:00	96	96	120	0	0

Figure 3-18 - Event manager - 8 1/2" section.

#	Parallell / verifications	Activity description	Risk experience
		Surge & Swab interface / Add experience	
S&S	**Automated Surge and swab calculations are linked and activated by activity in «Event manager»** Linked BHA: BHA5_R1 Linked fluid and section geometry: 51. Process environment	**Triggering activity in «Event manager»:** 51. MU BHA	(See event manager line 51 for more info)
51, SS p1	**Verify BHA «As run» vs as planned (in LCWIM)** 1. Effective / hydraulic diameter of tools 2. Fill up ports and converting floats to be defined	**Verify Surge and Swab calculations - Prepare** SS p1a. Verify BHA components SS p1b. Verify mud properties	**General:** 1. Under-gauge hole 2. Poor hole cleaning / pack-off 3. Unstable formations
51, SS p2	**Verify automated calculations** 1. Perform simulations in 3rd party software (e.g. fluid contractor) 2. Independent verification of input and calculations	**Verify Surge and Swab calculations - Prepare** SS p2a. Verify subsurface data: Pore pressure, frac and shale stability SS p2b. Verify BHA	**General:** 4. Tine factor / hole stability 5. Bit balling 6. Other
51, SS 1	**Verify S&S limitations** 1. Swab: Minimum margin 0.02 Sg 2. Surge: Max 0.01 Sg below frac (LOT) 3. Surge in formations prone to losses: 0.01 Sg below min. horizontal stress	**Compare 3rd party and automated calculations** SS p2a. Verify subsurface data SS p2b. Verify BHA	
51, SS 2	**Verify with hand calculation** 1. Swab: Minimum margin 0.02 Sg / 0.167 PPG 2. Surge: Max 0.01 Sg / 0.083 PPG below frac (LOT) 3. Formations prone to losses: 0.01 Sg 0.083 PPG below min. horizontal stress	**Hand calculation (metric) [Sg]** $Trip\ Margin = \frac{0.01 \cdot YP}{g(D_{hole} - D_{pipe})}$ **Hand calculation (Imperial) [ppg]** $Trip\ Margin = \frac{YP}{11.7(D_{hole} - D_{pipe})}$	**Where:** a. YP is fluid Yield Point b. D_{hole} is open hole diameter c. D_{pipe} is drill pipe diameter d. g is the gravitational constant 9.81 m/s^2

Figure 3-19 - Surge and swab calculations.

S&S in Figure 3-19 refers to surge & swab.

"51, SS p1" is a line reference, where 51 points to the operative activity (line) in the original program calling for the engineering. SS is short for Surge & Swab and p1 refers to "preparation step no1 in the specific engineering". "51, SS p1" is a way of referencing the lines in activities, engineering calculations and detailed procedures, i.e. a counting system.

#	Parallell / verifications	Activity description	Risk experience / other
57, p1	**RSS - Precautions and steps:** A. LCM pill limitations for BHA4_R1: *320 kg/m^3 / 20 lb/ft^3* **[automated from technical specification in contract]** B. Perform «finger printing» to establish reference and Potential seepage loss **[automated: for rigs with automated equipment]** C. Automated detection and mitigation of stringers **[automated response for rigs with automated equipment]** - Reduce pump rate - Reduce RPM for optimal torque response - Adjust WOB for optimal torque response D. Automated well control support: - Kill sheet and detailed (preferred) kill procedure - Drill break, torque and pressure signatures indicating kick **[automated: pit and well control drills => time based for automated rigs]** E. Automated evaluation of cuttings in hole - Hole cleaning parameters, ROP and circulation time **[automated: Alarm when theoretical accumulation of cuttings]** F. Automated recommendation to stuck pipe response G. Automated *tripping* [NOV, Sekal, others: RIH]	Add experience **Functionality with «RSS» in «Event manager»:** Standard connection procedure: (SCP) - Drill off WOB - PU to slips depth and establish free rotational weight - Stop rotation, then stop pumping - Establish up/down weight while releasing torque in pipe - Set slips - Make connection *- PU from slips and start rotating with 30 – 50 rpm (=> constant torque)* *- Bring up pumps slowly to 350 LPM / 1300 gal/min (=> full return)* *- Bring up pumps in steps of 350 LPM / 1300 gal/min to «full rate»* *- Open compensator if required* *- Survey* *- Set down weight slowly and establish drilling parameters* (Cursive: *Initiate drilling*) Automated directional corrections and response: - Not activated in this version - Down link while drilling Run in hole: (RIH) From «Length of BHA5_R1" to «TD OH» IWCF: - Riser margin - Fill pipe depth (over balance – $P_{float\ fail}$):	**Comment:** - Interfacing with NOVOS or equivalent software - FIT / LOT / XLOT performed - Wear bushing installed - Status: Bit at depth - BHA5_R1 on 5 ½" 21.9# S135 NC50 drill pipe **Priority:** A) Well control B) Directional objective C) Mud properties and hole cleaning D) Logging objective E) Rate of Penetration **[automated directional corrections and response: no]** **Depths:** RKB – Top BOP: *x* MD RKB – Annular: *x* MD RKB – WH datum: *x* MD RKB – Landing Collar: *x* MD RKB – Casing shoe: *x* MD RKB – TD OH hole: *x* MD RKB – Section TD: *x* MD
57, p2	**Well control and integrity** 1. Highest pore pressure in planned section: x.x Sg / x.x ppg 2. Lowest frac pressure in planned section: x.x Sg / x.x ppg 3. Mud in well: x.x Sg / x.x ppg 4. Kick tolerance: 4.0 m^3 / 25 bbl 5. Kill / Choke lines conditioned: mm.dd.yyyy, hh:mm 6. BOP tested: mm.dd.yyyy BOP function tested: mm.dd.yyyy BOP config: Annular bag — All sizes Blind Shear ram — CDVS Upper pipe ram — 3 ½" - 7 ⅝" — Variable Ram Middle pipe ram — 3 ½" – 6 ⅝" — Variable Ram Lower pipe ram — 3 ½" – 6 ⅝" — Variable Ram	**Anti collision and other risks:** 1. Unstable formations 2. Losses (cement to cure losses) 3. Differential sticking 4. OH side track Procedures: A) Derrick-man: empty ditch magnets and log (daily) B) Driller: jarring procedure and max pull on pipe C) Mud pump maintenance and config - Filters - Spare parts D) Drill bit nozzle config and accessories E) Supervisor: Verify automated road map F) Drift, gauge ring and BHA check list on drill-floor G) Maintenance of well control equipment (pressure, level -sensors, etc.)	**HSE:** 1. Pre-job meeting to be held before job starts 2. Post job experience meeting to be performed 3. All lifting operations to adhere to regulations - Certified equipment - Certified personnel - According to valid procedure 4. Drill-floor: - All equipment static before personnel enter - Driller control access - Kelly cock (with XO) readily available 5. Radioactive source in BHA 6. Mudlogger and driller: volume control of mud 7. Mud engineer: chemical risk with mud

Figure 3-20 - Drill RSS event: preparations, well status and safety.

#	Parallell / verifications	Activity description (Add experience)	Risk experience / other
57, S1	**RSS prepare** 1. Test BHA5_R1 Shallow 2. RIH with BHA5_R1 to TD OH - Automated tripping	**Initate drilling** 1. Test BHA5_R1 Shallow 2. RIH with BHA5_R1 to TD OH 3. Test BHA5_R1 4. *Initiate drilling*	**Risk:** 1. Set down slowly to break in bit 2. BHA across rat hole: old cement / stuck 3. Low RPM => stick slip 4. Position: change MWD tools => survey overlap
57, S2	**RSS verify** 1. Prepare casing / liner tally 2. Drilling parameters: - 120 – 200 rpm - Max section flow rate: 1200 – 2400 lpm / 4500 – 9000 gpm - Max ECD: x.xx Sg / x.xx ppg - WOB: 1 – 16 tons	**Drill – RSS** 1. Drill from TD OH to base Daleland formation. - Loop: If TD OH is < Daleland formation SCP Else 58, S1	**Experience:** Ream Stringar formation (above Daleland fm.)
58, S1	**RSS verify** 1. Prepare casing / liner tally 2. other	**Ream stringar formation** 1. Experience «Ream Stringar formation»: - Apply 130 rpm - Apply max pump rate - Ream down > local ROP (pevent side track) - Repeat reaming sequence	**Experience:** Stuck while reaming Stringar formation
59, S1	**RSS verify** 1. Drilling parameters: - 120 – 200 rpm - Max section flow rate: 1200 – 2400 lpm / 4500 – 9000 gpm - Max ECD: x.xx Sg / x.xx ppg - WOB: 1 – 16 tons	**Drill – RSS** 1. Drill from TD OH to Section TD. - Loop: If TD OH is < Section TD SCP Else 60, S1	**Experience:** Ream Stringar formation
60, S1	**RSS verify** 1. Prepare casing / liner / screen 2. Preapre cement	**Circulate well clean** 1. Pump at max rate while rotating max at Section TD 2. Etc.	**Experience:** Well not clean, casing / liner / screen unable to reach Section TD

Figure 3-21 - Drill RSS event: operational steps.

3.4.8 Drilling parameters

Drilling parameters have 3 sources. Often, the primary limitation is given by each component in the drill string. The secondary limitation given by exposed formations and infrastructure such as casing and liners. The third source is "best practice" which is a combination of experience and common sense covering most scenarios for most hole sizes. Best practices cover how to drill shoe tracks, weak formation, hard formation, stringers, transition from a weak formation to a hard and vice versa, parameters for high overbalance, salts, unconsolidated and unstable formations, etc. These conditions tie into other matters such as hole cleaning, minimum string weight and torque. To derive the optimal set of parameters, the design in WOS is planned with a structure resembling "self-learning machine learning" technique. Section 3.9 "Optional features" discuss how to derive the combination of parameters while the legal range of parameter and their internal priority is discussed below in section 3.5.2 "Iteration example".

3.5 Establishing a digital program – iteration sequence

The WOS is designed with logic to handle the iterations between the listed activities and the engineering models. There are two angles of discussing the iteration sequence. Here, the flow of data and the progression of the digital program is covered. Section 3.6 is dedicated the different planned functionalities in the WOS. This section presents the designed workflow and section 3.6 explains how it is possible.
The sequence in the workflow is shown in a flow diagram, see Figure 3-22. It can be summed up to the following steps:

1) The event manager runs the input in Table 3-6 to a "control system", see section 3.6.5, where the variables are checked if they are changed so much that the engineering needs to be recalculated.
2) The "control system" is connected to a "variable map" which has the current value of all variables, in addition to the min and max value allowed per engineering.
3) If a variable need to be changed, all engineering calculations using the variable (parameter) will change status from "green" to "yellow".
4) In a case where the calculations are not within acceptable range, logic apply to either change tools involved or adjust other parameters using the "Method manager". Where applicable, all influenced engineering will be re-run individually with the new tool / design to identify new min and max values. This thread reverts to step number 1 above, where the event manager is set up with the new information. E.g. new drill pipe size, different casing setting depths or sizes, etc.
5) In a case where the variables / parameters in step 3 above are all in acceptable range, a loop of three steps follows:
    a. Calculate required engineering. All engineering is set up with an internal priority and will be processed one at the time through this loop
    b. The control system verifies if the updated parameters are changed more than the lower limit for re-calculation or if the old value should be kept. Note to reader: in the first iteration, there will be several engineering designs that are in varying state and need to be tuned through these iterations. I.e. just as drilling engineers are and have been doing for every program and well.
    c. If the variables / parameters are not between set min and max, the loop aborts and reverts to step 4 above. If the variables / parameters are all between set min and max, the loop starts at step 5a with the remaining engineering calculation according to their given priority. Once all calculations are within acceptable range, the loop exits and moves on.
6) With all engineering calculations verified to be in range, the methods listed in the event manager are checked towards digital experience. A digital experience can comprise any number and type of identifications of what operational sequence to replace with more desired method, service or tools. Digital experience is discussed further in section 3.7. Where changes take place, the

iteration reverts to step number 4 above. Once all parameters are optimized and experiences are incorporated, the loop proceeds to the next line in the event manger until the last. Once the last activity with the associated detailed procedure is processed through the workflow, a digital program ready for user's verification and input.

A more practical example of the generic workflow described above and visualized in Figure 3-22, can used the same data as in the previous chapter. The data in Table 3-6 serves as input. Precising that all designs have been run to find min and max values and the variable map is updated accordingly, see Figure 3-23. Planning of drilling operations require several iterations and each round takes time. Especially the initial iterations. The same is true for the software design since there are many adjustments to be made initially. For this reason, the example will focus on the drilling activity marked as step 5 in Table 3-6 and limit the engineering to a few models to demonstrate the process. Note that corrections of designs in the iterations are defines as "*design mitigations*".

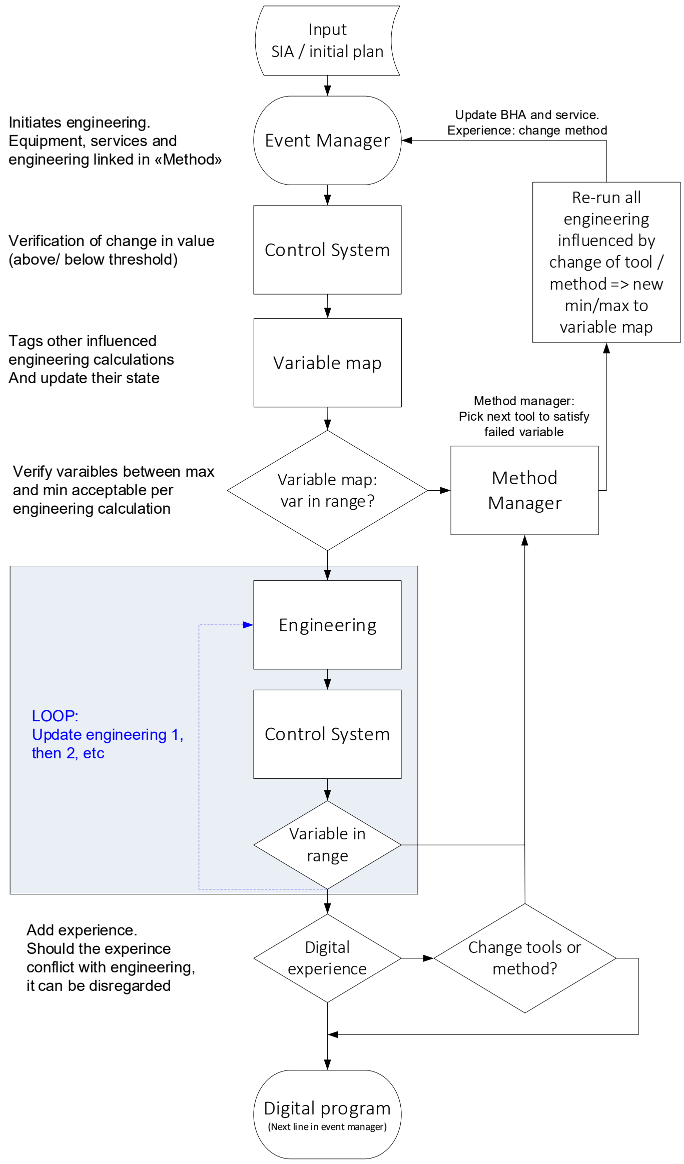


Figure 3-22 – Overall flow diagram for the "*iteration sequence*".

Tubular design - forces	Tubular design - burst	Tubular design - collapse	Kick tolerance	T&D	Subsurface input	Wellbore (geometry)	Bit hydraulic	Hydraulic	Surge & Swab	Survey		Reference	Other	Unit	Description
											Survey calcs				
										x	Length	MD (CL)		m MD	Measured depth – length along the wellbore (Course Length)
										x	North	North (N)		m	North component of the horizontal displacement
										x	East	East (E)		m	East component of the horizontal displacement
										x	Z	TVD		m TVD	True vertical depth – vertical component of the measured depth
										x	α	Inc (I)		degrees	Inclination from vertical
										x	β	Azi (A)		degrees	Azimuth - compass direction
										int	RC	RC		degrees	Radius of curvature
										int	Φ	DL		degrees	Dogleg
										x	DLS	DLS		degrees/30m	Dogleg severity (per 30 meter)
											Surge & Swab				
									x		n			NA	power law exponent
									x		K			NA	fluid consistency unit
									int		v_{dp}			m/s	fluid velocity around (drill) pipe
									int		v_{DP}			m/s	pipe movement velocity
									x		$ø_{DP}$			inch	drillpipe diameter
									x		$ø_{hole}$			inch	hole diameter
											Hydraulic				
								x			τ			Pa	is the shear stress
								int			γ			s^{-1}	is the shear rate
								W17			K			NA	is the Power law correction factor
								W18			n			NA	is the dimensionless Power law exponent
								x			ECD			Sg	Equvivalent circulating density
								int			PV			cP	Plastic viscosity
								int			YP			Pa	yield point
								W65			MW			Sg	Mud weight
								x			Q_mud			Lpm	Pump rate, mud (per section)
								x			ROP			m/hr	Rate of penetration
								int			$\rho_{cuttings}$			Sg	Density of cuttings
											Bit hydraulic				
							int				Jet_area				Jet area =(Jet size/32)^2*Π/4

Figure 3-23 – Extract of an early copy of the variable map: shared and internal variables organized. The red frame is a magnification of the segment market with the stapled line.

3.5.1 Introduction to example of automated iteration

The sequence is not random. The design is set up to be as close to how drilling engineers develop designs as possible. This means that engineers can operate and manipulate the parameters easily and that the programming follows a structure proven to produce well designs. The structure and workflow follow the same sequence and logic in selecting and changing tools and parameter values as done in the industry today. The process demonstrated in the example is a bit more detailed than the overall flow chart in Figure 3-22. A feature not discussed in the example is how and where the user can manipulate the parameter settings. The example uses a few simplified calculations to demonstrate the functionality. The introduction to these calculations also discusses their priority internally and a short status coming from the "*initial planning*". The internal priority is used when re-calculations of the engineering models is required.

3.5.1.1 Well path calculations

The engineering with the highest priority is the well-path calculation since it does not use any parameter from other engineering calculations as input and because most of the other calculations depend on correct survey as input, see Figure 3-24. Anti-collision is not discussed in this thesis.

Wellpath positioning

Term	Symbol	Comment
MD	L	Measured depth – length of the wellbore Measured by the drill string
TVD	ΔZ	True vertical depth – vertical component of the measured depth
North	ΔN	North component of the horizontal displacement
East	ΔE	East component of the horizontal displacement
Delta (Δ)		Difference or change in quantity
CL	L	Course length – the Measured length between two points
I	α	Inclination from vertical
A	β	Azimuth of the survey
RC		Radius of curvature
VS		vertical section
DL	Φ	Dogleg severity
DLS		Dogleg severity
DEP		the departure in the horizontal plane

$$\Delta N = \Delta L \cdot \sin I \cdot \cos A$$
$$\Delta E = \Delta L \cdot \sin I \cdot \sin A$$
$$\Delta Z = \Delta L \cdot \cos A$$

$$\text{DLS} = \frac{(\phi \times 30)}{\text{CL}}$$

$$RC_I = \frac{(180)\cdot(30)}{\pi \cdot B}$$

$$CL = \Delta L = \frac{RC \cdot \pi \cdot (I_2 - I_1)}{180}$$

$$\text{DLS} = \sqrt{\text{B}^2 + \text{T}^2 \times \sin^2(I_2)}$$

$$SF = \frac{S}{e_r + e_0}$$

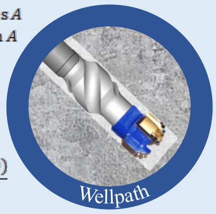


Figure 3-24 - Wellpath calculations.

From the "*initial planning*", there will be a well path following basic regulations such as dog leg restrictions. The well paths need updated anti-collision, T&D optimization and updated with any restriction to azimuthal or inclination in any formation.

3.5.1.2 Section outline

More involved in the initial planning than in the iteration round, "Section outline" provides e.g. standard tubular programs, i.e. what are the best practice casing and open hole sizes coupled together for the different number of sections (using the standard contracted tubulars). Tubing size is essential input. The Section outline is not really required during the "*Iteration sequence*", but it will be a good visual aid and helpful when programming and manipulating how the software is planned to run. Should the calculations indicate that a different size casing is required, the section outline function provides the logical alternative with priority after any well-path calculations.

#	Logic	Comment
1	Sections by pore pressure	Preliminary outline of sections
2	Tubular and OH dimentions	Standard tubular program
3	Bit runs per OH	Simple logic based on depth and length
4	Other	Not discussed here

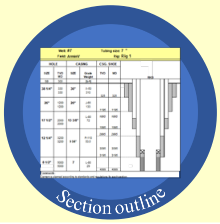


Figure 3-25 - Section design logic.

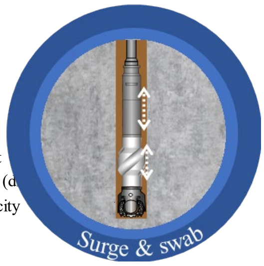
The status from the "*initial planning*" is shown in Table 3-6. There are basic estimations of time per activity in the section outline. Also, some standard drilling parameters per section are assumed form best practice.

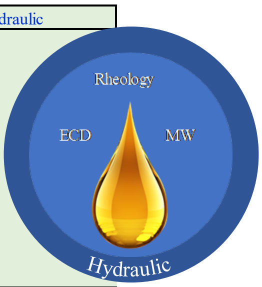
3.5.1.3 Hydraulic calculations

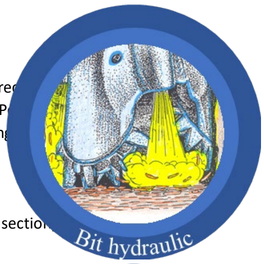
There are several calculations in the hydraulic category, see Figure 3-26. Standard logic to verify pump pressure, mud weight, rheology, ECD, bit hydraulic, hole cleaning and mud type are discussed in section 3.4.4. Adding surge & swab, there are still several calculations left out of this example. E.g. cement pumping us not listed in Figure 3-26. Cement operations often have the highest hydraulic force the formations are exposed to excluding fracturing operations.

Many other calculations rely on updated hydraulic parameters, which means influenced hydraulic calculations will run after verification of well-path and section outline should they require recalculations.

Bit hydraulic	Hydraulic	Surge & Swab	Survey		Reference	Other	Unit	Description
				Surge & Swab				
		x		n			NA	power law exponent
		x		K			NA	fluid consistency unit
		int		v_{dp}			m/s	fluid velocity around (d
		int		V_{DP}			m/s	pipe movement velocity
		x		$Ø_{DP}$			inch	drillpipe diameter
		x		$Ø_{hole}$			inch	hole diameter
				Hydraulic				
	x			τ			Pa	is the shear stress
	int			γ			s^{-1}	is the shear rate
	W17			K			NA	is the Power law correc
	W18			n			NA	is the dimensionless P
	x			ECD			Sg	Equvivalent circulatin
	int			PV			cP	Plastic viscosity
	int			YP			Pa	yield point
	W65			MW			Sg	Mud weight
	x			Q_mud			Lpm	Pump rate, mud (per sectio
	x			ROP			m/hr	Rate of penetration
	int			$\rho_{cuttings}$			Sg	Density of cuttings
				Bit hydraulic				
int				Jet_area				Jet area =(Jet size/32
int				Jet_size			(X/32)"	Jet size
int				TFA			in^2	Total flow area
int				Jet_velocity			m/s	Jet velocity =flow/(T
int				Jet_impact			kg	Jet impact
x				dPbit			bar	Pressure loss over bit
int				HSI			Hp/in2	dPbit * Q / (351.64 * OH
W32				Flow_rate			lpm	Pump rate
W65				MW			Sg	Mud weight







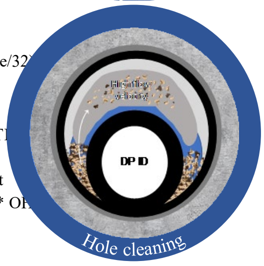


Figure 3-26 - Some hydraulic calculations extracted from the variable map.

The status in hydraulic calculations is shown in are Figure 3-14. Key values are in place based on standard designs in contract. Any adaption to accommodate local conditions can be set after the simulations here in the "*iteration sequence*" are done.

3.5.1.4 T&D

Torque and drag are "end calculations", i.e. no engineering calculation depend on modelled T&D as input. If a section proves difficult to drill due to high drag forces, there are a number of parameters to change before the well configuration needs to change. Presuming the well-path follows the standard restrictions in dogleg per depth, the priority list is as follows, case is "low surface weight":

1. Verify friction factor: range will be set according to casing and another range for OH.
2. Add heavy weight tubulars (HWDP) as deep as possible but in inclination less than 65 degrees. Application will add heavy weight in lengths of 30 m up to 150m.
3. If step above do not solve the case, add the 150 m heavy weight tubulars in steps of 100 m higher to see if this changes the surface weight
4. With the 150 m HWDP in position as in step 2, add a stand of drill collars (DC)
5. Etc.

The content of the above list may not be the best approach, it is merely an example to demonstrate programmable steps to be taken to mitigate light string weight. There are a number of ways to circumvent light string weight. All of these can be programmed in a prioritized order. And the user can choose to pick one that fits best for the well. The same goes for torque and for buckling. This research has developed a prototype application for buckling but will not discuss issues related to buckling or the application. Figure 3-27 shows T&D calulations.

Torque & Drag calculations

Param.	Comment	Link	Optimization
F	force from calculating tubular [kN]	BHA	NA
F_{n-1}	force from tubulars below [kN]	BHA	NA
N	Normal force [kN]	BHA	NA
W_{BHA_DP}	buoyed weight [kN]	BHA	NA
T_n	torque to turn work string [kNm]	BHA	NA
T_{n-1}	torque from tubulars below [kNm]	BHA	NA
$r_{tubular}$	radius OD of work string component [m]	Wellpath	NA
θ_{avr}	average inclination [deg]	Wellpath	NA
$\Delta\theta$	change in inclination [rad]	Wellpath	NA
β	buoyancy from fluid [1]	Mud	NA
$\Delta\varphi$	change in azimuth [rad]	Wellpath	NA
μ	friction factor [1]	USER	Friction factor

BHA details
Wellpath
Fluid program
Section design (start and end -depth, size of casings and bits)

$$N = \sqrt{(F_{n-1} * \Delta\varphi * \sin(\theta_{Avr}))^2 + (W * \sin(\theta_{Avr}) + F_{n-1} * \Delta\theta)^2}$$

$$W = \omega_{mass/length} * L_{length} * \beta_{bouyancy} * g$$

POOH $F_n = F_{n-1} + W_{BHA\_DP} * \cos(\theta_{avr}) + \mu * N$

RIH $F_n = F_{n-1} + W_{BHA\_DP} * \cos(\theta_{avr}) - \mu * N$

Torque $T_n = T_{n-1} + \mu * N * r_{tubular\ radius}$

Depth [mMD]	Force [kN] Optimal value: μ=0.3	Force [kN] Min value: μ=0.2	Force [kN] Max value: μ=0.4
900	500	475	525
930	495	470	520
960	490	466	515
990	485	461	509
1020	480	456	504
1050	475	452	499
1080	471	447	494
1110	466	443	489
1140	461	438	484
1170	457	434	480
1200	452	430	475
1230	[illegible]	[illegible]	470
1260	[illegible]	[illegible]	465
1290	[illegible]	[illegible]	461
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
1590	[illegible]	[illegible]	417
1620	[illegible]	[illegible]	412
1650	[illegible]	[illegible]	408
1680	385	366	404
1710	381	362	400
1740	377	358	396

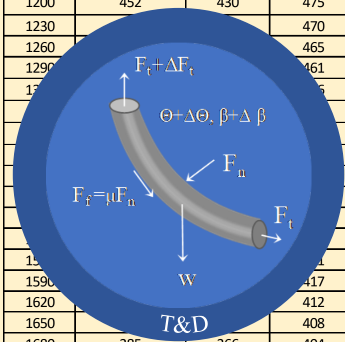


Figure 3-27 - T&D calculations.

Status in T&D after "*initial planning*" is shown in Figure 3-15. Priority of T&D is after update of the above engineering calculations should any of them require recalculation. T&D can be used to as an indicator of possible high casing wear.

3.5.1.5 Event manager

The event manager is updated as show in Figure 3-28 after the "*initial planning*".

Drilling objective

#	Objective	Event	Equipment	Process Environment	Working Depth	Effective/total depth	Start	End	Paralell / verifications	Activity description	Risk / Experience
51	Drill	MU BHA	BHA5_R1	Rig, D&I, Bit	0	3195	11.12.12 23:00	12.12.12 00:00	Prepare: Mix mud	MU BHA #5 8 1/2" RSS	
	Procedure	MU BHA	BHA5_R1	Rig, D&I, Bit, Contracts	0	3195	12.12.12 00:00	12.12.12 01:00		Surge & Swab	
	Engineering	MU BHA	BHA5_R1	Well path, BHA, Fl. prog, hyd, casing wear,	0	3195	12.12.12 00:00	12.12.12 01:00		Surge & Swab	
52	Drill	RIH	BHA5_R1	Rig, D&I, Mudlogging	3165	3195	12.12.12 00:00	12.12.12 01:00		RIH from 0 m to 3165 m	(See Appendix B)
53	Drill	Shoe track	BHA5_R1	Etc.	3195	3195	12.12.12 01:00	12.12.12 02:00	ROP <10 m/hr	Drill shoe track from 3165 m to 3195 m	
54	Drill	Rat-hole	BHA5_R1		3200	3200	12.12.12 02:00	12.12.12 03:00	ROP <10 m/hr	Drill rat-hole from 3195 m to 3200 m	
55	Drill	RSS	BHA5_R1		3205	3205	12.12.12 03:00	12.12.12 04:00	3m new formation	Drill with RSS from 3200 m to 3205 m	
56	Formation integrity	Circuate	FIT5		3195	3205	12.12.12 04:00	12.12.12 05:00	MW in = MW out	Circulate before FIT	
57	Formation integrity	FIT	BHA5_R1		3195	3205	12.12.12 05:00	12.12.12 10:00	>1.3 sg	Perfrom FIT	
58	Drill	RSS	BHA5_R1		3205	5000	12.12.12 10:00	12.12.12 12:00		Drill with RSS from 3205 m to 5000 m	
59	Drill	Circulate to POOH	BHA5_R1		4990	5000	12.12.12 12:00	12.12.12 18:00		Circulate to pull out of hole	
60	Drill	Flow check	BHA5_R1		4995	5000	12.12.12 18:00	12.12.12 21:00		Flow check	
61	Drill	Trip out to run casing/liner	BHA5_R1		0	5000	12.12.12 21:00	12.12.12 23:00		POOH with BHA #5 run #1 to run casing	
62	Drill	LD BHA	BHA5_R1		0	5000	12.12.12 23:00	13.12.12 00:00		Lay down BHA #5	

Figure 3-28 -Activity #55: Drill with RSS from 3205 m to 5000 m.

3.5.2 *Iteration example*

The example address step #55 in the event manager, drilling with RSS from 3205 m to 5000 m using the standard drilling BHA as proposed in Figure 3-13. The variable map and the control system will be referred to with icons as shown in Figure 3-29 respectively. The other engineering calculations will use the icons in the previous section where this example was introduced.

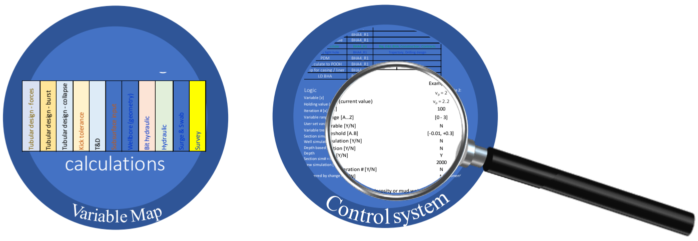


Figure 3-29 - Icons for variable map and control system used in example.

A blue frame around the icons for the engineering models indicates all engineering variables are being checked in turn, i.e. the state of the engineering calculation models verified and updated, see Figure 3-30. The reference to this step in the overall flow chart introduced in Figure 3-22 is added in the red frame in Figure 3-30 below.

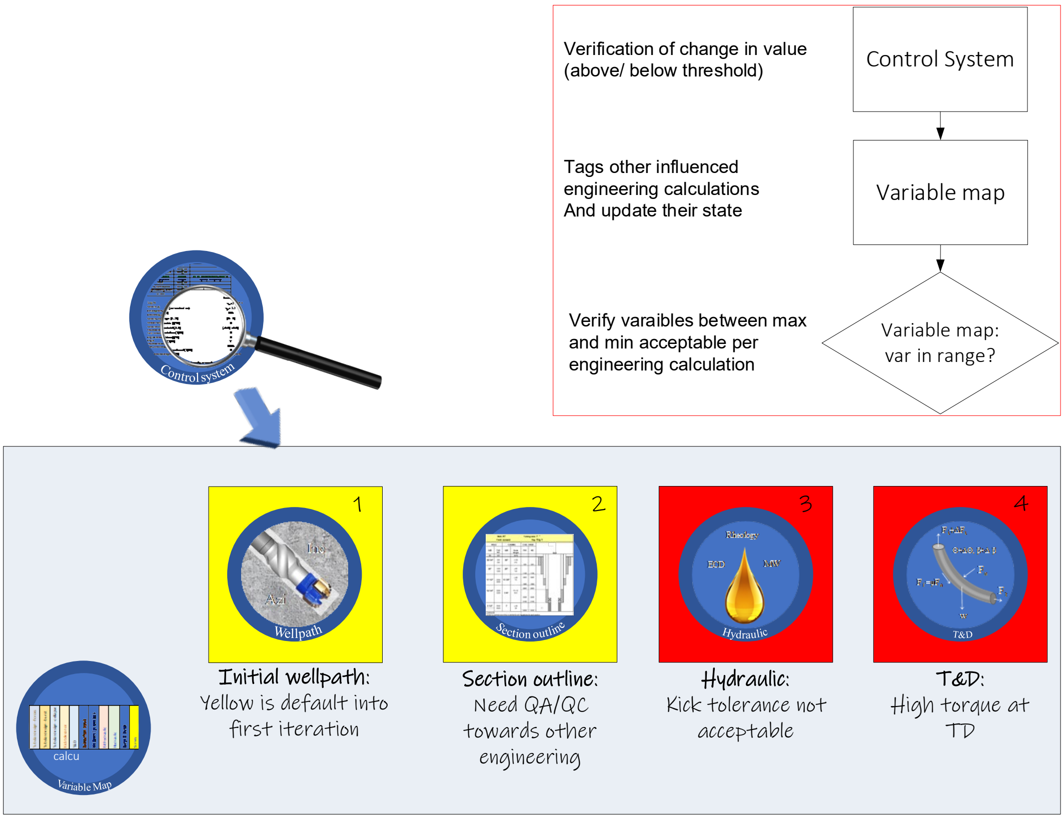


Figure 3-30 - Example of step in iterating engineering into optimal design.

A peach colored frame indicates internal calculation, i.e. where adjustment of an engineering is made and not all engineering models are run at the same time. In the 1st iteration, the control system checks if the engineered results are within acceptable range and updates the status, see Figure 3-31.

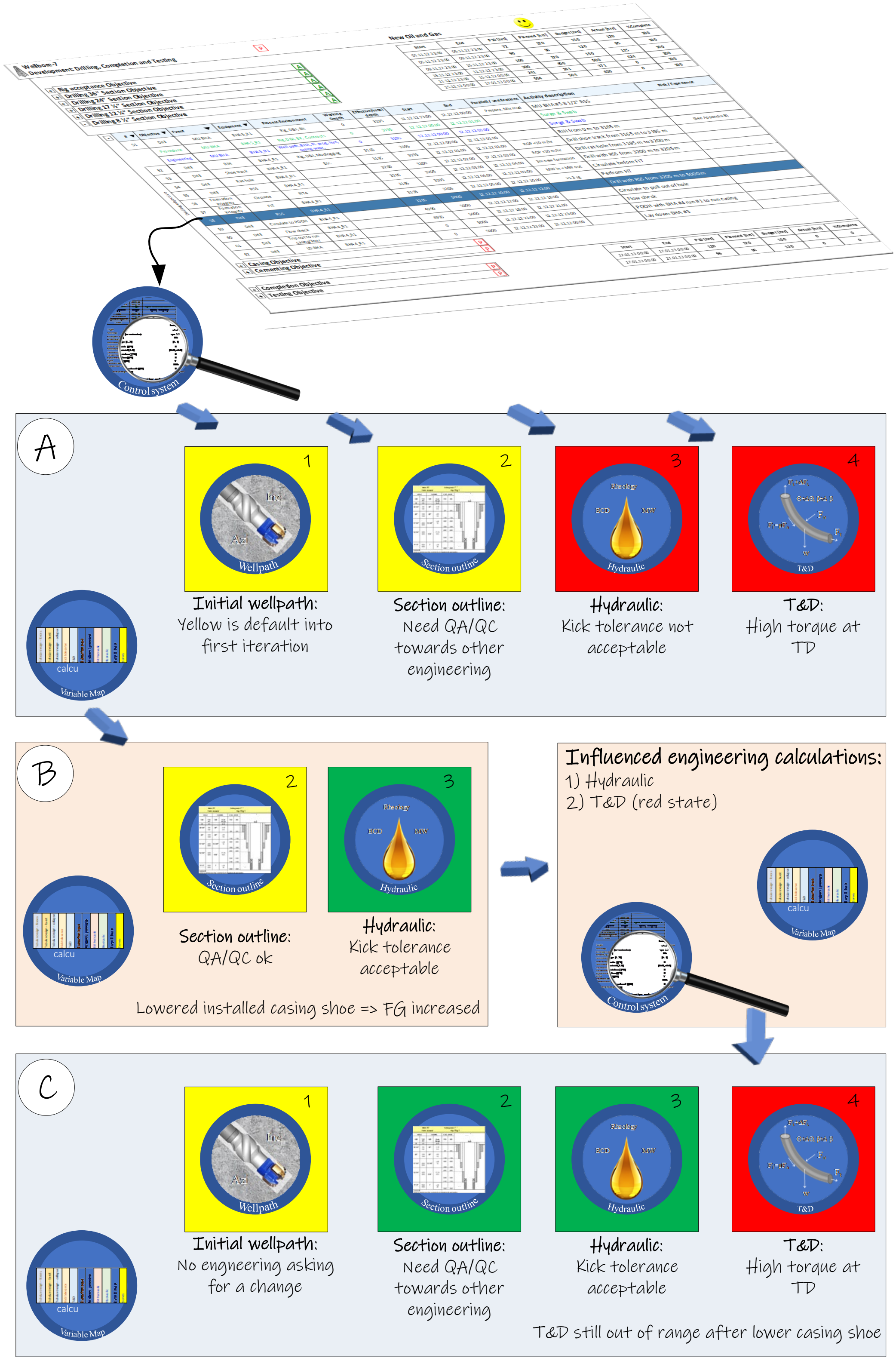


Figure 3-31 - Example of automated engineering – 1st iteration sequence.

3.5.2.1 *Band marked "A"*

As marked in the overall flow chart for the "*iteration sequence*", Figure 3-22, the data generated in the "*initial planning*" is scrutinized by the control system. By default, the first iteration needs to be verified and trusted only after a full evaluation of all data. Therefore, the state of all involved engineering is not likely to be "green". In the case of the example in Figure 3-31, the well-path is set to yellow, i.e. the initial quality assurance and quality control (QA/QC) comprises verification of dogleg per depth. This can be set to 2 degrees per 30 meter down to a specific depth, it can be tied to size of casing or both. A violation of these basic rules could result in a red state. The well-path should not be set to green state until it has been verified after the final casing program is determined. Then it is possible to verify which formations will be exposed in the different sections and which inclination and azimuth they will have. This may be essential in fields where hole stability is an issue.

In the example, there is an app called "section outline" organizing the information related to the well infrastructure such as the casing program and any update of it

The example shows "Hydraulic calculations" and "T&D" calculations in a red state due to insufficient kick tolerance and high torque at section TD. Internal priority favors the "Hydraulic calculations" to be addressed first.

3.5.2.2 *Band marked "B"*

The first "*design mitigation*[18]" for many drilling engineers to improve the kick tolerance in this situation would be to change the casing setting depth to increase the fracture gradient (FG). Then, the consequences of changed casing program needs to be verified with the other design calculations. Comment: *This changes the state of the entire engineering performed in the previous section, since the drilled distance will be different*. Another feature planned to be inherited from the current manual design process is to address one engineering at the time. In the design of the software, the Section outline will be updated with the first "*design mitigation*" changing both involved apps into a green state. The variable map has a twofold role, where the first is to ensure the changed casing does not go beyond the set maximum depth and the second is to convey the updated setting depth to other applications. The second peach colored frame indicates the control of the variables and their update in the map. This update is important as it initiates the change from the green state for engineering models where there are shared variables (other models with the casing setting depth as input) influenced by the change taken place. This example will not pursue the change to the previous section. T&D, however, is influenced by the change in casing setting depth and need to be re-calculated with this change before the state is further addressed. Note that changing the casing setting depth may in some wells be unacceptable for some engineering designs. It is therefore important to run calculations for all influenced engineering designs after every "*design mitigation*". The correct solution to mitigating the faulty kick tolerance may be the third or the fourth option on the list of mitigation. This is something the variable map and the control system will handle once the full consequences of the change take place, i.e. after re-calculating all influenced engineering calculations.

3.5.2.3 *Band marked "C"*

The update in the variable map after applying the first "*design mitigation*" (i.e. re-calculating all influenced designs) discussed for band marked "B" is shown in band marked "C". There are no engineering requesting a change to the well-path. The state is not changed since the first iteration is not complete. There has been an update to the section outline, so the state has changed to green. This function does not engineer the result it presents. It conveys company practice based on standardized tubulars. A change to green implies no more than it has been updated. The update of the Hydraulic application has led to all calculated parameters now are within the set min and max in the variable map, which is indicated by the switch to green state. The recalculation of T&D did not solve the issue with high torque at section TD when recalculating using the deeper casing as input. The first

[18] As said initially in section 0: corrections of designs in the iterations are defines as "*design mitigations*".

"*design mitigation*" to solve the situation is to straighten the well-path in the current section, see Figure 3-32.

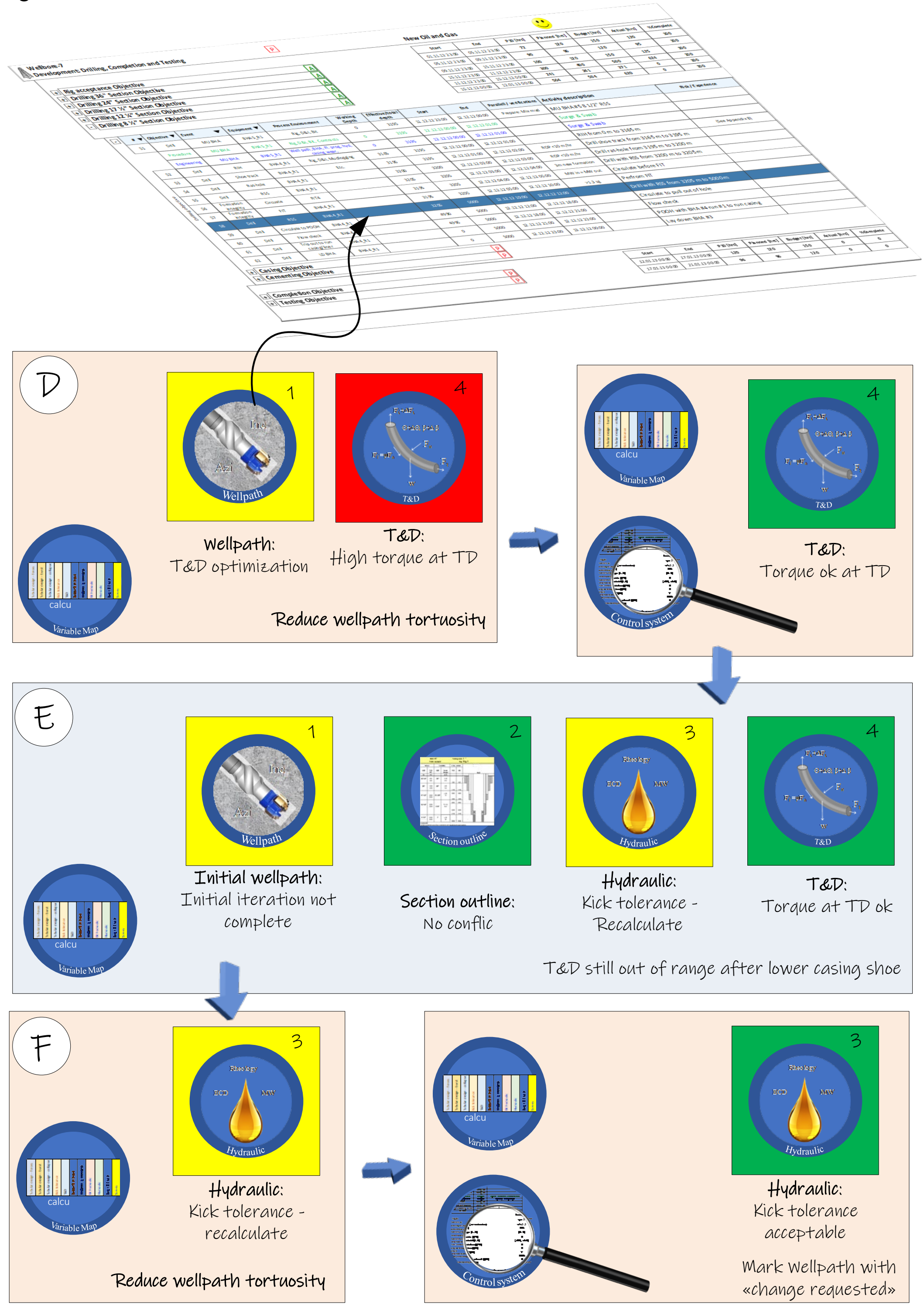


Figure 3-32 - Example of automated engineering – 1st iteration sequence continued.

3.5.2.4 Band marked "D"

The T&D calculation has requested a change in well-path to mitigate the high torque at section TD. The well-path can be optimized for T&D. The most effective changes to reduce torque is often to reduce shallow doglegs, i.e. high in the well. Also adding lubricants are effective on friction factor, which is a mitigation with less impact. From a cost and HSE perspective, drilling a longer well path to lower T&D is less favorable over adding lubricant. Minor adjustments to the well path in the current section can be feasible in combination with lubricant. In this example, this is enough to lower the torque at section TD and the state of the T&D application switch to green.

3.5.2.5 Band marked "E"

The recent change in well path needs to be transmitted to the variable map and processed by the control system to verify which engineering calculations are influenced by the change in well-path. The hydraulic calculation has switched to yellow state since the kick tolerance for the section applies the well-path as input. The other calculations are in the green state.

3.5.2.6 Band marked "F"

The impact of the change in well-path is verified in the application for kick tolerance. In this example, the well-path is not changed significantly, so the kick tolerance is acceptable.

3.5.2.7 Band marked "G"

Revisiting the variable map, the engineering calculations in the example are in a state of green, Figure 3-33.

3.5.2.8 Band marked "H"

Figure 3-33 indicates some off the remaining engineering calculations to be verified. Referring to the overall work process in Figure 3-22, this initiates the loop indicated in the figure.

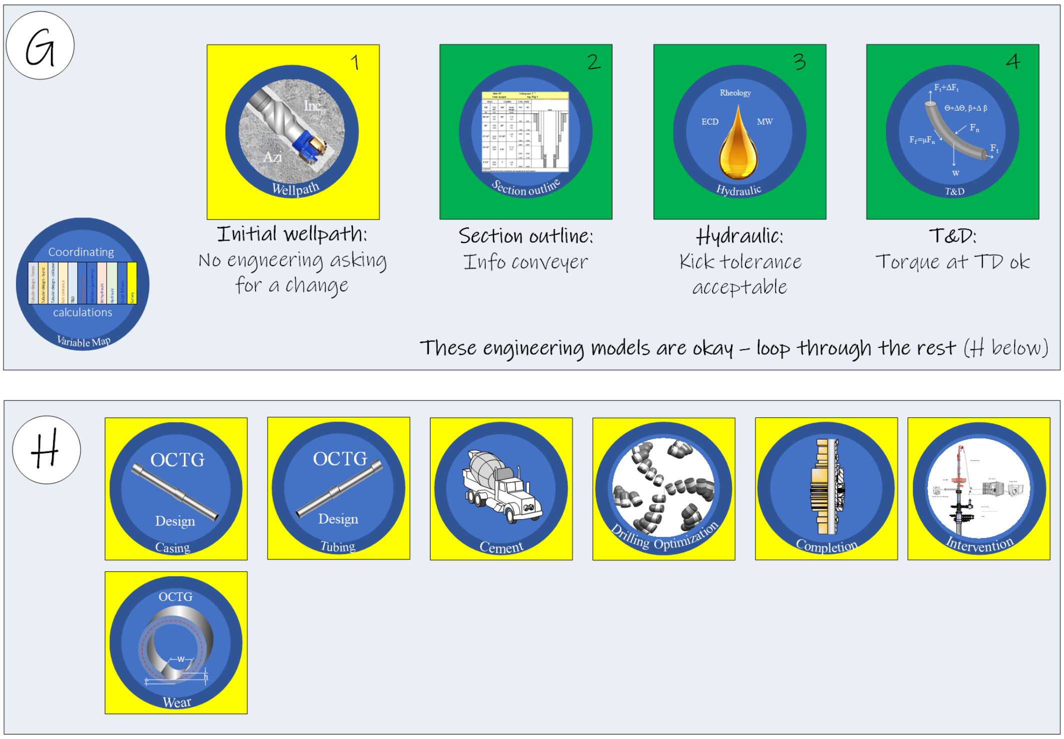


Figure 3-33 - Example of automated engineering – 1st iteration sequence continued.

3.5.2.9 *Summary iteration example*

Following the practical example of how to deduct and improve a well design fully automated, there are many iterations and combinations of “design mitigations” before arriving at an optimal design. The many variations of “*design mitigations*” is illustrated in Figure 3-34. It shows 9 engineering models with 6 options each, which represents 9^6 (531 441) possible combinations. And there are more engineering models than shown in the figure. However, the reality is that experienced drilling engineers does not spend as much time deducting the designs as the vast number of combinations imply. For one thing, there are combinations that are not possible. And for another, there are combinations of “*design mitigations*” frequently used to solve many of the issue’s engineers are facing in well design. These are often field specific. Preparing systems of “*design mitigations*” and their priority, paired with error handling, can provide an effective way of producing digital programs for well designs fully automated.

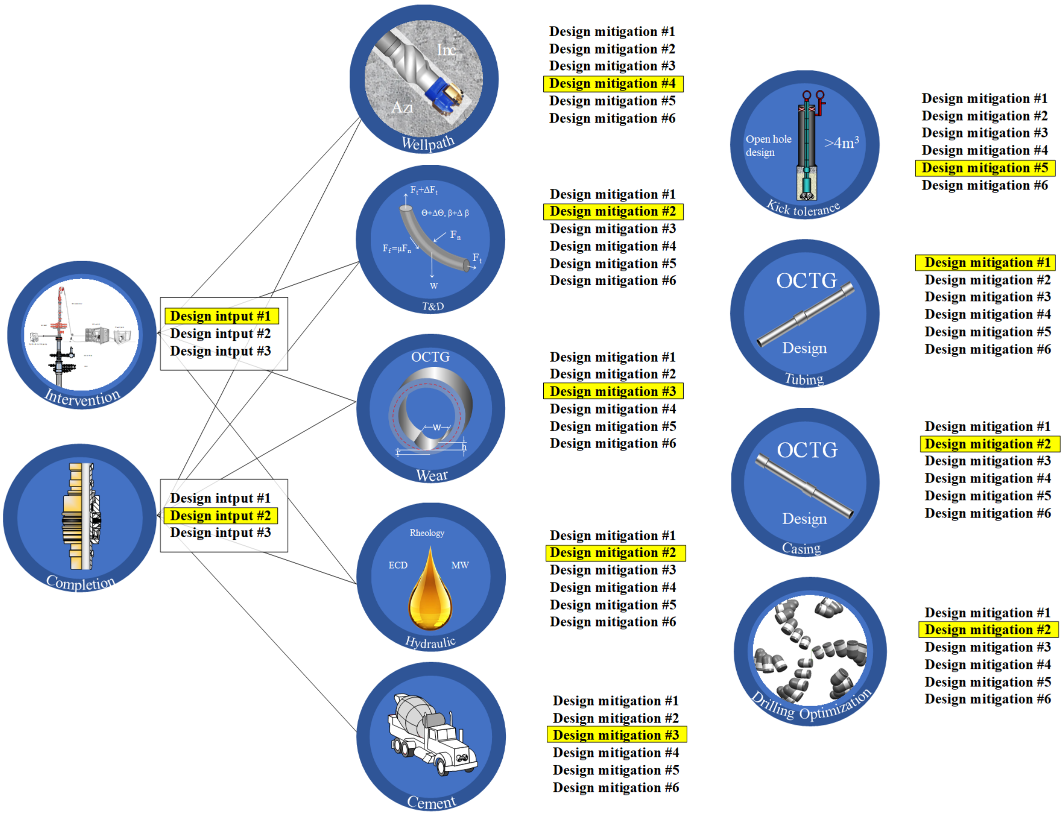


Figure 3-34 - Combinations of design mitigations.

This example addresses one line in the digital program, see line #55 in Figure 3-28. It means that many of the engineering designs have been addressed before the planned software has worked its way down to the discussed line in the Event manager marked blue, ref Figure 3-28. More on the Event manager and how it is developed can be found in chapter 3.6.4.

Following the set conditions for internal priority of engineering, legal range of parameters and rules given in digital experience, there are only a few of all possible combinations indicated in Figure 3-34 that remains due to the given objective. The figure also indicates that there are several combinations satisfying the given objective. The “optimal solution” is then derived from all legal combinations by the machine learning technique called “gradient descent” which is discussed in section 3.9 “Optional” features.

3.6 Applications enabling automated activity planning

The "*initial planning*" discussed in chapter 3.4, is already commercially available with some vendors of software for the oil and gas industry. Taking the next step and enabling the "*iteration sequence*" may represent a new generation software support since it is fully digital. The designed programing planned to drive the next step is a combination of functionalities as seen in Figure 3-35. The working title is Well (design) Operative System – WOS.

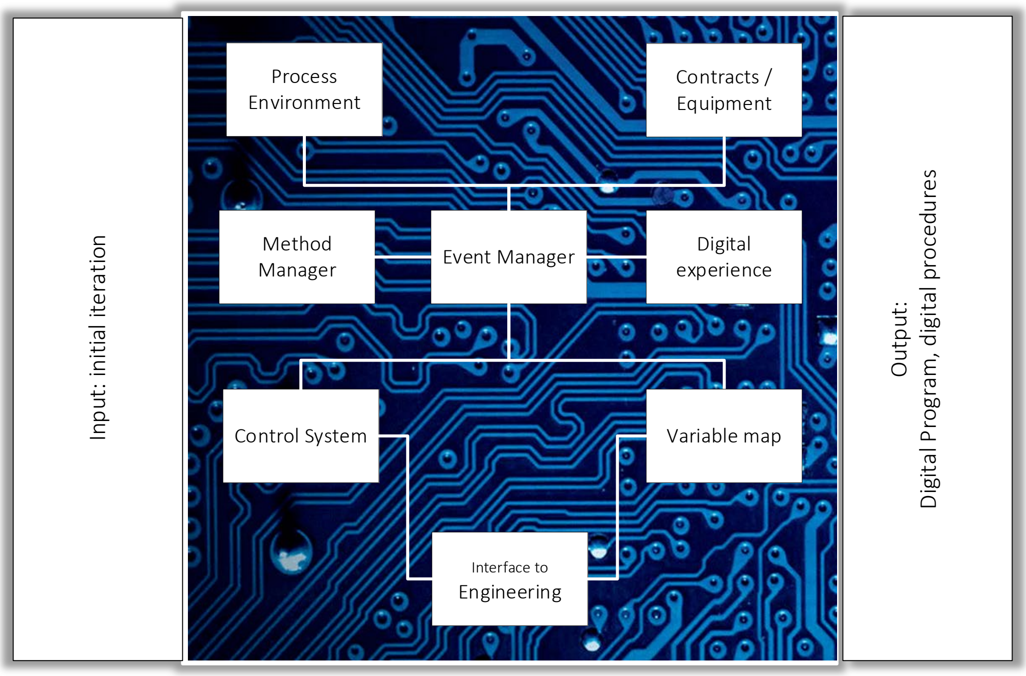


Figure 3-35 – Combined functionality that makes up the "Well operative System" - WOS.

The following applications are involved to manage the automated iteration delivering the bullet

1. Process environment
2. Contracts / Equipment
3. Method manager with "sequence manager"
4. Event manager
5. Control system
6. Variable map
7. (Interface to) engineering
8. Digital experience – see section 3.7

3.6.1 Process environment

Every activity is linked to installed equipment, services and "service equipment" involved. For rig operations, the service equipment is typically, running tools, top drive, slips, tuggers, etc. This enables detailed description in procedures for each single task such as e.g. "MU BHA". It also enables tracking of the use of the service equipment for engineering, describes the task for automation software and automated invoicing. The content of the process environment is outlined in Figure 3-36 and it is discussed further in (Brechan(4), 2018).

MU BHA

Process Environment - Contracts

Rig	Downhole Environment	D&I, MWD	Casing running	Cementing	Mud	Mudlogging	Formation Logging	Survey	WH/XT	Cuttings handling	Drill bit	ROV
Roughneck	Riser	BHA components	Tongs	Cement unit	Mud chemicals	Data aquisition system	Data aqcusition unit	Data aquisition system	Well construction equipment	Cuttings processing unit	Bit #1	ROV
Drawworks	BOP	Surface logging and control system	HPU for tongs	Cement bulk system	LCM material	Gas detection	BHA	BHA	Running/ pulling tools	Personnel	Bit #2	Manipulation tools
Top Drive system	XT	Personnel	JAM unit	Cement displacement tanks	Personnel	Cuttings analysis equipment	Personnel	Personnel	Personnel			Personnel
Torque wrench and iBOP	WH		Personnel	Cement head		Personnel						
Rig tongs	Choke/kill line			Darts and accessories								
Catheads	Casing			Personnel								
Tuggers	formation											
HPU	Liner											
Tail In Arm	Tubing											
Manipulator Arm												
Back-Up Tong												
Pipe shuttle / V-Door Machine												
Pipe racker												
Pipe racking arms												
Work Basket												
Compensator												
Tensioner system												
Mouse-hole												
BOP handling system												
BOP												
Pipehandling control system												
Drillers control system												
Mud mixing equipment												
Mud control system												
Pit system												
Diverter system												
Personnel												

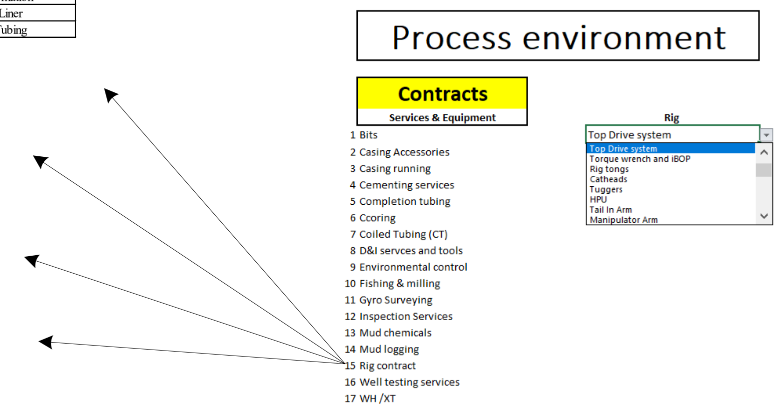


Figure 3-36 - Process Environment links activities, equipment and services.

3.6.2 *Contracts / Equipment*

Every project has a set of contracts covering all services, service equipment and purchased equipment for installation. Also, personnel involved in every type of task is described in contracts as well as their pricing. Information such as specific identifier[19] (ID), dimensional, material and other properties are important details specifying contracted items. Contracted equipment and services build on engineering, which details requirements and specifications such as listed above. Digitalization of today's text-based formats allows contracts to take an active part of planning, engineering and operations. In planning, standardized tools, equipment and services can be defined from the type of service outlined by the nature of the task. E.g. drilling BHA for overburden in a given size and mud quality for a well path of moderate steering, is often standardized. Any tool or service can be defined for the software to do planning, engineering, invoicing or other modelling by picking from the list of contracted tools and defining the operations / involvement it has. Figure 3-37 shows an extract of contracts and their content defined for the prototype software under development.

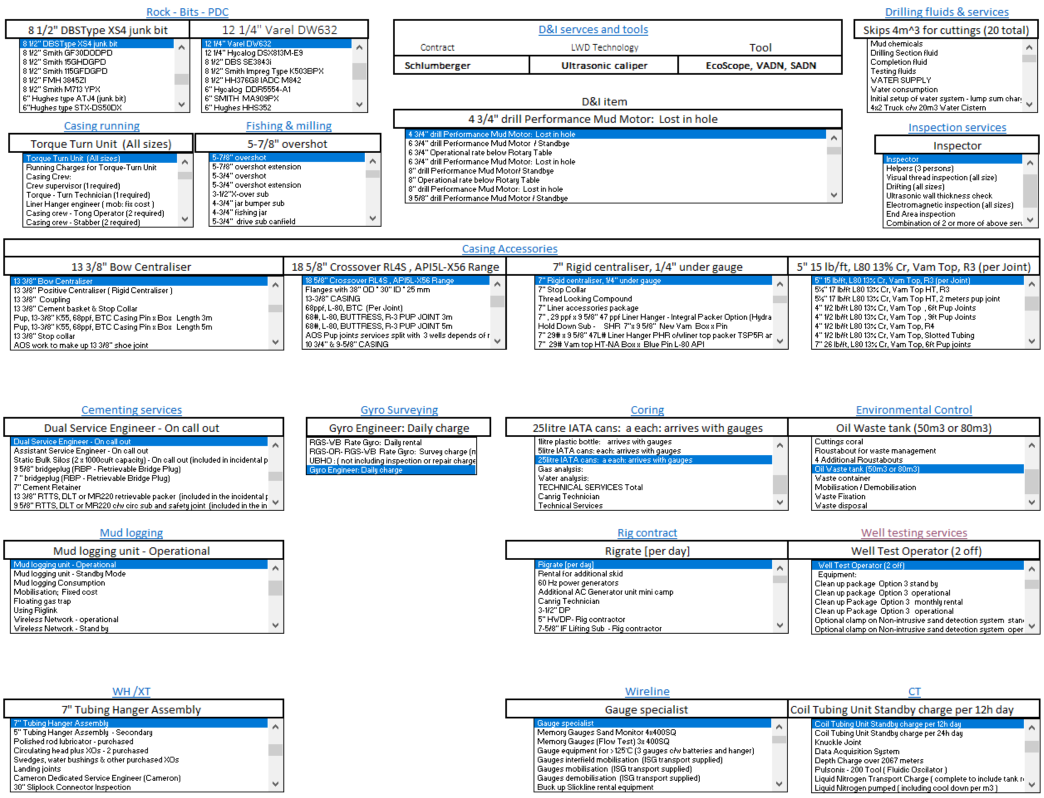


Figure 3-37 – Contracts for well construction and basic intervention.

Typically, the Subsurface teams and governing documentation provides standardized requirements for measurements according to type of formations exposed. From formation properties follows well design pressure, tubing size, well design, section design, logging requirements, etc. These form the base for best practice which can be used as algorithms for establishing automated proposals of BHA, mud quality, etc., see Figure 3-38.

[19] All major companies have systematically described their equipment with a part number, serial number and a specific SAP code. I.e. all items down to the smaller parts have a unique ID.

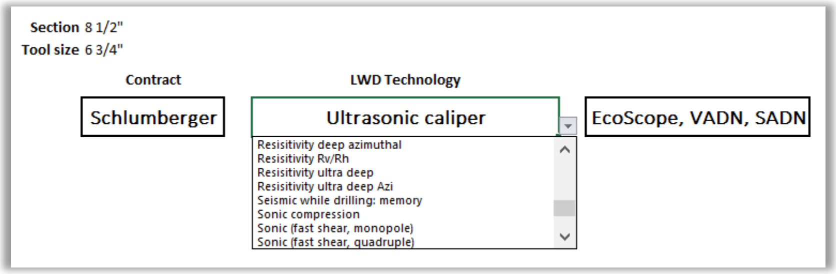


Figure 3-38 - Selecting tools from digital contracts.

3.6.3 Method manager

Research conducted to collect and systemize all possible events in drilling, completion, well testing, interventions, well integrity and P&A activities resulted in a comprehensive list of ID-codes or "methods" as discussed in section 3.3. An example of legal combinations of codes defining specific activities for a rig performing completion can be seen in Figure 3-39. The Method manager has several fields which specifies what equipment and engineering is linked to the selected method. Method has the headline "Event" in the Method manager since "method" is more a computer programming term than a term used in well construction. The engineering linked to the method/event "Run tubing" can be seen in Figure 3-39. In the design of the WOS, each method / event has been predefined with link to equipment and engineering. These methods, or events, are activities and steps as seen in programs used in well construction today. So, when the Event manager is developed and the logic behind this development picks methods, the engineering and involved equipment are linked.

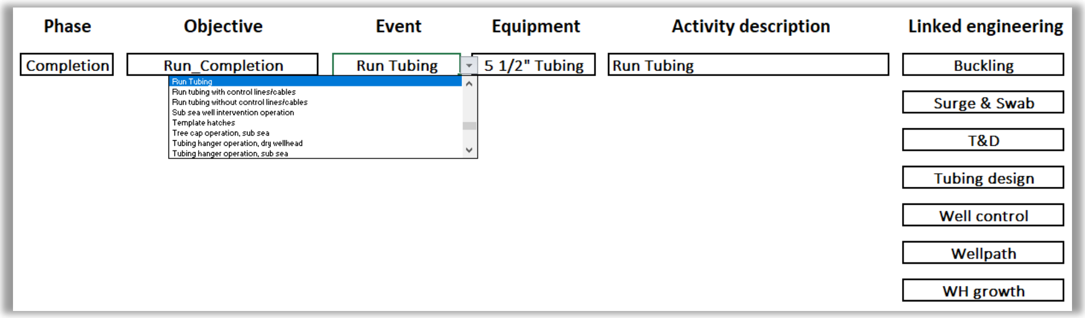


Figure 3-39 – Method manager organizes activities per phase, objective, event, and also link engineering to activity (event).

The design intent is for the methods to form the basis for communication with software for automated rig equipment. Every specific task is described with the engineering it may have an influence on, see blue text in Figure 3-39. In cases where multiple engineering calculations are influenced, their order of sequence is described. This is discussed further under the section for control system and was shown in the example in section 3.5.2.

The design is set up so superusers can access the Method manager to edit which engineering should be linked to the different methods and tune the default text displayed accompanying the different methods in the "Activity description" field in the Event manager.

Legal sequence of activities (methods) sits behind the Method manager. A small organizer of this logic sits with the library of phase, objectives and methods/events, so the development of the Event manager can be automated. This is the Sequence manager, which is described below.

Table 3-7 shows the level of detail possible and in some cases necessary to describe operations in sufficient detail.

Table 3-7 - Method Manager: Listed events under the "Sand Control" -objective.

CODE	Sand_control
Snd_CHE_CH	Change handling equip., CH
Snd_CHE_OH	Change handling equip., OH
Snd_CHE_Hgr	Change handling equipment - MU Hanger
Snd_Exp_MU	Expandable - Make-up
Snd_Exp_Pkl	Expandable - Perform workstring Chemical Pickle
Snd_Exp_PohRT	Expandable - POOH with Running Tool
Snd_Exp_Rih	Expandable - RIH
Snd_Exp_Set	Expandable - Set hanger
Snd_ExtGP_MU	External Gravel Pack - Make-up
Snd_ExtGP_Pkl	External Gravel Pack - Perform workstring Chemical Pickle and Gravel Pack
Snd_ExtGP_PohRT	External Gravel Pack - POOH with Gravel Pack Service Tool
Snd_ExtGP_Rih	External Gravel Pack - RIH
Snd_ExtGP_Set	External Gravel Pack - Set Gravel Pack Packer
Snd_ExtGP_Flwch	Flowcheck
Snd_Fm_Tst	Formation Strength/Limit Test
Snd_Fra_Opr	Frac pack operation.
Snd_Gen_Inv	General Investigation
Snd_GP_Opr	Gravel pack operation
Snd_HWO_Opr	Hydraulic Workover Operations
Snd_Inf_Tst	Inflow Test
Snd_IntGP_MU	IntGPernal Gravel Pack - Make-up
Snd_IntGP_Pkl	IntGPernal Gravel Pack - Perform workstring Chemical Pickle and Gravel Pack
Snd_IntGP_Poh	IntGPernal Gravel Pack - POOH with Gravel Pack Service Tool
Snd_IntGP_Rih	IntGPernal Gravel Pack - RIH
Snd_IntGP_Set	IntGPernal Gravel Pack - Set Gravel Packer
Snd_Eqp_Work	Manipulate Downhole Equipment
Snd_Shoe_ MU	MU Shoe
Snd_No _Activ	No Activity
Snd_Pmt_Work	Permit To Work
Snd_Rt_Poh	POOH and LD RT
Snd_Pre_Test	Pressure Test
Snd_Pump_Circ	Pump / Circulate / Displace
Snd_Rep_Replace	Repair or Replace
Snd_Rig_Up	Rig Up
Snd_Rig_Down	Rig Down
Snd_RU _ScrEq	RU screen equipment
Snd_Scr_RihCh	Run screen CH
Snd_Scr_RihOh	Run screen OH
Snd_ScrLS_wshOH	Run screen on landing string, washwork, OH
Snd_Scr_CircCh	Run screen, circ, CH
Snd_Scr_CircOh	Run screen, circ, OH
Snd_Scr_wshCH	Run screen, washwork, CH
Snd_Scr_wshOH	Run screen, washwork, OH
Snd_ScrLS_Ch	Run screenliner on landing string CH
Snd_ScrLS_Oh	Run screenliner on landing string OH
Snd_ScrLS_wshCH	Run screenliner on landing string, washwork, CH
Snd_Scr_Rih	Run screens
Snd_Saf_Rel	Safety Related
Snd_Scr_SasMU	Standalone Gravel Pack Screen - Make Up
Snd_Scr_SasRih	Standalone Gravel Pack Screen - RIH
Snd_Str_Equipment	String – Work / Jar / Free Stuck Equipment
Snd_Wel_Loss	Well Control (Losses)
Snd_Wel_Press	Well Control (Pressure)

Note that only standard operations have been investigated at this time. Establishing methods and best practice for special operations such as e.g. Managed Pressure Drilling (MPD) can be developed and added later.

3.6.3.1 Sequence manager

How the logical sequences are built up follow industry "best practice" for well construction. The seven-point list of basic steps in chapter 3.4.7 are an example of this. The design of the software allows superusers to access the Sequence manager to detail sequences

The way the Sequence manager works is to combine possible sub-states per phase, which forms the basis for how the Method manager adds the engineering and default text to the activity. The "Phase" contains the states Move, Prepare, Drilling, Completion, Intervention, Workover, Well Integrity, P&A and Other. For each of the phases, there are multiple objectives which can be described as sub-categories. E.g. for completion, these are Liner, Sand control, Wellbore preparation, Perforation, Run Completion, Well testing, Suspension and Other.

3.6.4 Event manager

The Event manager has been discussed in several occasions earlier. How it is initiated and formed was discussed in chapters 3.4 and 3.6 respectively. Maybe a bit modestly described, the Section outline function verifies if there is a need for e.g. an extra bit run. Otherwise, the development of the Event manager follows the structure of industry best practice such as in the generalized example of MU BHA in Figure 3-45. The Event manager is a hub for the program information, for people and machines to read the steps of activities required to achieve the planned well design. Also, it is the hub for the development of the engineering design. The functions displayed in Figure 3-35 ties into the Event manager, which makes it the information hub as stated. It also holds a "time planner" function, program overview and display detailed procedures. Not elaborated in this thesis is the planned link to automated logistics. With the equipment digitally tied to when and where it should be used, and their technical specifications, it is a function planned for the software.

3.6.5 Control system with interface to engineering

The control system for performing engineering is designed as part of the design logic. Examples of when and where the Control system is used was discussed in chapter 3.5.2. A closer look at how the Control system works can be seen in Figure 3-40. Up to the left in the figure is an extract of the event manager with activities and linked engineering in blue. As seen in the magnifying glass, there are few rules that needs to be satisfied before engineering calculations are triggered. Where the change in value for a variable is less than the threshold, the calculation will not take place.

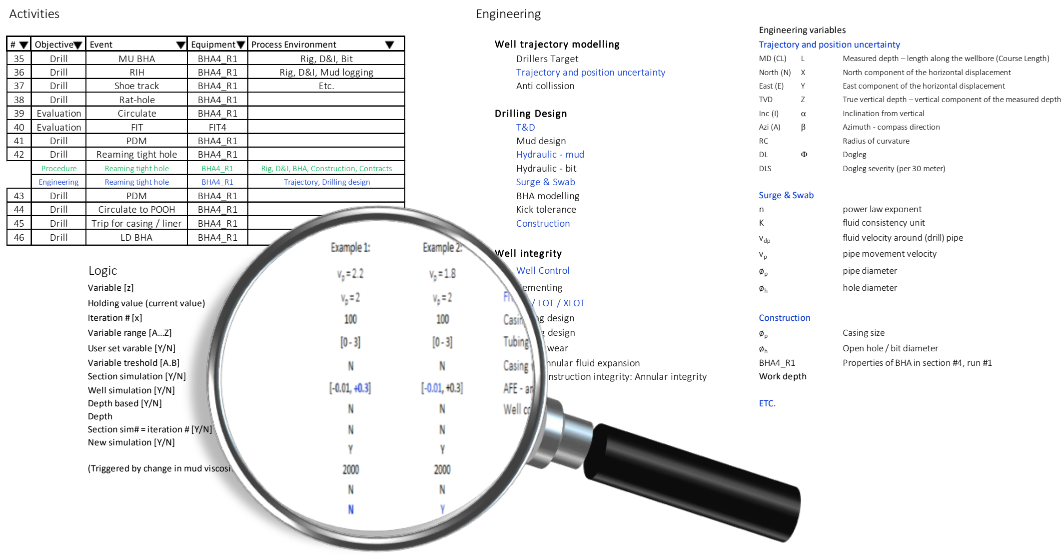


Figure 3-40 - Logic controlling simulations.

Following the examples in Figure 3-40, surge & swab calculations are evaluated for the "reaming tight hole" event. Looking at the variables for surge & swab to the right in the figure, a situation where the viscosity of the fluid is altered has an impact to the pipe velocity. Before the re-calculation takes place, there is a check to avoid calculation of an insignificant change.
Example 1 in Figure 3-40 shows a change in viscosity sent to the logic. The variable for resulting pipe velocity is "z" and the new value is 2.2. The value in the previous calculation was 2, i.e. an increased velocity of 0.2. The thresholds for recalculating pressures are an increase of 0.3 or if the new value is lower than the current, which is indicated by the -0.01. Other logic controlling initiation of engineering depends on the type of calculation. Kick tolerance is typically carried out for the full section and needs only a single simulation while e.g. torque and drag are depth based and need simulations at multiple depths.

3.7 Digital experience

Digital experience is important in many applications. It is already a part of our private lives. E.g. when asking the virtual assistant on a smart phone about a recommendation for a good restaurant, a machine learning technique for speech recognition transforms the request into a format the software and processor can handle. Machine learning (ML) for speech recognition is often based on a recurrent neural network (RNN). This is a network of "neurons" trained with digital examples of sound[20]. From there, the smart phone software connects to the web to examine customer reviews on the specific information requested. E.g. Apple is using the reviews on Yelp (https://yelp.com/). This experience or reviews are written by consumers, who in turn assist others, and forms the basis of the answer of the query.

This experience reveals some of the difficulties sharing learning in the oil and gas industry. Experience is available for anyone asking in our everyday life while most systems in the industry are not as easy to query and get the intended information. But the design of the planned software in this thesis is to go one step further. It should not be necessary for the user, i.e. engineer, to query relevant information. It will be provided by the planned software automatically. Another aspect is the availability across an organization, across projects and nations using the planned software.

In many contexts, experience is what prevents failure and offer guidance towards effective ways of working. In the petroleum industry, regulations at national and company levels have been developed over years based on experiences. Standards also contribute with collections of experiences and best practices. Today, experience transfer is hampered due to dependency on text-based documents, continuity of people and their level of experience, as discussed in section 2.2. The WOS encompass all types of experience and is designed to use these in deduction of method selection and design of programs for activities in drilling, completion, intervention and integrity, see Figure 3-41.

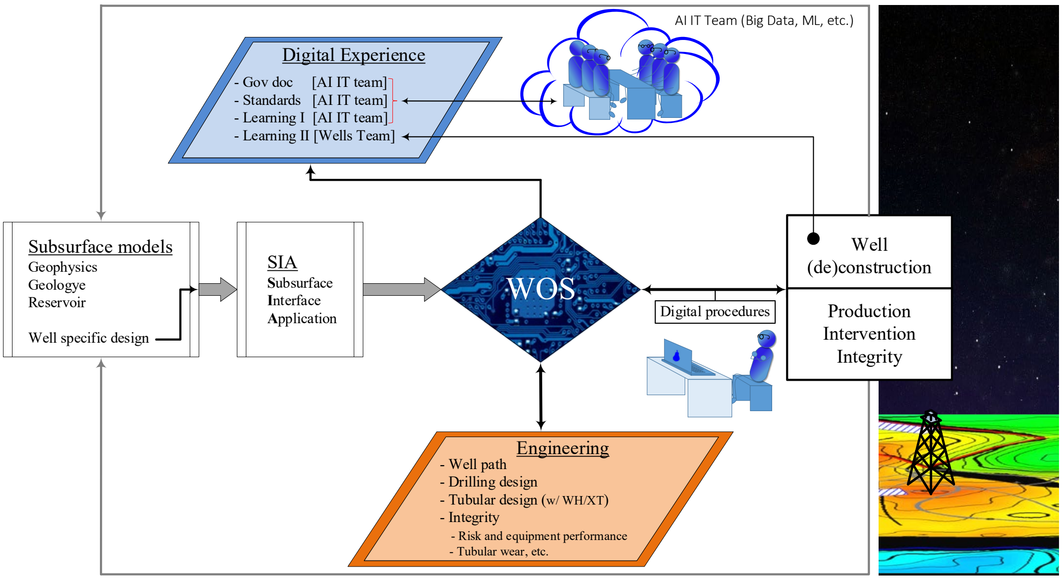


Figure 3-41 - Digital experiences act as governing algorithms for the WOS.

As in the example of the restaurant query above, the software requires a digital format to be able to understand and perform the designed tasks. The WOS is fully digital as described in the previous sections. The planned experience feature takes advantage of this and use the methods or ID-codes[21] to identify conditions using combinations of equipment, formations, events (drilling / completion,

[20] For readers with little background in Artificial Intelligence, a small introduction has been made in "Appendix F".
[21] Marked "Event" in the Event manager

etc.), services, etc. with a consequence such as a specific action. Some examples of digital experiences and how these can work:

- Initial easy example with code: When MU BHA with Positive Displacement Motor (PDM), it is important that a company representative verifies the scribe line orientation. Mitigation actions the experience feature can handle:
  - When the experience feature recognizes the code combination for MU BHA and a PDM, a text can be displayed with the program and the detailed procedure reminding that company representative to verify the scribe line as shown Figure 3-42.

Phase	Objective	Event	Equipment	Activity description	Risk / Experience
Drilling	Drilling_BitSize_section	MU BHA	BHA3_R1	MU 17 1/2" BHA #3, run #1	Verify high side orientation

Figure 3-42 - Simple text response from experience module.

- Formation with poor stability in combination with water-based mud of a low weight planned to be drilled with an angle partly below “critical”: Mitigation actions the experience feature can handle:
  - Reduce the inclination of the planned well path as recommended in the experience
  - Change to higher mud weight as proposed in the experience
  - Only notify user about a violation of practice

- Formation with interchanging strength: frequent change between hard and soft formation combined with a demanding trajectory: Mitigation actions the experience feature can handle:
  - Propose specific drilling BHA, e.g. point the bit 3DRSS over push the bit
  - Change well path with less steering, if possible and feasible
  - Notify user about a violation of practice

- Completion planned installed over an open hole completion: losses may be experienced, and a plug may be required to set the production packer. Mitigation actions the experience feature can handle:
  - Design a middle completion to protect the reservoir and avoid losses
  - Design the open hole completion with a liner/blank section for a retrievable plug
  - Other solutions and notification to the responsible user

- Intervention planning a P&A job with punching of tubing: punching depth is close to the packer and the selected puncher is a 10 ft puncher: 4 shots per foot (SPF), i.e. 41 shots with medium charges. Danger is poor communication when circulating tubing to annulus. Mitigation actions the experience feature can handle:
  - Design punching depth 2 joints above packer in case of debris in annulus
  - Add message in program: ensure supplier add centralizer for orientation of puncher

As indicated by the few examples above, the method describing experiences from operations in well construction, interventions, etc., is designed to be flexible and to automatically recognize plans (code sequences) and take action as established by the user team.

3.7.1 Establish experience

Events normally taking place during the life cycle of a well is mapped and made unique, see background in section 3.3. As seen in the above examples, the events are narrowed down from phase to objective, then under any objective there are only few specific events or methods allowed. This means that each single task normally performed by a rig in well construction has a unique digital description. The prototype is based on drop down menus, as seen in Figure 3-42, that allows the user to describe any objective through a series of tasks involving any condition. By default, every task has a connection to engineering, which means that the planned software is designed to let users manually specify experiences using operational conditions described in entries of "Phase", "Objective" and "Event".

Examples of experiences as in the bullet list above can be recognized by the planned software through their sequence of ID-codes[22] describing the specific tasks. Experience often comprises an undesired sequence of tasks and a series of desired events. Once the planned software recognizes the sequence of undesired tasks, it can replace these with the sequence of preferred operational approach as made by the users.

These codes are based on the current reporting system used on drilling rigs worldwide, as presented in section 3.2.1. The similarity between the current reporting system and the system methods used by the planned software, shows how experiences can be made. Table 3-8 is a copy of a line from a daily drilling report. It describes one event "drilling" and is established using drop down menus and specified sequences of codes. The interface for making digital experiences is identical to Figure 3-42. It is a sequence of drop down menus that narrows down the desired info to specific actions, which in the end may look like the specific example in Figure 3-42 or it can comprise several lines to fully describe equipment and desired activities. It is the same system as for making manual entries in the Event manager where the user can select methods. This Thesis refers to the established universal language as the "report language". For experienced wells engineers, the procedure of documenting activities is therefore familiar, and they can operate it without requiring programming skills.

Table 3-8 - Example of standard reporting with codes

Operations Summary							
From-To Op. Depth	Hrs (hr)	Phase	Task	Activity	Code	NPT	Operation
00:00-03:00 1,107	3.00	INT1	DRILL	DRL	P		Drill 17-1/2" hole 1085m - 1107m w/ controlled parameters 850 - 1000 gpm, 1850 -220 psi, 20-30 tons WOB , 60-80 rpm, 2900-3300 ft/lbs, ROP @ 6.5-8.5 m/hr.(Run centrifuge, mud cleaner & dilution to keep density @ 1.13 SG).increase losses to 77 bbls/hr.

3.7.2 Area of use and limitations

In an object-oriented environment, digital experience can be used to connect any legal task, engineering and equipment. Any objective automatically planned, may show default sequences of tasks which a user may manipulate using single entries or standardized sequences of tasks.

The WOS is designed to produce digital programs in sequences specified according to best practice and to be updated with experience as learning is obtained.

Digital experience was discussed in (Brechan(4), 2018) and (Brechan(5), 2018) discussed a special variety of experience. As a test, the section of casing design in NORSOK-D-010 rev4 was described using the reporting language in the WOS. Every task could be described up to the point when the standard expresses a condition as a "philosophy". A general idea becomes difficult to define in computer programming. The case referred to is in section 5.6.1 of the standard, and the requirement is stated as follows:

"*Casing, liner and tieback-strings shall be designed to withstand all planned and/or expected loads and stresses including those induced during potential well control situations*"

This is a requirement which is not sufficiently concrete. It needs to be formalized in detail by a breakdown into the specific situations to form an adequate basis for a logical sequence. A possible workaround may be to specify a minimum set of "load cases", i.e. apply all industry consensus scenarios for the casing, liner and tieback-strings.

[22] Methods

3.7.3 *Standards and governing documentation*

After investigating the possibility to define the NORSOK D-010 section for casing design (Brechan(3), 2018), it was concluded that the sections for governing documentation covering well construction, well planning and well control can be incorporated in the planned software. These documents typically describe methods, engineering requirements and other physical conditions. All of which was found to be possible to establish in the object-oriented environment applied in and by the WOS. Standards covering the same areas can also be merged in the application using the reporting language.

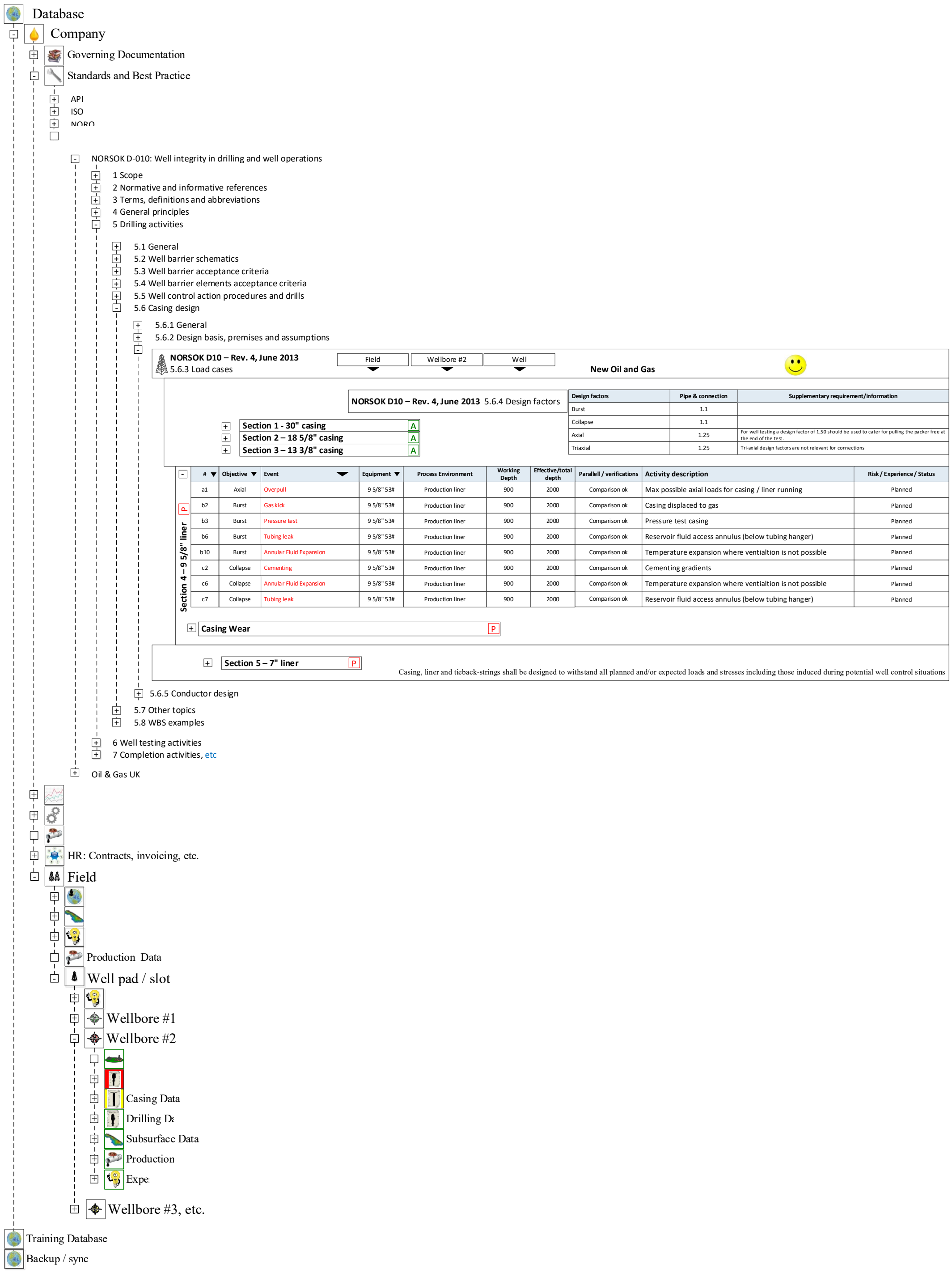
By using the "reporting language", the requirements and guidelines in governing documentation and standards can be defined in the planned software. The role of the governing documentation can take part of the planning and construction cycles in several ways[23]. There are multiple benefits with integrated standards and governing documentation. Every team have their own KPIs. An example related to requirement for cement can be as follows:

- The drilling engineers see the cement as a means to drill the next section trouble free
- The completion engineers see the cement as the space where the packer is set
- The intervention engineers often log the cement, but has no direct stake
- The well integrity engineers see the cement as part of the barrier and move to shut down production should the barrier be inadequate
- Subsurface see cement as a barrier controlling injected fluids and zonal isolation for optimal drainage

The value chain of the company builds on requirements, which in the example above a length set by the individual companies. Activating the digital governing documentation on report language format can determine whether a planned activity is compliant or need to apply for dispensation. Figure 3-43 shows the red, yellow and green status for the different elements in planning. The system runs from input to complete digital programs with detailed procedures, but the wells team need to verify the designs before they can be used in operations. The proposed colors indicate:

- Green: verified design and method
- Yellow: not verified
- Red: not according to governing documentation or standards

[23] Different roles are discussed further in OTC-28988.



Design factors	Pipe & connection	Supplementary requirement/information
Burst	1.1	
Collapse	1.1	
Axial	1.25	For well testing a design factor of 1,50 should be used to cater for pulling the packer free at the end of the test.
Triaxial	1.25	Tri-axial design factors are not relevant for connections

#	Objective	Event	Equipment	Process Environment	Working Depth	Effective/total depth	Parallell / verifications	Activity description	Risk / Experience / Status
a1	Axial	Overpull	9 5/8" 53#	Production liner	900	2000	Comparison ok	Max possible axial loads for casing / liner running	Planned
b2	Burst	Gas kick	9 5/8" 53#	Production liner	900	2000	Comparison ok	Casing displaced to gas	Planned
b3	Burst	Pressure test	9 5/8" 53#	Production liner	900	2000	Comparison ok	Pressure test casing	Planned
b6	Burst	Tubing leak	9 5/8" 53#	Production liner	900	2000	Comparison ok	Reservoir fluid access annulus (below tubing hanger)	Planned
b10	Burst	Annular Fluid Expansion	9 5/8" 53#	Production liner	900	2000	Comparison ok	Temperature expansion where ventialtion is not possible	Planned
c2	Collapse	Cementing	9 5/8" 53#	Production liner	900	2000	Comparison ok	Cementing gradients	Planned
c6	Collapse	Annular Fluid Expansion	9 5/8" 53#	Production liner	900	2000	Comparison ok	Temperature expansion where ventialtion is not possible	Planned
c7	Collapse	Tubing leak	9 5/8" 53#	Production liner	900	2000	Comparison ok	Reservoir fluid access annulus (below tubing hanger)	Planned

Figure 3-43 - Standards and governing documentation in digital and automated well planning.

3.8 Digital program and procedures

The WOS is designed to produce digital programs. The program expands to display detailed procedures as shown in Figure 3-44 (heading of the procedure) and Figure 3-45 (main body of the procedure). The object-oriented environment develops these into a series of steps of "report language". There are no limitations identified using the digital format over the text-based formats in operations today. Rig projects with little or no automation can benefit from the improved planning process since it is possible for humans to read the digital programs. For projects with automated rigs, there is an advantage in the layout as shown. Linking up a software such as ProNova can make an immediate and automated change in the ongoing event changing the status from planned to "as run". This may provide a powerful cross disciplinary documentation of important well integrity data. The operational data can be stored in the "well" for each object-oriented item or task, servicing any discipline live or in hindsight. Coupling a well integrity software to the "well", it may provide any operational data such as cementing parameters, full or partly returns during displacement, etc.[24]

The designed steps in the detailed procedures are similar to what is used in operations today, see Figure 3-45. An important note on the detailing level is the planned opening for rig contractors' procedures, which can be described using the "reporting language" and displayed in the same way.

A benefit with a digital planning cycle is the insight from tuning of operational parameters and limitations. The well planning sequence may be run with a variation of all parameters and repeated by the planned software 10,000 to 100,000 times to tune the final plan. The parameters may be tweaked by the engineers to deliver an optimized end result through manipulating the input, see section 1.1. This can be used to establish a desired focus: cost, risk, time, HSE or other sequence of priority.

This approach can be used to develop special parameters for extreme ERD projects, HPHT, ultra-deep wells, etc. The model can run during operations and deliver updated engineering parameters, provide support in troubleshooting, have governing documentation actively analyzing the well construction as it progresses, and other support.

-	Well status
-	Objectives
-	Risks
-	Safety
-	Check list - operational readiness
-	Critical depths
-	References: Gov. doc, standards, MOC, relevant procedures (connection procedure, drilling fluid management), etc.
-	Dispensations

#	Activity description	Parallell / verifications Add experience	Risk experience
51, P1	MU BHA - Delivery from supplier 1. All tools to be shipped pre-made up in racking lengths 2. All tools to be fitted with recess for pipe handling – no lift subs 3. Required XOs to be fitted from base 4. All connections with MU certificate 5. Bit MU to PDM / RSS from base	MU BHA - Detailed Procedure – Prepare P1. Delivery from suppliers base	

Figure 3-44 - Heading of detailed procedure.

[24] Original operational data will always take part in the integrity evaluations of wells.

#	Activity description	Parallell / verifications	Risk experience
		Add experience	
51, P1	MU BHA - Delivery from supplier 1. All tools to be shipped pre-made up in racking lengths 2. All tools to be fitted with recess for pipe handling – no lift subs 3. Required XOs to be fitted from base 4. All connections with MU certificate 5. Bit MU to PDM / RSS from base	MU BHA - Detailed Procedure – Prepare P1. Delivery from suppliers base	
51, P2	MU BHA - Detailed Procedure - Offline preparations 1. Remove papers (delivery notes), tape and protection from tools 2. Verify Bit nozzles, inspect all tools and make fishing diagram 3. Gauge stabs, bit, 4. Locate and prepare all required handling equipment for BHA 5. Tool programming / memory dump prior to PU or safe area	MU BHA - Detailed Procedure – Prepare P2. Offline preparations	(Handling) Equipment Elevator inserts for Lift Subs Slips / Dog Collar for DC and RSS DP Slips Bit braker Hinged ring gauge Stabbing Guide Kelly cock and grey valve Totco for drifting
51, S1	MU BHA – Prejob meeting: verifications 1. Check strainers on mud pumps 2. Check pressure in the pulsation dampeners 3. Function test degasser 4. Check slip joint seals. Adjust pressure if required 5. Flow line magnets installed, procedure for cleaning and maintenance prepared and agreed with Halliburton 6. Jar schematics, with work hours and procedure on DF 7. Kill sheet prepared 8. Wash pipe and top drive saver sub condition 9. MWD / LWD programming verified with company 10. Magnetic input data updated 11. Work permits prepared 12. BHA components data (MU torque, lengths, etc)	MU BHA - Detailed Procedure – Prejob meeting 1. Prejob meeting	
51,S2	RIH to verify float holding and fill to verify nozzles ok	2. PU Assembly 1: RSS with premade bit	
51, S3		3. PU and MU Assembly 2: Near-bit GR/res sub and Vibration - Stick Slip (VSS) sub	
51, S4		4. PU and MU Assembly 3: Image tool	
51, S5		5. PU and MU Assembly 4: Deep res. (transmitter) and Azimuthal res subs	
51, S6		6. PU and MU Assembly 5: MWD	
51, S7		7. PU and MU Assembly 6: Stab and NMDC	
51, S8		8. PU and MU Assembly 7: Deep res. (receiver)	
51, S9	Hold TBT and PU to Image tool to install RA source	9. PU and MU 1 stand DC with XO	
51, S10	Verify MWD / LWD sensors and programming	10. PU to MWD, connect and verify sensors	
51, S11		11. MU 2 stand HWDP	
51, S12		12. PU and MU jar assembly	
51, s13		13. MU stand with HWDP and accelerator	
51, s14		14. MU 2 stand HWDP and XO to DP	

Figure 3-45 – Digital Detailed Procedure in the event manager: MU 8 1/2" drilling BHA.

3.8.1 Completion, intervention, well integrity and P&A

These disciplines are not often discussed in the literature or in the wave of digitalization washing over the industry. All of them have an unlocked potential for improved HSE, reduced risk and saving time. One thing these disciplines have in common is the dominance of text-based procedures and experience transfer.

3.8.1.1 Completions

Completions used today are often a few standard types. In a case where the casing program is determined, the automated engineering of the completion has a clear physical frame. With all physical boundaries, the report language can automate the tubing design and establish program and detailed procedures based on required integrity.

3.8.1.2 Well intervention

Well intervention, however, is a bit more complex. Typically, the reason for many well intervention operations are not specific or tied to a physical boundary. E.g. the need to change a gas lift valve to a lower position, re-perforate, stimulate or straddle off a formation need a separate approach to initiate operations. In some cases, well intervention can be tied to well integrity. Where one or more of the annuli are pressured up due to migrating gas or other reason, an investigation of the background is required. In cases of a leak from tubing to annulus, well interventions are required to assist in troubleshooting or to patch the leak. Another example of "diffuse" initiation is logging such as saturation logs, PLT, etc.

Well interventions are very diverse in the nature of the work and in the number of tools involved. Investigating the possibilities to produce a digital program automated as with drilling and completion, shows some interesting alternatives, see section 1.1 . Investigating the potential in automating P&A has a preliminary conclusion that it may be automated. The method would depend on the integrity of the cement and formations. Should the object-oriented environment be developed with this capacity, the development of automated digital programs using the "reporting language" is possible.

3.8.1.3 Well integrity

Well integrity engineers often perform manual work to deduct and verify integrity designs. Typically, the integrity evaluations are modelled in the well planning phase by the Wells team. The wells are drilled and handed over to the Production department. The initial work of the Well integrity often starts at this point. Due to compartmentalization and differences in discipline objectives, the first tasks are often to collect data from operations. The Well integrity teams study activity reports to identify isolation and integrity quality of the cement jobs, updates of formation strength particularly at the casing shoes, pressure tests and fluids used to certify the cavities of the well for production, and other integrity data. The collected information is often extracted and established in a system for evaluation of the containment capacity of the well. Especially the pressure tests are given importance. As long as the observed annuli pressures are within boundary, often limited by the pressure test performed, the well is believed to be in sound condition. Most of this legacy workflow can be automated using a software with object-oriented environment. Operators can have faster and more accurate evaluations of the integrity of wells and assets.

Asset life extension is often connected with in depth analysis of the different barriers, their history and the remaining integrity. This is an area that may be automated and updated on every event through the life cycle of wells.

3.9 "Optional" features

A digital base enables several new features. Figure 3-47 propose machine learning to tweak well planning parameters towards optimization of the well design in planning. In section 3.5.2, well planning arrived at an optimal design with a combination of "*design mitigations*". Figure 3-46 is an example of possible "*design mitigations*", including governing documentation.

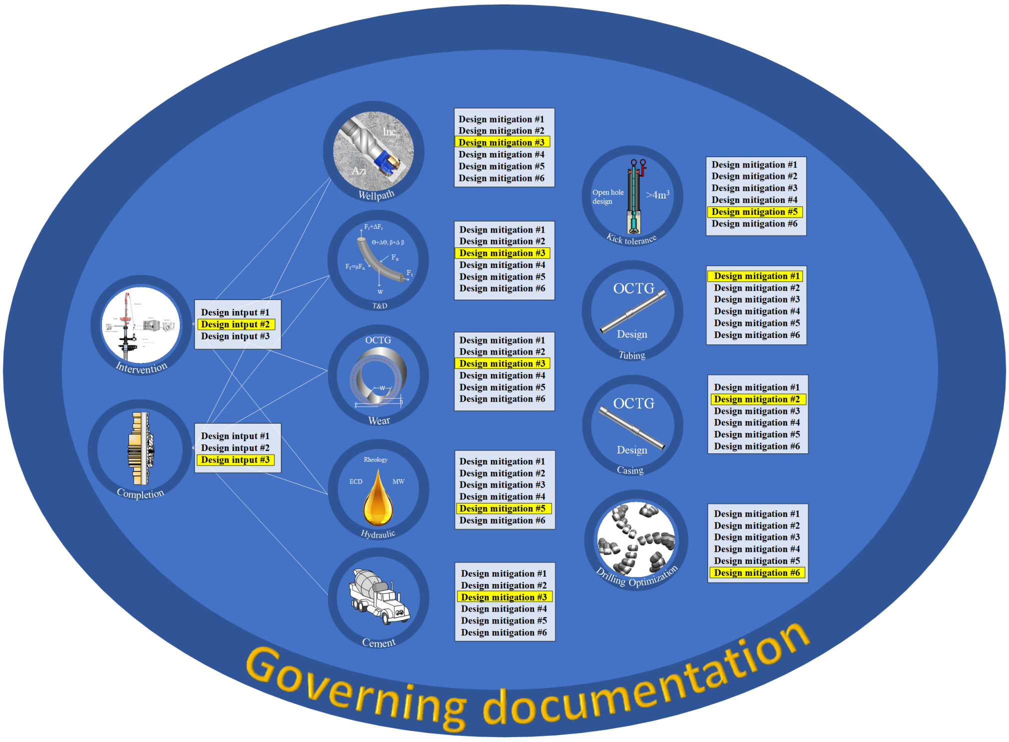


Figure 3-46 - Design mitigations - optimal design.

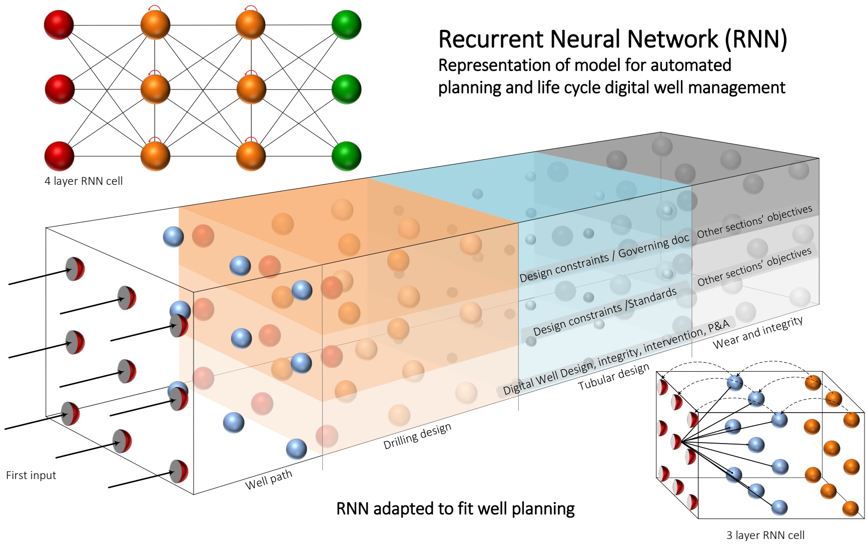


Figure 3-47 - Machine learning applied to tweak well designs.

Since the variable map applies minimum and maximum for each value, an adapted type of machine learning can derive optimal designs. Machine learning often works with individua weighting of each evaluation to arrive at the desired result. In well planning, each “method” and each “variable” can be defined with a risk and a cost for each desired profile. Planning HPHT wells and exploration type wells typically have different priority for each variable. Applying different cost and risk profile for each variable and calculation, machine leaning may establish optimal designs using e.g. the “gradient decent” method, see Figure 3-48. The method is further discussed in Appendix F.
Looking at each calculation as a neuron, the input values of each calculation can be tried with either a slightly higher or lower value until the total cost, risk or both is reduced. Traditionally, each neuron is a mathematical function, which means that a simple academic explanation of the gradient decent method is the derivative of each calculation. Combining all calculations with all allowed values of the variables can produce a 3D surface as in Figure 3-48. Since this thesis outlines a complete digital planning cycle, the planned software design enables iterations until the optimal combination of parameters is achieved without human intervention and within hours. The software design is then planned to develop the combination of variables which yields the lower point in cost, risk or any other sought goal. E.g. for Extended Reach Development (ERD) wells, the priority can be well path, hydraulic and T&D over other designs. Focus and priority of optimization can be tailored using the planned RNN control system.

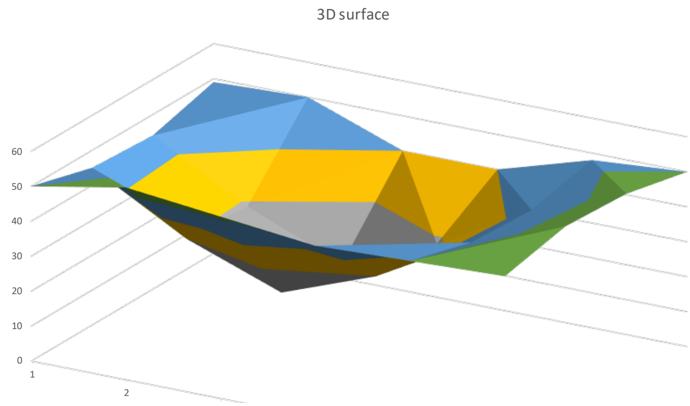


Figure 3-48- Example 3D surface of all engineering variables in a well planning cycle.

3.10 Planned software interface

The main working interface with the planned software is decided to be a 3D representation of the well, where all components are tied to the object oriented information they are part of. This will then act as a menu of information for any discipline. E.g. a casing is tied to casing design, the running procedure it once had, the cementing program and parameters, its cement bond log, the drilling parameters and BHA used through it (foundation for casing wear), and so on. Interacting with the components can be a portal to the integrity information many companies are using many manhours per discipline to establish for every investigation carried out for every well. A term found useful to describe this is “information management”. In a manual text-based environment, there are many hours of operator’s time spent to collect and re-distribute information that sits in different systems. Collecting the information and attach it to a 3D representation of the component it was originally used for, can act as a portal for any discipline throughout the lifecycle of the well. Such a menu is a natural choice for all involved disciplines, and it has a potential for saving many hours for every operator.
Another application is to initiate well intervention. Several of the interventions listed in the previous chapter can be initiated by interacting with a 3D menu sitting in an object-oriented environment. The planned software may react to e.g. “drag and drop” for initiation of moving of gas lift valves or other standard operations.

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4 Engineering module for tubular design

A significant part of the research was spent checking tubular design. This chapter exemplifies some of the work done with engineering in well construction. Several models for different calculations were investigated for possibility to fit in an automated object-oriented environment. The investigations also evaluated “state of the art” engineering, i.e. where do errors occur and how can a new model prevent these. Engineering for well construction is adequate in many areas but can be improved in other areas[25]. The purpose of the research behind this thesis has been to mobilize wells engineers and get more involvement in working smart in operations and planning, better engineering and better understanding of engineering. This Thesis has pointed out two main factors enabling these improvements: Automate most of the engineers daily administrative tasks and enable “open” engineering. The latter means that calculated results can be followed, so engineers can better verify the modelled results. To make step changes in engineering, more engineers need to take part in what is under the “hood” and not be just a chauffeur of the modeling software.
All investigated models were found to be eligible for full automation. Furthermore, the investigations evaluated the quality of the industry standard calculations and identified areas of improvement. Tubular design was identified as the area where improvement in cost and environment can save the most. The conducted research entails improved models for burst and collapse. Both models were developed in prototype applications, which were presented in separate papers. Some of the other areas investigated are:

- Automated casing wear
- Casing pressure limitation to avoid cement sheath failure
- 2D Fracturing model
- Drilling optimization application
- Application for buckling
- Temperature model
- Annular Fluid Expansion (AFE)
- Well integrity - automated risk assessment

A summary of this research can be seen in Appendix B.

4.1 Automated tubular design – fundamental material theory

Tubular design is one of the areas where engineering can be improved both in understanding of the topic and in the actual modelling practices in the industry. Starting with the published material, introduction and overview of the philosophies and models used in the industry could be better for the new generations of engineers. The foundation for modeling practices and what they mean would then be better understood and designs can be more fit for purpose.
The standard for tubular design states that for collapse predictions, the Klever & Tamano calculations are the most accurate. And the same standard is warning against the Barlow formula, which was the most used method in the industry for burst over many decades. The model promoted as the more accurate by API/ISO TR 10400:2018 is the Lamé equations inserted into von Mises, which was an approach presented over 40 years ago (Lubinski, 1975). The Barlow formula was presented in 1836 before modern theory of elasticity was developed, see Table 4-1 for an overview. Tubular design builds on modelling of material failure. Theory of failure is a question of perspective. E.g. for burst, the industry sets the criterion to yield which is not recognized as failure per se in material science.

[25] Engineering calculations in well construction are not often changed significantly. Updates are most times small and result in minor effect to designs.

Von Mises is the undisputed limit for failure in tubular burst design. Supported by more than 100 years of scientific testing and verification[26], the "maximum distortion energy criterion" (von Mises, 1913) is used in all industrial designs limited to yield for isotropic materials such as steel. Before discussing failure from burst or collapse, a recap of the von Mises failure criterion can be useful since both use this criterion.

4.1.1 Von Mises (VME)

Stress in a material is a tensor not a vector, see Figure 4-1. As seen in the figure, stress is distributed through the material.

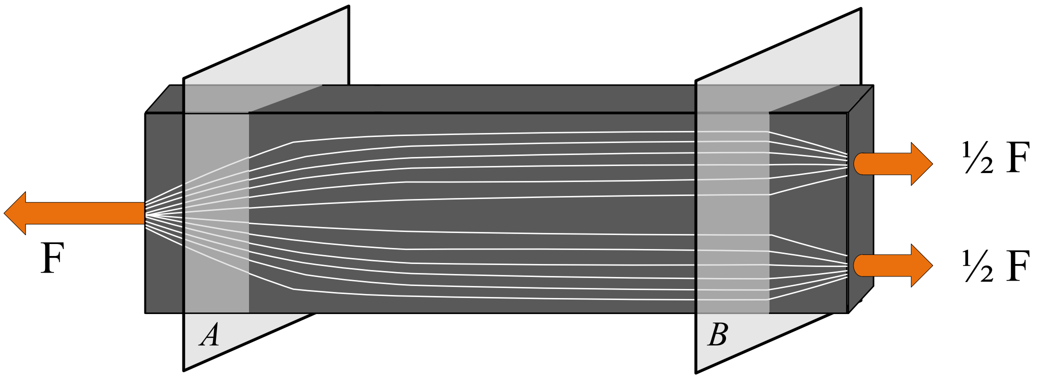

Figure 4-1 - External and internal stress of an object.

In classes and literature, forces are often presented as vectors for simplification. To fully understand the limitation of loads to any steel construction, it is necessary to know the nature of stress and how it acts inside the material. Figure 4-1 shows the principal components and the most relevant of the fundamental theories for stress and load limitation of steel pipe is summed up in Table 4-1.

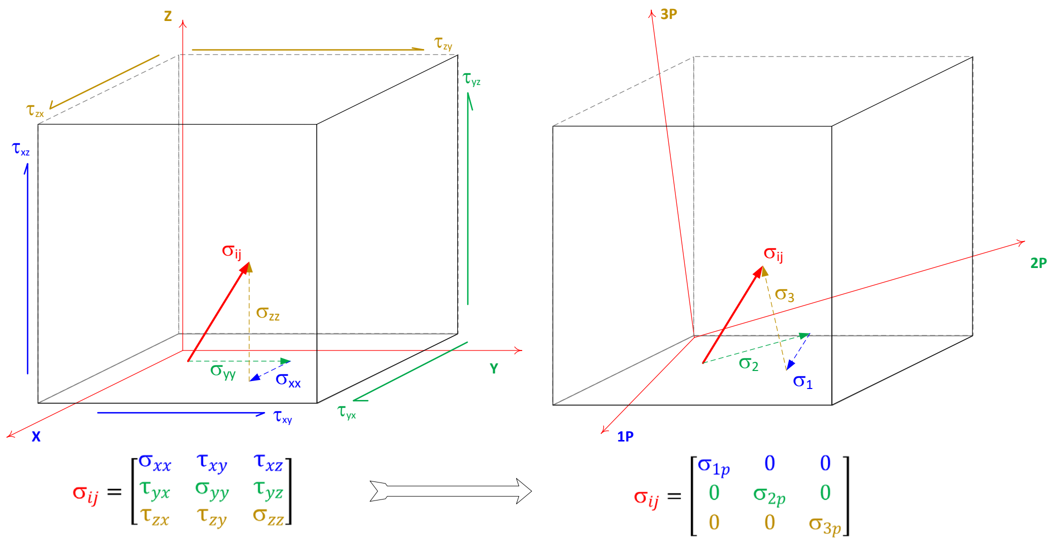

Figure 4-2 - Left: stress components in a tensor matrix. Right: Transformation to principal direction.

Tensors as σ_{ij} in Figure 4-2 have 9 variables as seen to the left in the figure. Rotating the reference axis in the direction of the principal stresses makes the shear components disappear as seen to the

[26] (Christensen, 2010), (Hill, 1990), (Tsai, 1971) and others.

right in Figure 4-2. The mathematical evidence for this has been derived in Appendix A "Octahedral shear stress criterion (von Mises)".

Table 4-1 - Historical development of failure theory in modern casing design.

1678	1	Robert Hooke: Hook's law (springs and materials with small/little deformation)
1744	2	Leonhard Euler: presented the first theory of (column) buckling
1823	3	Augustin-Louis Cauchy: Cauchy stress tensor
1836	4	Peter Barlow: Burst
1852	5	Christian Otto Mohr: "Mohr's circle" and failure theory
1852	6	Gabriel Lamé: Solutions for elastic stress in tubes as a function of internal and external pressure (principal stresses).
1855	7	Saint-Venant: The "St.Venant principle.
1864	8	Henri Tresca: Shear failure criterion
1913	9	R. von Mises: yield / maximum distortion energy - criterion
1924	10	Henrich Hencky: 1st to plot and publish the von Mises yield criterion as an ellipse
1946	11	Bridgman: Influence of Hydrostatic pressure on yield point of steel

Equation (4-1) describes stress in situation as the left side in Figure 4-2:

$$\sigma_{ys}^2 = \frac{1}{2}\left[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_x - \sigma_z)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2)\right] \quad (4\text{-}1)$$

Where:

σ_{ys} is the material yield strength
σ_x is the stress component along the x axis
σ_y is the stress component along the x axis
σ_z is the stress component along the x axis
τ_{xy} is the shear stress component along the xy plane
τ_{yz} is the shear stress component along the yz plane
τ_{xz} is the shear stress component along the xz plane

Note that the shear stresses annotated xy, yz and xz are not related to torsion (torque in pipe). They describe the shear components of the stress tensor. For a system with only principal stresses:

$$\sigma_{ys}^2 = \frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2\right] \quad (4\text{-}2)$$

Where:

σ_1 is the stress component along the principle axis annotated 1
σ_2 is the stress component along the principle axis annotated 2
σ_3 is the stress component along the principle axis annotated 3

The von Mises criterion has many names. E.g. Maxwell–Huber–Hencky–von Mises theory, maximum distortion energy criterion and "Octahedral stress criterion". To develop visualization of the octahedral shear criterion, it is convenient to set the one principal stresses to zero, i.e. $\sigma_3 = 0$. Eq. (4-2) becomes:

$$\sigma_{ys} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - 0)^2 + (\sigma_1 - 0)^2} \quad (4\text{-}3)$$

$$\sigma_{ys} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + \sigma_1^2 + \sigma_2^2} \quad (4\text{-}4)$$

$$\sigma_{ys}^2 = \frac{1}{2}\left((\sigma_1 - \sigma_2)^2 + \sigma_1^2 + \sigma_2^2\right) \quad (4\text{-}5)$$

$(\sigma_1 - \sigma_2)^2 = \sigma_1^2 - 2\sigma_1\sigma_2 + \sigma_2^2$
$\sigma_{ys}^2 = \frac{1}{2}\left((\sigma_1 - \sigma_2)^2 + \sigma_1^2 + \sigma_2^2\right) = \frac{1}{2}\left(\sigma_1^2 - 2\sigma_1\sigma_2 + \sigma_2^2 + \sigma_1^2 + \sigma_2^2\right)$

$$\sigma_{ys}^2 = \sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2 \quad (4\text{-}6)$$

Eq. (4-2) represents the ellipse first produced by Heinrich Hencky (Hencky, 1924). Eq. (4-2) is plotted in Figure 4-3.

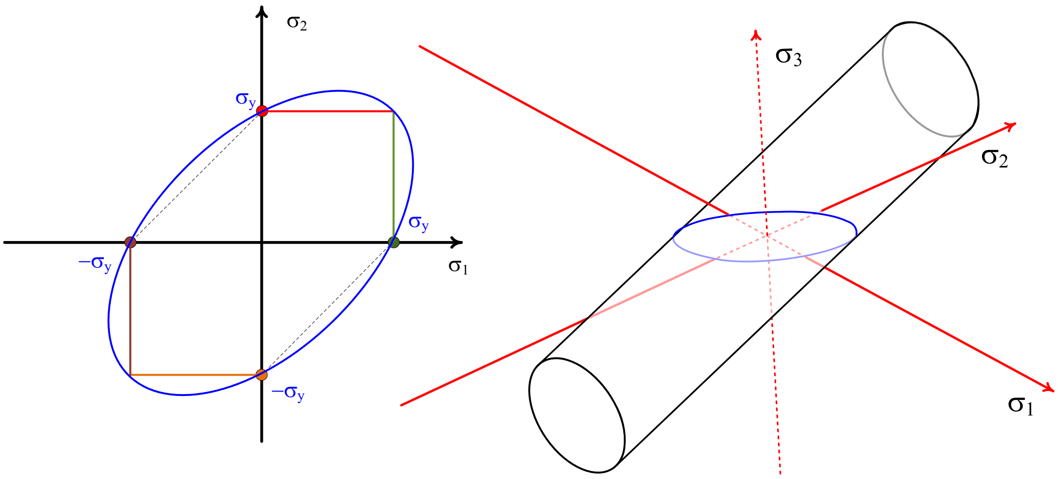

Figure 4-3 - Maximum distortion criterion (von Mises) surface.

The ellipse crosses both σ_1 and σ_2 at yield, i.e. σ_{ys}. These intersections are known as the points of maximum shear stress, which is the Tresca criterion. Tresca is discussed further in Appendix A.2 "Maximum shear stress criterion – Tresca". Another visualization of the shear stress criterion (Tresca) can be seen by plotting equation (4-7).

$$\tau_1 = \frac{\sigma_1 - \sigma_2}{2}, \qquad \tau_2 = \frac{\sigma_2 - \sigma_3}{2} \; and \quad \tau_3 = \frac{\sigma_1 - \sigma_3}{2} \tag{4-7}$$

The shear stresses τ_1, τ_2 and τ_3 occurs in specific planes as the difference between the principal stresses. Figure 4-4 visualize Eq. (4-7):

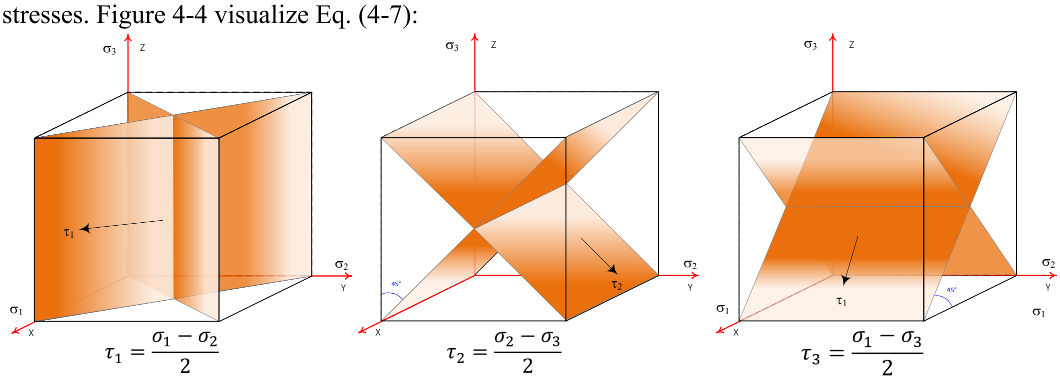

Figure 4-4 - The physical interpretation of maximum shear stresses and principal directions.

Going back to the stress in Figure 4-2 and decomposing the stress along the planes in Figure 4-4, failure can be stated as:

When the combined sum of the shear stresses along the shear planes reach the material yield strength, the pipe will start to deform.

The same type physical representation of the von Mises planes of failure can be seen in Figure 4-5.

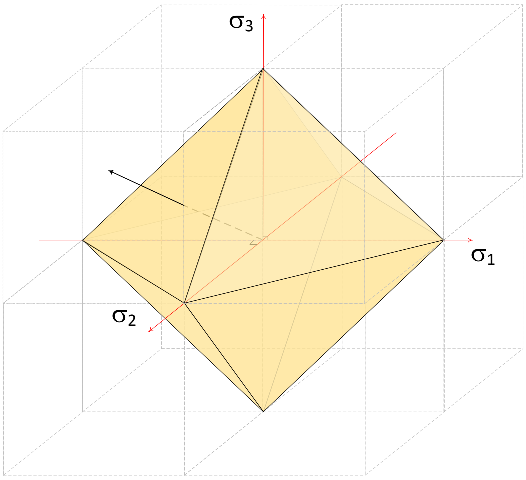

Figure 4-5 - Octahedral stress planes, where tubulars fail according to the von Mises criterion.

Another physical meaning of the Tresca and von Mises criterion is that when yield occurs as seen in Figure 4-6, the material subjected to load has reached a point where combined shear stress of equation (4-2) has exceeded the yield stress of the material along any of the planes in Figure 4-5.

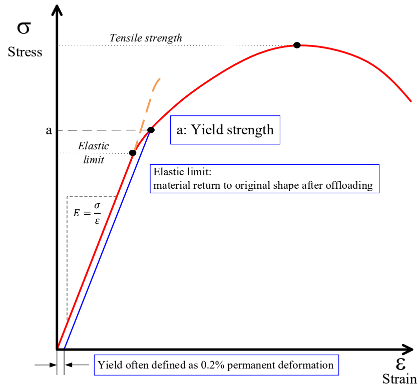

Figure 4-6 – Conventional stress-strain curve from tensile test to confirm material properties.

Steel atoms are arranged in a lattice where there sometimes are voids or inconsistencies. Figure 4-7 displays such a void in the atomic lattice marked with an upside down "T". This is a symbol for a "dislocation", which sometimes is a termination of a plane of atoms in the middle of a lattice. Dislocations enables more easily "re-shaping" of steel as the horizontal row of atoms can move like a wave as shown in Figure 4-7.

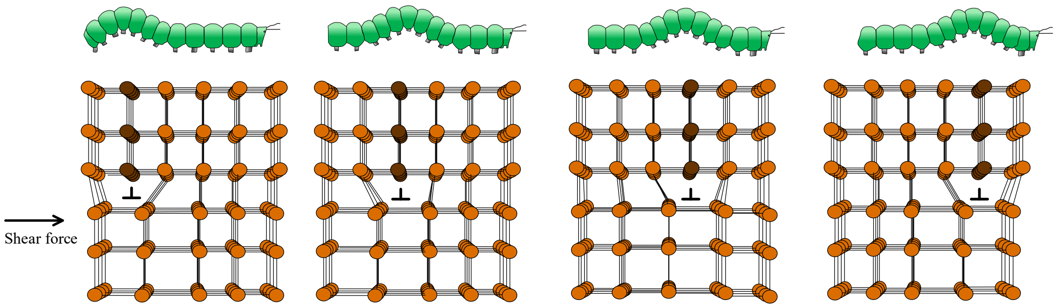

Figure 4-7 - Dislocation movement: deformation and work hardening of steel

Dislocations are often produced when the steel is subjected to a load. They start to appear and move around the yield point, as exemplified in Figure 4-6.
One of the main reasons why steel is hardening when it has seen loads past the yield point is that the dislocations are increasingly more limited in movement. As can be seen in Figure 4-7, the atomic metal bonds are stretching around the dislocations. When there are multiple dislocations assembling in an area, the metal bonds in the lattice are stretched to their maximum.
A simple explanation of the dislocation movement is to think of a long red carpet. Moving this red carpet is very hard, just like deforming metal. However, a local bulge in the carpet can be moved like a wave (as a caterpillar moves) along the carpet quite easily.

Figure 4-8 shows the yield limit plotted as an ellipsis, i.e. the von Mises ellipsis.

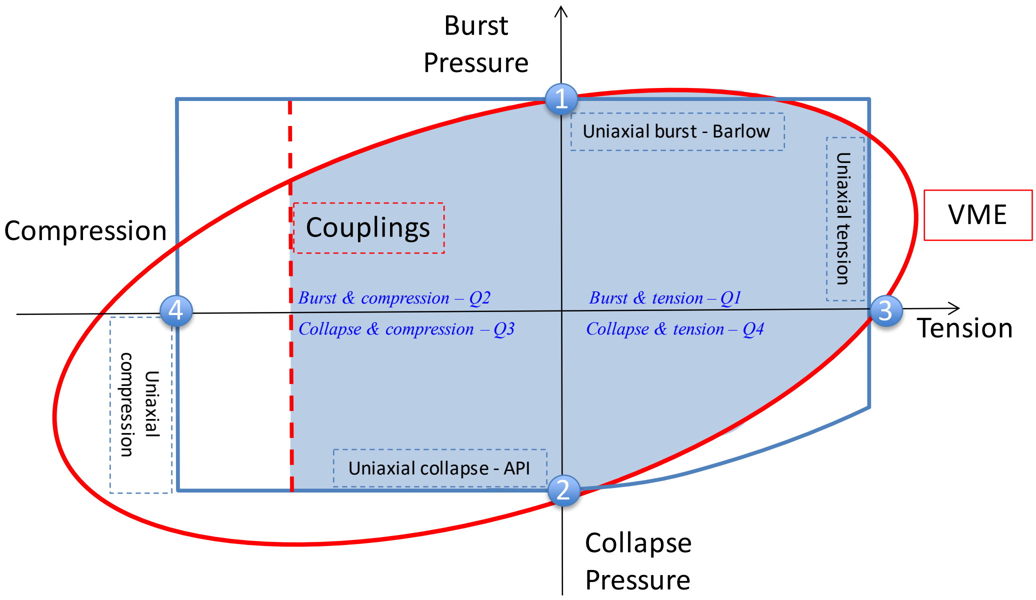

Figure 4-8 - von Mises in triaxial plot.

4.1.2 Burst

From a material science point of view, failure due to burst is rupture. But in well construction, it is solely governed by the von Mises failure criterion. Point marked 1 is the uniaxial condition often set to a limit given by the Barlow formula (2-1). As discussed in section 2.5.4.2 Error in burst prediction, API/ISO TR 10400:2018 states that the Barlow formula is not valid for thick-walled pipe. I.e. pipe with an outer diameter to wall thickness ratio (D/t) need to be greater than 20 for the formula to give valid predictions. Tied to the Barlow formula is the triaxial safety factor set to 1.25. The crossing of the uniaxial point on the vertical axis marked as “1” in Figure 4-8 , is DF_{burst} / t_{wall} = 1.2571, where DF_{burst} is design factor for burst and t_{wall} is the traditional manufacturing tolerance for pipe wall thickness

According to API/ISO TR 10400:2018, failure due to internal pressure in combination with axial stress is governed by the von Mises failure criterion as stated in equations (4-2) and (4-3). For tubulars, equation (4-2) can be written as equation (4-8)

$$\sigma_{ys}^2 = \frac{1}{2}\left[(\sigma_\theta - \sigma_r)^2 + (\sigma_r - \sigma_z)^2 + (\sigma_r - \sigma_z)^2\right] \qquad (4\text{-}8)$$

Where:

σ_θ is the tangential or hoop stress

σ_r is the radial stress

σ_z is the axial stress

σ_θ, σ_r and σ_z are principal stresses, which can be understood from equation (4-8), since the tensor shear stresses are not present. Looking at equations (4-2) and (4-3) with their physical interpretations in Figure 4-4 and Figure 4-5, it is clear that all pipe exceeding the yield criterion from internal pressure will be subjected to shear failure.

Expressions for σ_θ, σ_r and σ_z were deducted by Gabriel Lamé in 1852:

$$\sigma_\theta = K + \frac{C}{r^2} \tag{4-9}$$

$$\sigma_r = K - \frac{C}{r^2} \tag{4-10}$$

$$\sigma_z = \sigma_z \tag{4-11}$$

Where:

r is the pipe radius of investigation (normally inner radius)

r_i is inner radius of pipe

r_o is outer radius of pipe

p_i is internal pressure of pipe

p_o is external pressure of pipe

$$K = \frac{r_i^2 p_i - r_o^2 p_o}{r_o^2 - r_i^2} \tag{4-12}$$

and

$$C = \frac{(p_i - p_o) r_i^2 r_o^2}{r_o^2 - r_i^2} \tag{4-13}$$

Inserting (4-9), (4-10) and (4-11) into (4-8) as proposed by API/ISO TR 10400:2018, the following expression arises:

$$(p_i - p_o) = \frac{A_x}{2A_o}\left\{\frac{2A_i A_o (p_o + \sigma_z)}{3A_o^2 + A_i^2} + \sigma_{ys}\sqrt{\frac{4A_o^2}{3A_o^2 + A_i^2} - \frac{12(p_o + \sigma_z)^2 A_o^4}{9A_o^4 {\sigma_{ys}}^2 + 6A_i^2 A_o^2 {\sigma_{ys}}^2 + A_i^4 {\sigma_{ys}}^2}}\right\} \tag{4-14}$$

Where:

A_i is the area of inside wall of pipe

A_o is the area of outside wall of pipe

A_x is the area of pipe's steel cross section

Derivation of equation (4-14) was part of presenting article "Improved model for tubular burst" (Brechan(7), 2019). It produces the "exact von Mises", a name that originates from the fact that external pressure is incorporated in the resulting VME ellipsis, see Figure 4-9.

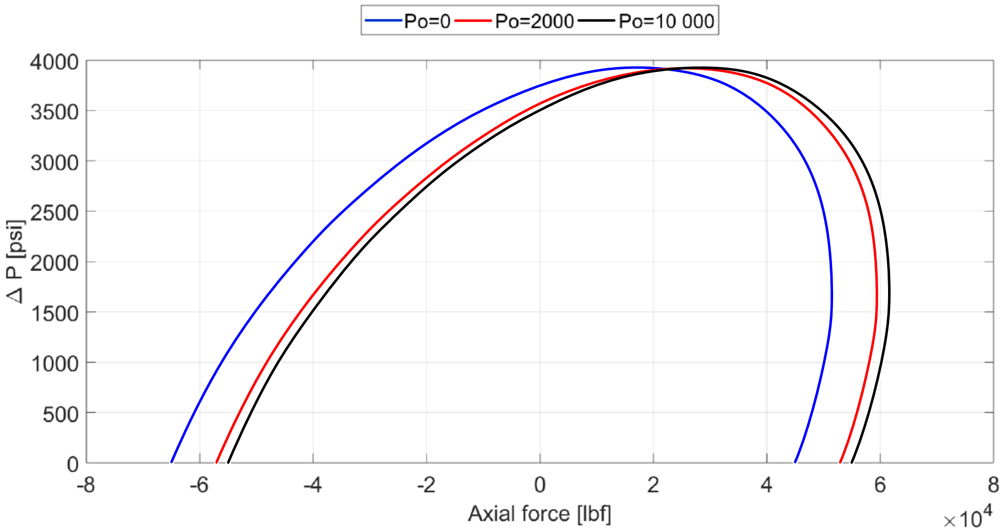

Figure 4-9 - Exact VME ellipsis as presented by the developed prototype.

The prototype developed for burst prediction using the exact VME includes the Klever and Stewart (K&S) rupture prediction, see Figure 4-10. API/ISO TR 10400:2018 promotes the K&S as the most accurate rupture prediction. Adding this feature to burst design evaluations, gives the well construction engineers an extra perspective of the integrity.

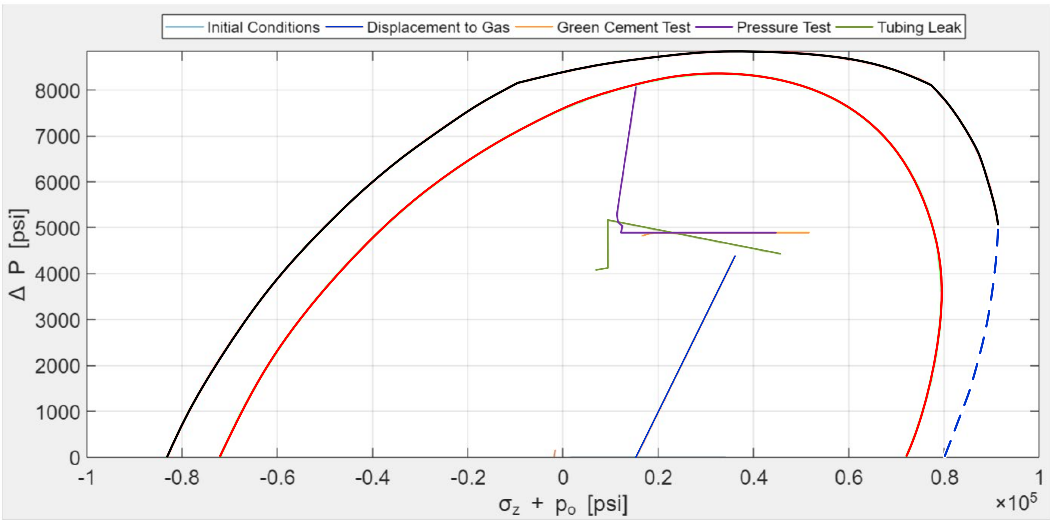

Figure 4-10 - Burst prediction with ductile rupture and exact VME.

Going back to the stress-strain curve in Figure 4-6, the "neck" of the curve going from yield to rupture is the distance from yield marked in red in Figure 4-10, to rupture marked with a black curve in the figure. Materials with higher yield tend to have a shorter neck than materials of lower yield. Figure 4-11 shows different failure modes where internal pressure is dominant.

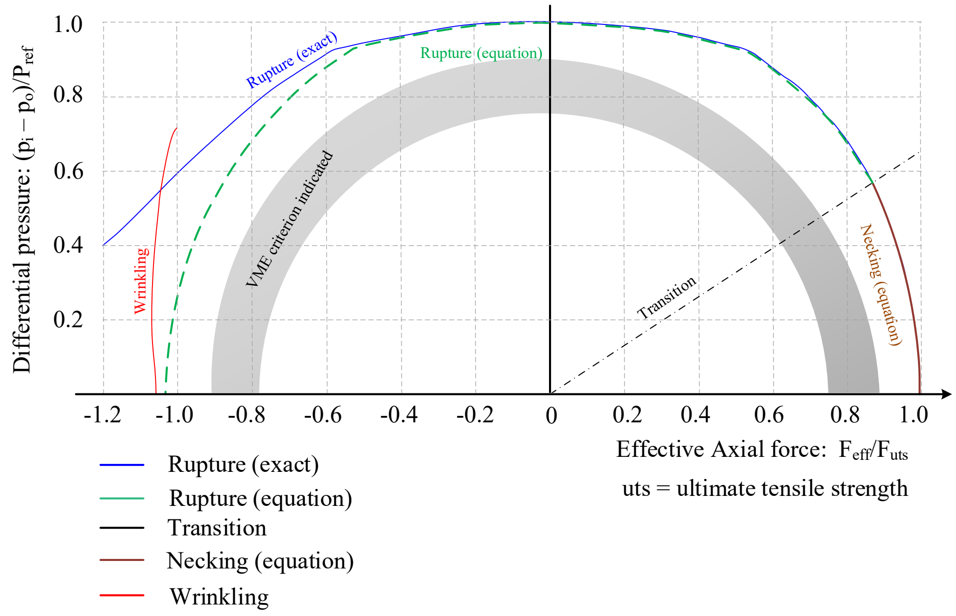

Figure 4-11 - Failure modes due to internal pressure. Modified from API/ISO TR 10400:2018.

4.1.2.1 Prototype application for burst

Figure 4-9 and Figure 4-10 are from the prototype developed using exact VME. With the use of a fully scientific design limit such as the exact VME, it is possible to make good designs fully automated. Temperature deration is missing from the prototype and need to be added for an industrial design application. Equation (4-14) presents the triaxial capacity of the pipe directly so no further analysis is required.

4.1.3 Collapse

Integrity failure due to collapse is not governed yield alone. Collapse has relations to Euler's column theory, which is shown to the left in Figure 4-12. Elastic collapse is not influenced by axial stress, only governed by the pipes' geometrical diameter and wall thickness.

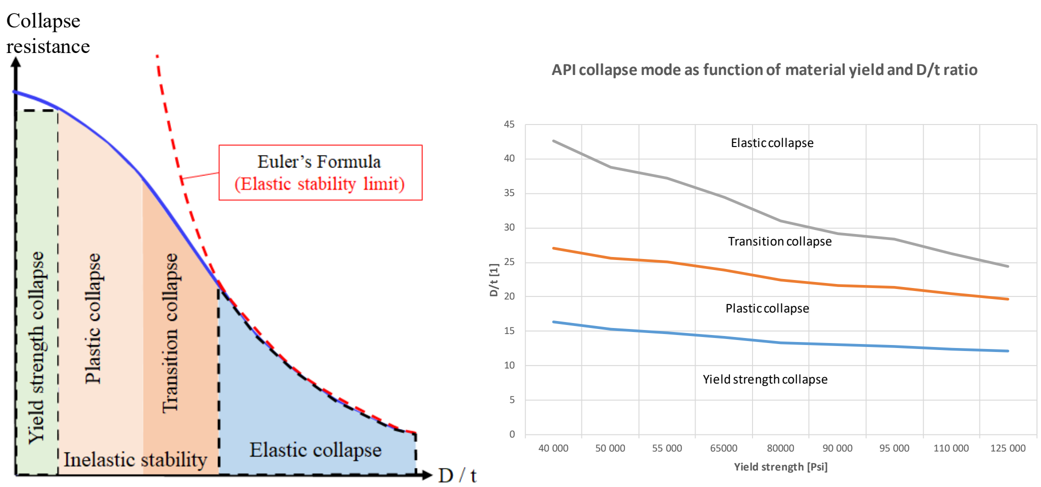

Figure 4-12 - API categories of tubular collapse.

Figure 4-13 shows the most common pipes in well construction and how these are distributed over the different categories of collapse.

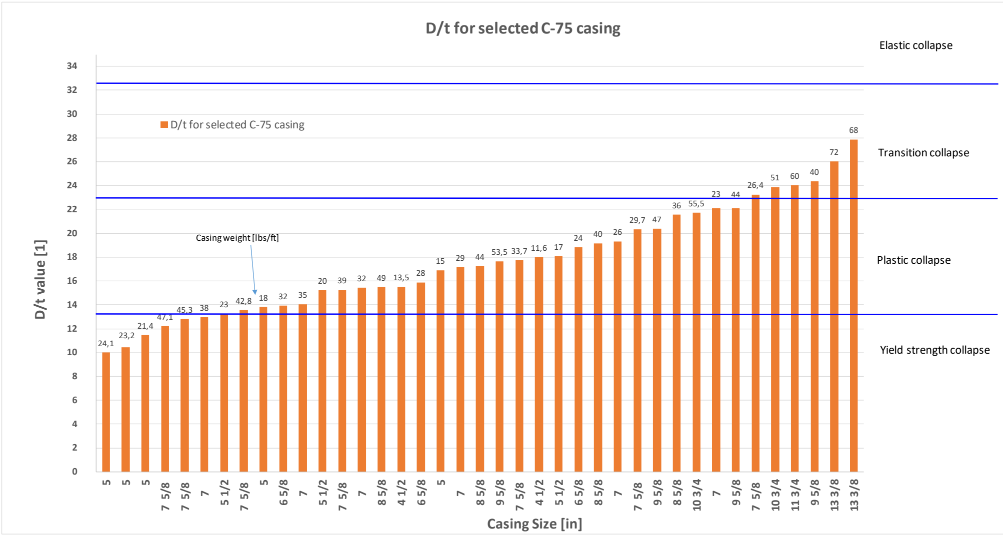

Figure 4-13 - Collapse regimes as function of D/t ratio for C-75 pipe.

The industry standard API calculations for collapse predicts for the uniaxial situation as seen marked as the neutral point in Figure 4-14. Below this point, the casing is in compression and above it is in tension. The figure represents a typical stress situation in casing, where the forces acting upwards are often generated from buoyancy, and friction as the pipe is run in hole. Cementing the casing often add some buoyancy and it locks in the stress at the time the cement sets up. This means that most casing without external support from cement is in tension.

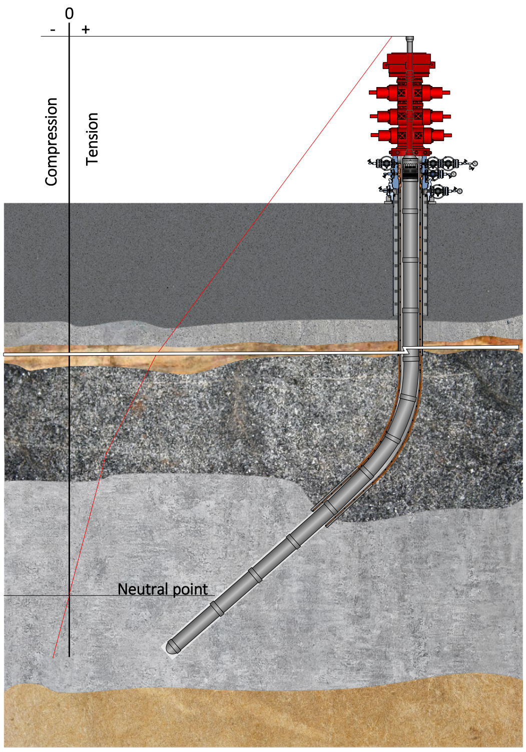

Figure 4-14 - Typical axial stress distribution in casing.

API's approach to handle this triaxial situation was updated in 2015 in a separate addendum to API/ISO TR 10400:2007. The update can be seen in equation (4-15), which was added internal pressure. As always, the API collapse method accommodates the shift from the uniaxial point marked "2" in Figure 4-8, which is identical with the "neutral point" in Figure 4-14 to the triaxial situation with added axial stress by adjusting the yield of the pipe to $\sigma_{ys,e}$. This is an approach that should be used with some caution (Greenip, 2016). E.g. elastic collapse is not influenced by tension and the predictions makes an artificial "jump" when changing collapse mode at high tensions, see Figure 4-15. As can be seen to the right in Figure 4-12, a reduction in yield results in a "higher" collapse mode.

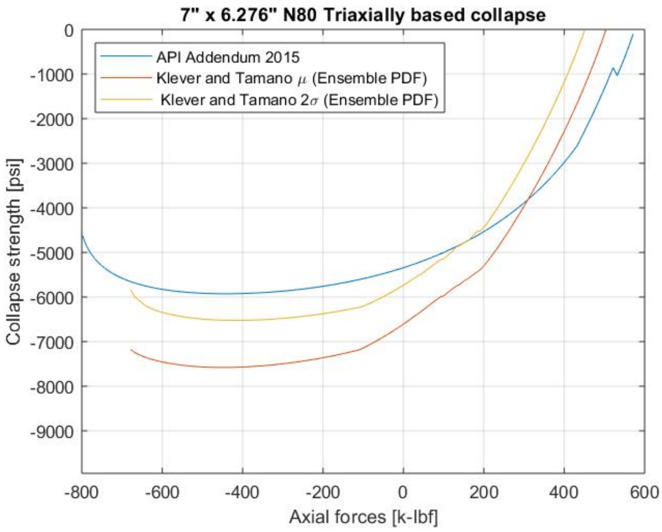

Figure 4-15 - Triaxial collapse prediction. The plot is approximate and shows principal results.

Equation (4-15) is the API triaxial collapse prediction published in separate addendum to API/ISO TR 10400:2007 which is plotted in blue in Figure 4-15.

$$\sigma_{ys,\ e} = \sigma_{ys}\left[\sqrt{1-\frac{3}{4}\left(\frac{\sigma_a+p_i}{\sigma_{ys}}\right)^2}-\frac{1}{2}\left(\frac{\sigma_a+p_i}{\sigma_{ys}}\right)\right] \tag{4-15}$$

Where:

σ_{ys} is the specified minimum yield strength
σ_a is the component of axial stress not due to bending
p_i is the internal pressure
$\sigma_{ys,e}$ is the combined loading equivalent grade, the equivalent yield strength

4.1.3.1 Collapse state of the art – Klever & Tamano

Early 2000, API/ISO initiated a large project to develop an accurate model for collapse prediction of oil field tubulars. API/ISO Work Group 2b (WG2b) under the Steering Committee 5 (SC5) for tubular goods. Following 2986 collapse tests of quenched and tempered tubular specimens, the Klever & Tamano (K&T) model has since been presented as the most accurate ULS model for collapse prediction. A K&T collapse prediction model was therefore developed to support the planned software for automated well planning in this PhD.

API/ISO TR 10400:2018 lists 11 collapse models investigated. The comparison between four of the most accurate models can be seen in Figure 4-16. The standard justifies the choice of the K&T model with the following statement:

"*The Klever-Tamano (KT) formulae have the best combination of a near-unity mean and a low covariance, for both the API and HC ensembles. Moreover, they give by far the flattest actual/ predicted collapse strength response over the dataspace*[27]"

API/ISO 10400:2018 use the term "dataspace" when discussing Figure F.1, see Figure 4-16. This is the physical range of values pipe can have, where the input is strength and geometry variables such as yield stress, average OD, average wall thickness, etc., and the output dataspace is the collapse

[27] Dataspace is discussed below; it refers to all parameters influencing collapse, see Table 4-3 for overview.

prediction range. Parameters influencing collapse and their type of probability distribution is listed in Table 4-2.

Table 4-2 - Probability distribution and data representativeness for each input parameter

Parameter	Data representativeness	Probability distribution
Yield strength	Grade, heat treatment, and rotary straightening type	Gaussian
Ovality	Forming process	Two-parameter Weibull
Eccentricity	Forming process	Two-parameter Weibull
Residual stress	Rotary straightening type	Gaussian
OD	Forming process	Gaussian
Wall thickness	Forming process	Gaussian
Collapse pressure	Product	Gaussian

To easier see the meaning of the API/ISO evaluation of collapse prediction models to the left in Figure 4-16, the figure to the right supports understanding the unit on the x-axis. This is the logarithm of the ratio yield to elastic strength[28]. As seen to the right in Figure 4-16, this is specific to the yield strength of the material.

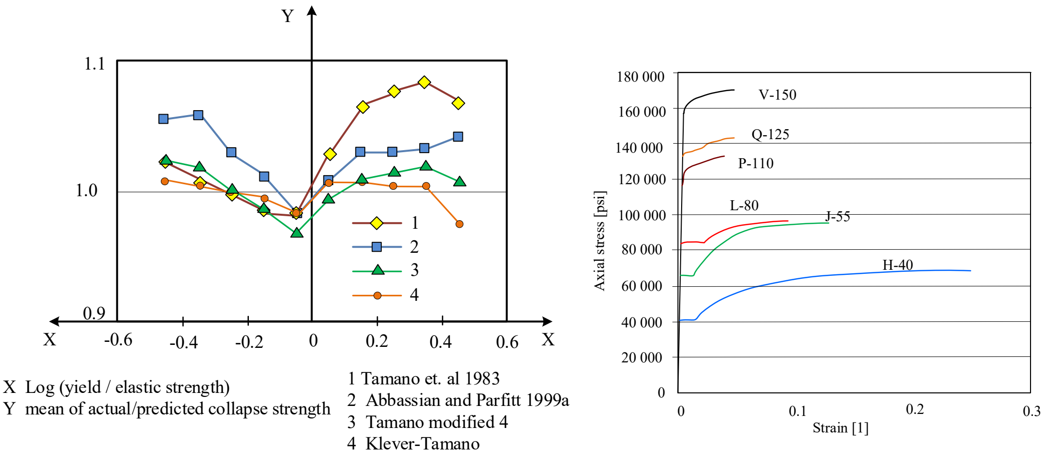

Figure 4-16 - Evaluation of models for collapse prediction: modified from API/ISO TR 10400:2018 fig. F.1.

API/ISO Work Group 2b developed a range for every physical parameter or "dataspace" depending on the manufacturing process of the pipe. Categories of pipe are e.g. seamless, welded and the finish of the pipe separates between hot rotary straightened and cold rotary straightened. This is a clear improvement over the traditional API formulas for collapse, which do not consider the manufacturing process. Table 4-3 lists the model input derived by the API/ISO work group developing the modified Klever & Tamano model.
The Klever and Tamano formulas per collapse model:

[28] Looking into this, it is not straight forward to see how log (yield/elastic strength) can be a positive number. Compression does not explain the numbers either. Investigating the research work of the API/ISO work group, the X-axis has the unit "Predicted/transition strength" (Adams, 2001). The transition strength refers to the section of the stress – strain curve going from the elastic point to the yield point as marked in Figure 4-6. The research project originally used predicted/transition strength on the x-axis as it is a direct measure of physical material behavior, which can be seen to the right in Figure 4-16.

$$\Delta p_{yc} = \min\left[\frac{1}{2}\left(\Delta p_{yM} + 2\xi\sigma_y'\right),\ \Delta p_{yM}\right] \tag{4-16}$$

$$\Delta p_{yM} = \xi\sigma_y' \frac{4(1+2\,\xi)}{3+(1+2\,\xi)^2}\left(-S_i \pm \sqrt{1+3\frac{1-S_i^2}{(1+2\,\xi)^2}\,\xi}\right) \tag{4-17}$$

$S_i = \frac{\sigma_a + p_i}{\sigma_y'}$

$\xi = \frac{1}{\frac{D_{av}}{t_{av}} - 1}$, where D_{av} is the average outer diameter and t_{av} is the average wall thickness.

$$\sigma_y' = k_y\left(1 - H_y\right)\sigma_y \tag{4-18}$$

$$\Delta p_{yT} = \frac{2\sigma_y t}{D} \tag{4-19}$$

Variables and parameters are declared in Table 4-3

Table 4-3 - Parameters in K&T model specific for simulation with 7" 26# L-80 in Figure 5-15 and Figure 5-17.

INPUT				
Variable	Explanation	Distribution	Value	
c	Parameter for wall thickness	Constant	6.00	
v	Poisson's ratio	Constant	0.28	
h_n	Shape of the stress strain curve	Constant	0	
k_e	Model bias factor	Constant	0.825	
E	Elastic modulus	Constant	2.068*10^11 N/m^2	
k_y	Model bias factor	Varying	0.865	
rs	Residual stress	Gaussian	Mean (μ) Standard deviation (σ)	-0.138 0.06997
σ_y	Yield strength (L80)	Gaussian	Mean (μ) Standard deviation (σ)	1.10 0.04642
t	Wall thickness	Gaussian	Mean (μ) Standard deviation (σ)	1.0069 0.02608
D	Outer diameter	Gaussian	Mean (μ) Standard deviation (σ)	1.0059 0.00182
ov	Ovality	2-parameter Weibull	Scale para. (λ) Shape para. (κ)	0.236 1.53
ec	Eccentricity	2-parameter Weibull	Scale para. (λ) Shape para. (κ)	4.42 1.60

4.1.3.2 K&T triaxial collapse prediction

Using test data from 26 collapse tests of 7" 26# L-80 pipe subjected to various axial stress, see Table 4-4, the K&T prototype was compared to the API triaxial equation (4-15) in the amendment of API/ISO TR 10400:2007 issued in 2015. The results can be seen in Figure 4-17, where the K&T predicts collapse with a known "confidence", e.g. 2 standard deviations (2σ). The P-50 or mean value is close to the actual collapse of the pipes, and the 2σ or 95% confidence is ~11% below any actual collapse test. The API triaxial collapse prediction overlaps exactly with the 3σ K&T prediction. For pipes with another manufacturing process, the overlap is likely to be at a different level of confidence.

Table 4-4 - Collapse test data.

Open/closed -end		Internal pressure [psi]	Collapse [psi]: specimen 1 through 5	Mean [psi]	St-dev	Test #
1	OE	0	7339, 7419, 7023, 7218 and 7631	7326	226.6	
2	OE	5000	7352, 7588, 7178, 7222 and 7361	7340	159.9	
3	OE	7500	7372, 7619, 7004, 7130 and 7418	7313	249.9	
4	CE	0	7221, 7388, 7286, 7608 and 7641	7429	188.7	
5	CE	5000	-NA-, 7445, 7680 7398 and 7460	7496	125.6	

Open End Samples:
- Length: 8 x outer pipe diameter = 56”
- Tests performed according to latest revision of API 5CT and ISO 10400 in 2013.
- No axial stress

Closed End Samples:
- Length: 10 x outer pipe diameter = 70”
- Tests not in compliance with API / ISO 10400.
- Axial stress induced from capped ends

Further detail related to the tests can be found in the original paper (Greenip, 2016).

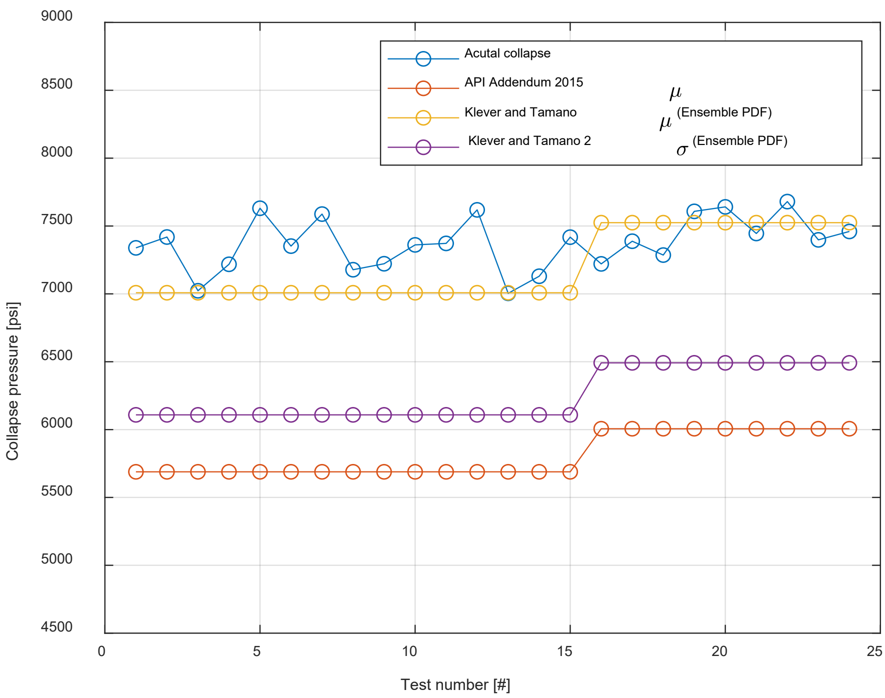

Figure 4-17 - Simulated collapse pressure for test samples and recorded collapse pressure failure.

The prototype K&T model for collapse is discussed in a paper (Brechan(2), 2018) and journal article “*Collapse prediction of pipe subjected to combined loads*” (Brechan, 2020). The abstract of the latter is amended in Appendix D.13.

Summary and conclusions (Brechan, 2020):

- Working with a minimum performance model and an ultimate state model requires some adjustments to arrive at "common ground" and enable comparable results.
- The API model does not consider the manufacturing method in collapse prediction and considers only the poorest performer as tested in the 1960s, leaving a hidden design margin for many manufactured pipes today.
- The K&T model gives good collapse prediction in the combined stress states investigated
- The safety factor of the prediction using the API model is equivalent to 3.0 standard deviations using the Klever and Tamano model with ensemble PDFs.
- There is potential for significant environmental and cost savings by careful analysis of the true safety margins in well designs.

5 Discussion

Petrowiki provided by Society of Petroleum Engineers (SPE) states:
"*Well planning is perhaps the most demanding aspect of drilling engineering. It requires the integration of engineering principles, corporate or personal philosophies, and experience factors. Although well planning methods and practices may vary within the drilling industry, the end result should be a safely drilled, minimum-cost hole that satisfies the reservoir engineer's requirements for oil/gas production.*"

Discussing the goal of the research and development of this project, many industry professionals have expressed that it is an impossible task with background in the same understanding as SPE above – well planning is too complex. The feedback from industry professionals varies. As said, there are alternating motives for concern, since many fears for the changes coming to the industry. But others see that technologies most of us use in our everyday life are not in the portfolio of the well planning tools.

The researched design in this PhD can overcome the expressed hurdles, as the reader would have insight in Appendix B. The fundament for the design of the LCWIM was introduced in chapter 1 and discussed with the pros and cons of the current work process and software in chapter 2. In a way, chapter 2 holds a significant part of the discussions of the central topic in this Thesis.

5.1 Transition from human oriented to DWM

Currently, the oil and gas industry operate with a human-oriented work process when planning, constructing repairing, stimulating or plugging wells. Communication in human-oriented processes is a constraint. There are often large amounts of electronic information required. An example of this is the many failures repeated over the years. Analysis of root causes, development of tools, methods and other initiatives to prevent failures have been made. Still, the industry has maintained an NPT of 15% to 20% depending on the complexity of the operations. Getting the learning across from one team of professionals to another separated by geography, time or both constitutes an unresolved challenge in human-oriented processes. Other comparable industries have moved to digital processes, where the information resides in one shared site and the different disciplines can extract what they need to deliver their part of the projects. The DWM process is designed to automatically populate such a shared "database".

DWM is designed to allow the standardized information sharing (documentation) for each project to be extracted directly from the shared database. The DWM process is fully automated, so a report ca be made as long as the subsurface and other data is available. But it relies on verification of the assigned / responsible engineers. Automatically generated data / report is only valid with a marked verification.

5.2 Value chain

The SPE definition states "integration of corporate or personal philosophies and experience factors" are important to achieve a well design. Corporate experience is often "governing documentation". One of the main pillars of the LCWIM design is the digitalization of governing documentation to minimize compartmentalization and focus on the full value chain. The discussions in project meetings will not end for those who start to apply a software like the planned LCWIM. Quite the opposite. Because it is a tool automating many of the administrative tasks, there is more room for creative discussions and testing alternative theories and solutions. Multiple well design can be simulated with cost to substantiate e.g. new completion designs and methods to find the best solution and hydrocarbon recovery. It can be a step in the right direction as the completion, intervention,

integrity and P&A phases are automatically considered when developing designs. The process will be less people dependent.
DWM can save operators and service providers a lot in the area of "information management". Being a hub with all vital information collected, the LCWIM can be the "go to" source for all disciplines.

5.3 Role of humans

Modern computer science can provide tools and technology to improve the work processes for all teams supporting hydrocarbon recovery. The current work processes have been discussed as foundation and motivation for a new and more coherent work process, addressing the full value chain of hydrocarbon recovery. The proposed work process changes the roles in the Wells team from driver to controller, as human involvement is oriented towards method selection, experience handling, and engineering. Reducing the workload with administrative tasks is an important improvement.

There are many signals about changes coming over the next few decades. Some say roles such as cashier, newspaper delivery, travel agents, taxi dispatchers, etc., are disappearing due to AI technology automating these tasks. Big Data analysis can replace manual search and analysis of different formats of information and data. But the typical journalist role is not likely to be replaced but rather be faster, smarter and better with AI. The article acts as an example of what some in the petroleum industry are expecting from AI, digitalization and automation. The new work processes are designed to enhance the human contribution. Computers are incredibly fast, have an impeccable memory but are not smart (limited problem-solving). Humans are slow, have a faulty and fading memory but are clever in problem-solving. Going from the process of today, where each step in the development of a plan is human driven to a fully automated digital process that can empower each wells team member to excel in their area of expertise. The WOS is made with a lot of potential, but only experienced engineers can make the planned software smart.
The new work process in the wells team domain is designed with advanced AI techniques. Going back to Figure 3-41, where the new proposed work process is depicted, a wells team member is sitting central and have the responsibility of the planning and operations. There is a team working in "the cloud", meaning they are updating the WOS with new rules from governing documentation and standards, oversee experience from operations and do any other required coordination between projects. Simply put, experienced well personnel will contribute with their competence and new roles will be added to the team to take advantage of the new techniques.

5.4 Software support

As discussed earlier, the current software platforms for planning well designs are made to support a human-driven workflow, where the models act as advanced "calculators". For most platforms, the engineering models are closely connected to reduce the need for entering the same data many times or transferring of computed results between the applications. They are still work-intensive, as the engineer has to manually identify each "design mitigation" and update the simulations. The change to a more effective and supportive workflow can enable better well designs. The engineers are in better control of design parameters as the modeling is open, designed with better visualization and the accumulated time to design a well is a fraction of today's process.
It is essential for a digital and automated planning software to be transparent in order to build a new and sustainable workflow. Engineers have to intuitively find their way through the software and easily be able to adjust and tweak parameters to achieve their goals.

The LCWIM design is planned to be able to interface with engineering from any provider of planning software. Operators use different calculation methods, which means that the WOS has to be adaptable to fit with any supplier of software support. Linking the WOS with other software is a question of the correct interface application.

5.4.1 Developed model

As with the current well planning process, the difficulties in planning well design is to decide what "*design mitigation*" is favorable to fit the optimal design. The first model of the WOS is designed to follow the typical "*design mitigation*" drilling engineers have been doing. There is often a pattern in the "*design mitigation*" related to the type of challenges the different fields have. Some fields are dominated by a difficult hydraulic window, others with slow drilling and high casing wear. These fields often follow a specific combination of design parameters to arrive at the best compromise for the design. It is not the intention of the planned software to solve all these, at least not in the early stage. The first priority is to establish a fully digital work process with capacity to solve standard designs. The second priority is to enable engineers to manipulate the "*design mitigations*" so they can solve more specialized deigns efficiently. The system for developing digital experience is a tool for the engineers to prepare safe and cost-efficient well designs. A similar tool is planned to target "design mitigations", so the engineering models conclude with a desired well design also in fields with special conditions.

For all software, error handling is essential. The WOS is a complex design. The user can help where the planned software finds no solution. The important part is to enable good error handling, so the engineer can see what is going on when the problem occurs. Good quality error handling can enable the engineers to do effective troubleshooting and get the simulations going again.

5.4.2 AI and petroleum engineers

Petroleum engineers will not develop AI applications, but they will be using them just as AI technology runs in the background when users are shopping on the web and doing Google searches. The WOS require no programming skills to be operated.

The next stage in development of the WOS can utilize modern AI techniques such as machine learning to manipulate the priorities in the different steps of iteration through selected sets of "*design mitigations*". Today, there are many examples of machine learning training and running other machine learning algorithms. This design will not be discussed here.

5.4.3 Cloud tech and security

The final product is designed to be a cloud-based application. Cloud-based technologies with high-performance computing servers will permit engineers to handle large data sets, including 3D data models. This can enable better tools for the multi-discipline considerations which currently are hampered by diverse and incoherent tools. Though networking has developed into the primary platform for information sharing, software for well construction and maintenance have typically been desktop applications.

Cloud-based engineering enables easily available and scalable engineering analysis and collaboration. Interactive performance can be achieved by a proper work distribution between local hardware and remote servers. However, security concerns have to be addressed to prevent disclosure of data. Details in cloud technology and IT security will not be elaborated here.

5.4.4 Development of model

Some prototypes for different engineering were developed through the PhD research but the main product of this PhD is the WOS. At this time, the WOS is only partially developed. The PhD is and has been a part time project along work. The plan is to continue to the next step and focus on programming of the application depending on support and funding.

A concern behind developing the model is its future. A successful application is tied to the number using it not necessarily how good the application is. For the WOS to be used by many, it needs support by funding to be tested and then presented to potential users. The planned software is one of the first of its kind, i.e. fully digital and fully automated. The road to success is to find key individuals who see the potential and have the means to support its development. It may be the best software of its kind, but still be unsuccessful if there is no support.

5.4.4.1 Engineering

The tubular design application is ready as a prototype and can be developed into a professional application. It is using the most accurate calculations in the industry for well planning of burst, collapse and triaxial stress, see ISO TR 10400:2018. This application is now running independent design checks, but it can be developed into a professional application as part of a support platform. This application has the capacity to reveal hidden design factors and predict a more precise integrity status of a well construction due to modern calculations. For operators who are interested in reducing cost and CO_2 footprint, challenging the current casing design and standardizing on a slimmer program can be an option using the new application.

5.4.5 Other models on the market

Schlumberger's DELFI was on the market in 2017 while software from Halliburton and Oliasoft are under construction. Halliburton Landmark initially planned to release a new generation software in 2018, but this edition is not yet public. The Oliasoft application is different from the others. Both DELFI and Landmark are "integrated suits" of software, while Oliasoft also have a suite of detachable modules. The slogans for the Schlumberger software are "Cognitive" and "integrated" due to more open and integrated platform allowing different disciplines to present and use their data in the same software suite. Looking at the well planning process as a whole, the Schlumberger software package is human driven. Cognitive software as discussed for some AI applications is therefore not applicable in this context. According to Figure 1-2, the level of software support provided by DELFI is level 3. "Human driven" and "visualized with subsurface models" are the key elements at this level. DELFI covers planning and operations, but routines for well integrity is not included.

Oliasoft is developing their software with capacity for fully automated engineering. The scope is to cover planning and some operations. According to Figure 1-2, the application will be a level 2 for planning. Key features at this level is "automated engineering". Currently, no features are designed specifically to support the operation and production phases as described in Figure 1-2. What is unique with the products from Oliasoft is the ability to shape the software in any way. It is developed in building blocks. Adding an application such as the WOS integrate a 3D viewer of reservoir data means that the total software package will be at support level 1.

Halliburton Landmark targets Well planning and operation. The latter often require integration with subsurface models, which is covered by the application called "Decision Space". Halliburton had at one time a white paper presenting the new platform much like the profile of the LCWIM. However, currently, the only available information points to "automation of engineering". This is level 2 for planning. And "3D viewer with all RTD" for operation is level 3.

The automation feature in the LCWIM is the WOS. IT is planned to run through the full lifecycle starting for early planning to final plugging. It is designed with automated planning including digital programs and procedures, integration with application for 3D view of reservoir data (Resinsight) and operational support such as forecasting of casing wear, casing design integrity, update of hydraulics, T&D, etc. All functions fully automated, which means it is the only level 1 for each of the phases. The difference between automated engineering and the outlined design for the WOS and LCWIM is significant. While engineering accounts for approximately 15% of the manhours, a fully digital workflow can automate much of the administrative portion of the manhours in planning. Also, a fully automated engineering sequence depend on humans applying experience to make optimal plans.

Note to reader:

It must be emphasized that design for models not on the marked may change by the time they are released for commercial use. Also, the quality of applications depends on the quality of the user interface. A complex interface may prevent many experienced engineers from applying their expertise efficiently.

5.5 Experience

Experience is essential in all aspects and all phases of petroleum activities. Discussed as one of the key drivers for the proposed work process, digital experience can make a step change in quality of planning and provide smarter operational methods.
The connection to AI is already materialized in many initiatives. Big data technology analyzing the vast databases of Norwegian and UK sectors can provide key data from existing well constructions. As with any analysis using big data technology, the background for the data should be known to understand if it is reliable. E.g. dependency of available technology, regulations and other key drivers for previous well construction processes may that not be valid today. Used with caution, AI technology can be a powerful assistant in petroleum activities.

5.6 Operator owned - user developed

Today, experience is written down when there are learning points. This process can be simplified using the "reporting language", i.e. like writing a line in a daily drilling report. These experiences are read by the WOS, which follows the recommendations given. I.e. the WOS can be "programmed" using the "reporting language". The planned LCWIM can therefore be described as a software framework. The initial state of the software will be developed only in engineering calculations, while the capacity to produce digital programs will require user intervention to hold a high standard. By adding digital experiences, engineers will develop the logic controlling the WOS to make intelligent method selections and precise operations. The initial model will therefore be helpful and save some time in the planning phase. But it will give optimal support and save significant time only when there are a good number of experiences and contingencies established.

Letting engineers take an active role in well planning software can give advantages. E.g. current engineers can be more familiar with the software and master it quicker. Also, the operator will build and own their model and method. It is practically the same as establishing best practice / operational program in the text-based systems used today. Only the planned WOS will always apply lessons learned when planning. And to give the reader a hint before moving to the chapter dedicated the software, governing documentation and standards are merely a series of experiences which can be defined using the reporting language. I.e. the LCWIM is designed to hold governing documentation and standards for verification of planning and operations adhering to the regulations unless the user defines an alternative.

5.7 Future generation

The generation entering the oil and gas industry is focused on environment, sustainable work and production. Any company with a low focus on these values will eventually find themselves in difficulties.
Today, several companies have proclaimed CO_2 targets for the future. The required changes to reach these goals are unknown, but likely to have an impact to affect how we work in future planning and operations.

5.8 Observations

Conducted research has made the following observations which were discussed as background and motivation for the proposed new work process:

- Improvement focus is on rig automation and the drilling process
  - Improving drilling may reduce cost significantly
  - Improvements in drilling are mainly by working smarter, higher ROP contributes less
- Smarter methods can be implemented in all steps of the value chain of wells

  - Automated planning by software
  - Digital procedures from planning connected directly to automated rig or intervention equipment
  - Automated risk level analysis of well and asset integrity from streamed standard surveillance data
  - Integrity is based on tubular design, equipment, cement design and formation strength. The WOS can run the load cases and update the integrity should the real time data be outside the range of input data in the original design.
  - Automated planning and digital procedures in P&A can promote smarter and more efficient solutions
- Incorporating all work processes in the value chain of wells into one arena eliminates barriers between disciplines and promotes the need of the well / operator rather than the different disciplines KPI / interests.
- Faster planning is a focus in many initiatives. However, reducing administrative tasks to free up capacity of experienced personnel and set focus on smarter methods
- Many engineers running well design software knows the routines of the software and the operational limitations reported. But few engineers understand the presumptions and limitations in the engineering calculations in the design software. Opening engineering so engineers can see the development of the calculations can give a better understanding of the design limits and more fit for purpose design can be made. With models active in the production phase, better evaluations of integrity can be made.

6 Conclusion

This thesis is an architecture of a model forming a new work process – digital well management. A digital work process can bring new opportunities. An important aspect with significant potential for added value is the shift from the current compartmentalization due to key performance indicator (KPI) per discipline over to a holistic perspective, where the total cost and integrity of wells can be optimized. The WOS is designed to apply digital algorithms of regulations, experience and cover needs for all disciplines through the lifecycle of the well. The shift is believed to provide value chain optimization across disciplines.
The system will be developed and run by humans, which will be the limitation in both the quality of the software and how it is used. The WOS can provide e.g. 90% of the program and the engineer will then do the last 10% as today, which will save time and provide better plans due to involvement of digital experience. The software will perform better and cover a larger portion without human interaction as more digital experiences are added to the system.
The conducted research was initiated to investigate if it was possible to improve the work process and engineering in well designs. New calculations for engineering designs were investigated, compared to the industry standard and checked if it is possible to integrate them in the new workflow. A system for automated planning of well construction and maintenance activities producing digital procedures have been made. It is designed to support rigs with automated equipment, but it can also be of great benefit to rigs with low level automation, well interventions such as wireline and fracturing and well integrity work.

The facts from the research are as follows:

- A software for automating planning is designed but not fully tested
- The software design is set up to handle issues from small texts to lager experiences such as standards and governing documentation
- The WOS is designed to produce digital procedures that are readable for man and software for automated rig equipment
- The work process is designed to reduce the volume of manhours for planning activities in well construction, intervention, integrity and P&A
- The work process is designed to reduce the volume of administrative manhours in planning and operations
- The “report language” offers a level of “abstraction” so any experienced industry professional can operate the application without any programming ability
- A technique copying the methods of recurrent Neural Network (RNN) with a self-learning routine to identify the optimal set of operational parameters has been designed as part of the WOS. Machine learning is normally quite accurate. But in the case of deriving key parameters for operations, it has to be 100% accurate. Therefore, each part of the network is under more control than traditional ML algorithms.
- LCWIM is the automated life cycle well integrity model enhancing all engineers supporting the different phases of the value chain of wells activities
- DWM is a digital work process, where the well act as a hub of information for all disciplines to get the information they need. It is possible to extend this to fully automated sharing, i.e. design models for all disciplines are updated automatically
- Adapting a digital work process can make a step change in quality of planning
- Several tasks are not feasible to automate. E.g. inspecting, pressure testing and preparing tools on pipe-deck before use in the well. Any operation done rarely and / or require extra sensors and delicate equipment would probably be best executed as today. Automation needs to be feasible either in HSE or cost.

6.1 Engineering in well planning and construction

To enable a fully automated planning application, the engineering calculations have to be adapted to this new environment. Some models have been verified while others remain to be checked. This PhD has looked into the engineering of wells for the purpose of automating the work processes and less for improving the calculations as such. Few areas of improvement have been identified and proposed:

- Limit pressure testing of deep casings to avoid cement sheath failure
- Wear for chrome tubulars are not supported – no modelling exists
- Casing design should use the K&T triaxial calculations to know the risk of collapse and Lubinski's method combined with Klever and Stewart rupture calculations for burst – traditional calculations (API collapse and Barlow for burst) are less accurate according to the API/ISO TR 10400
- Engineering for automated surveillance of well integrity is new. The prototype can be developed into a fully automated application supporting risk status and detailed analysis of integrity
- The WOS is a building block that can adapt to other suppliers engineering calculations
- Detailed status of programmed applications can be seen in Appendix H.

All engineering calculations should be adapted to a fully automated environment. Some models have been verified while others remain to be checked if they are suitable or need adjustments to be fitted in the automated environment

For a software to support a sustainable work process, the engineering calculations should be selective and easily replaceable. Not only because engineering is constantly improving, but mostly since operators and companies chose different calculations as their best practice.

6.2 Dynamic and adaptive planning software

Apart from providing a familiar work environment not challenging but supporting experienced wells engineers, the requirement to the software has been to adapt to any operation and support the full life cycle of any well for hydrocarbon recovery. Flexibility in planning is detrimental to a lasting and sustainable software and work process. The question of how flexible the planned system will be can only be answered in theory since the final model is not built. The design mitigations put in place to enable maximum flexibility are:

- Describe all involved equipment with their physical measurements used in engineering
- Describe all involved equipment with their physical limitations where tolerances are fixed (production packers, plugs, valves, etc.)
- Describe all methods, actions into detailed steps of events
- Every event needs to be placed in context of where it can take place (logic of events)
- Every event needs to have an activation link to all engineering it may influence
- All engineering needs to be completed with the planned parameters, no steps can be skipped
- Any parameter or event must allow users to determine and set them manually and run engineering with these as fixed inputs
- Sequences of events or scenarios involving specific equipment, formations are "digital experience" or can act as pre-programmed plans (i.e. how to handle a specific scenario)

Simple initial tests are good, but the success can only be fully determined when the system is challenged with full operational sequences from every phase of the life cycle of wells.

Digital processes can provide the base for improved quality of plans and operational support. Software such as ProNova analyzes how work is conducted and reveals hidden lost time. In drilling alone, the software has shown where and how to improve performance with ~10% and more. Digital planning software can have the same effects on the planning and make sure the learning from the operational performance is kept and automatically communicated to other projects. Experience management based on humans and text files is prone to error, which is manifested in the repeated failures in operations. Digital experience can be the key to a step change in quality plans, experience transfer and operational performance.

The current planning and construction processes have room for improvements, something that has been leveraged by the emerging rig automation technology and field trials. Analysis carried out shows that the number of manhours in planning of wells constitutes and accounts for up to 30% of the total time engineers spend per well. The remainder is administrative tasks such as ordering, invoicing, logistics and preparing information for stakeholders. Planning accounts for between 1 - 3% of well cost for onshore and offshore wells. From one perspective, the highest cost is the low efficiency of the traditional human oriented model.

(Intentionally left blank)

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7.3 Links

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Appendices

Appendix A Octahedral shear stress criterion (von Mises)

The stress invariants are the fundament of the von Mises stress. The equation is shown below.

$$\tau_{oct}^2 = \frac{1}{9}((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2) \quad \{A\text{-}1\}$$

As for maximum shear stress, the uniaxial testing conditions are used: $\sigma_1 = \sigma_y$ and $\sigma_2 = \sigma_3 = 0$.

$$\tau_{oct}^2 = \frac{1}{9}\left(\left(\sigma_y - 0\right)^2 + (0-0)^2 + \left(\sigma_y - 0\right)^2\right) \quad \{A\text{-}2\}$$

$$\tau_{oct}^2 = \frac{2\sigma_y^2}{9} \quad \{A\text{-}3\}$$

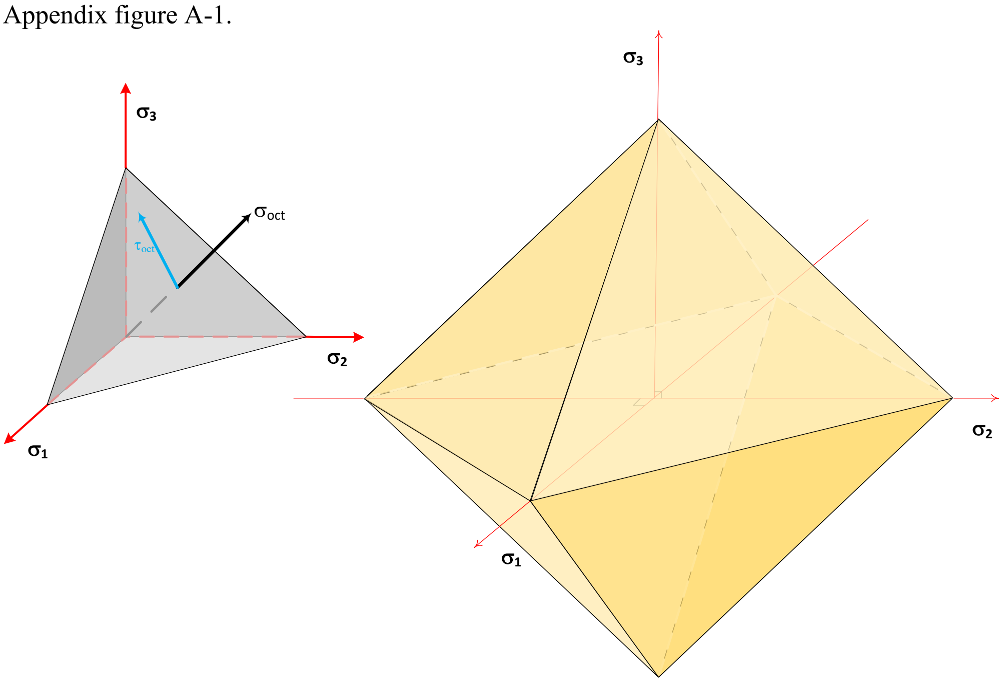
$$\tau_{oct} = \sqrt{2}\frac{\sigma_y}{3} \quad \{A\text{-}4\}$$

Eq {A-1} and {A-4}:

$$\frac{2\sigma_y^2}{9} = \frac{1}{9}((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2) \quad \{A\text{-}5\}$$

$$\sigma_y = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2} \quad \{A\text{-}6\}$$

Where σ_1, σ_2 and σ_3 are principal stresses. The octahedral shear stress planes are shown in Appendix figure A-1.



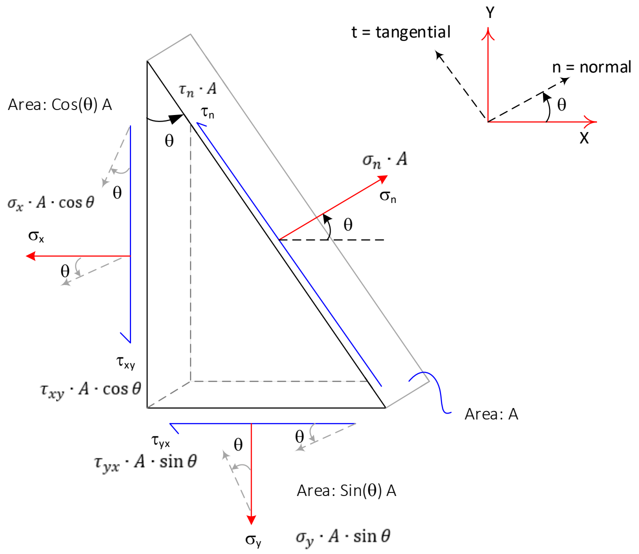
Appendix figure A-1 - Octahedral stress planes.

Appendix A.1 Derive principal directions

To find the direction of principal stress and planes for principal stresses, using plans stress simplifies the derivation.

Appendix A.1.1 Stresses on any inclined plane

Appendix figure A-2 shows plane stress from σ_x and σ_y. The figure has a pseudo area to convert the stresses into forces so equilibrium can be used to derive the desired relations for normal stress and tangential stress at any inclined plane.



Appendix figure A-2 - Applying equilibrium to find normal stress and tangential stress for any inclined plane.

Applying equilibrium:

$$\sum Forces = 0 \qquad \{A\text{-}7\}$$

The expressions in parentheses are converted stresses acting in the direction of the normal force:

$$\sigma_n A - (\sigma_x \cdot A\cos\theta)\cos\theta - (\sigma_y \cdot A\sin\theta)\sin\theta - (\tau_{yx} \cdot A\sin\theta)\cos\theta - (\tau_{xy} \cdot A\cos\theta)\cos\theta = 0$$

Eliminating area “A” from all terms and moving over negative terms:

$$\sigma_n = (\sigma_x \cdot \cos\theta)\cos\theta + (\sigma_y \cdot \sin\theta)\sin\theta + (\tau_{yx} \cdot \sin\theta)\cos\theta + (\tau_{xy} \cdot \cos\theta)\cos\theta$$

Simplify and using $\tau_{yx} = \tau_{xy}$ gives:

$$\sigma_n = \sigma_x \cos^2\theta - \sigma_y \sin^2\theta + 2\tau_{yx}\ \sin\theta\cos\theta$$

Useful trigonometry relations:

$$\cos^2\theta = 1 + \frac{cos2\theta}{2}, \qquad \sin^2\theta = 1 - \frac{cos2\theta}{2} \quad and \quad \sin\theta\cos\theta = \frac{sin2\theta}{2}$$

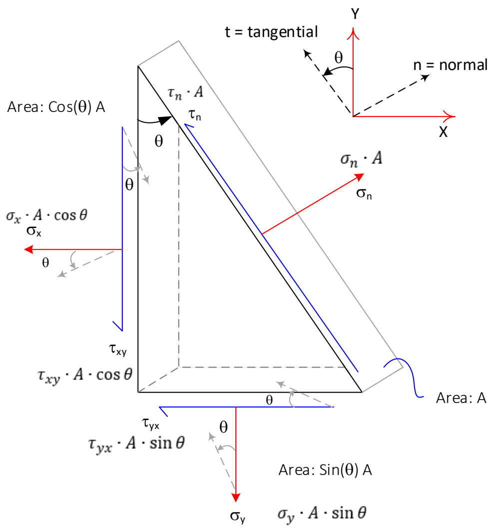
Substituting:

Arriving at:

$$\sigma_n = \sigma_x\left(1+\frac{cos2\theta}{2}\right) - \sigma_y\left(1-\frac{cos2\theta}{2}\right) + 2\tau_{yx}\left(\frac{sin2\theta}{2}\right)$$

$$\sigma_n = \frac{\sigma_x+\sigma_y}{2} + \frac{\sigma_x-\sigma_y}{2}cos2\theta + \tau_{yx}sin2\theta \qquad \{A\text{-}8\}$$

Now moving to the stresses acting in the direction of the tangential force, see Appendix figure A-3.



Appendix figure A-3 - Force balance to find an expression for tangential stress at any plane.

Selecting the marked tangential direction as positive.

$$\tau_n A + (\sigma_x \cdot A\cos\theta)\sin\theta - (\sigma_y \cdot A\sin\theta)\cos\theta + (\tau_{yx} \cdot A\sin\theta)\sin\theta - (\tau_{xy} \cdot A\cos\theta)\cos\theta = 0$$

Eliminating area "A" from all terms and isolating the tangential component:

$$\tau_n = -(\sigma_x \cdot \cos\theta)\sin\theta + (\sigma_y \cdot \sin\theta)\cos\theta - (\tau_{yx} \cdot \sin\theta)\sin\theta + (\tau_{xy} \cdot \cos\theta)\cos\theta$$

$$\tau_n = -(\sigma_x \cdot \cos\theta)\sin\theta + (\sigma_y \cdot \sin\theta)\cos\theta - (\tau_{yx} \cdot \sin\theta)\sin\theta + (\tau_{xy} \cdot \cos\theta)\cos\theta$$

$$\tau_n = -(\sigma_x - \sigma_y)\sin\theta\cos\theta + \tau_{yx}(\cos^2\theta - \sin^2\theta)$$

Useful trigonometry relations:

$$\cos^2\theta = 1 + \frac{cos2\theta}{2}, \qquad \sin^2\theta = 1 - \frac{cos2\theta}{2} \quad and \quad \sin\theta\cos\theta = \frac{sin2\theta}{2}$$

Substituting:

$$\tau_n = -\left(\frac{\sigma_x - \sigma_y}{2}\right)sin2\theta + \tau_{yx}\,cos2\theta \qquad \{A\text{-}9\}$$

Equation {A-8} provides the normal stress for a plane at any angle, and {A-9} provides the shear stress for planes at any angle. Since the equations are derived from equilibrium, there are no limitation in their use.

Appendix A.1.2 Derive expressions for the principal stresses

To find the angle at which the maximum normal stress and shear stress occur, the derivatives of equations {A-8} and {A-9} are set to 0:

$$\frac{d\sigma_n}{d\theta} = \left(\frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2} cos2\theta + \tau_{yx} sin2\theta\right)' = 0 \qquad \text{\{A-10\}}$$

(first term: no θ => 0), $(cos2\theta)' = -2sin2\theta \quad and \ (sin2\theta)' = 2cos2\theta$

$$\frac{d\sigma_n}{d\theta} = -(\sigma_x - \sigma_y) sin2\theta + 2\tau_{yx} cos2\theta = 0 \qquad \text{\{A-11\}}$$

$$2\tau_{yx} cos2\theta = (\sigma_x - \sigma_y) sin2\theta \qquad \text{\{A-12\}}$$

$$\frac{sin2\theta}{cos2\theta} = \frac{2\tau_{yx}}{(\sigma_x - \sigma_y)} \qquad \text{\{A-13\}}$$

Useful trigonometry relations:
$\frac{sin2\theta}{cos2\theta} = tan2\theta$

$$\tan 2\theta_{principal} = \frac{2\tau_{yx}}{(\sigma_x - \sigma_y)} \qquad \text{\{A-14\}}$$

$\theta_{principal}$ is the angle for the principal planes, where maximum and minimum normal stresses occur. These stresses are the "Principal stresses".

Appendix A.1.3 Shear stress is 0 on principal planes

Note the relationship between angle for max/min normal stress, Eq. {A-9} and {A-12} express the shear stress for planes at any angle:

{A-9} : $\tau_n = -\left(\frac{\sigma_x - \sigma_y}{2}\right) sin2\theta + \tau_{yx}\, cos2\theta$
{A-12} : $-(\sigma_x - \sigma_y) sin2\theta + 2\tau_{yx} cos2\theta = 0$

Divide {A-12} by 2, we get:
{A-9} : $\tau_n = -\left(\frac{\sigma_x - \sigma_y}{2}\right) sin2\theta + \tau_{yx}\, cos2\theta$
{A-12}: $-\left(\frac{\sigma_x - \sigma_y}{2}\right) sin2\theta + \tau_{yx} cos2\theta = 0$

Which shows why shear stress is 0 (nil) on principal planes. Eq. {A-9} and {A-12} are identical, and Eq. {A-11} is the derivative of the normal (principal) stress.

Appendix A.2 Maximum shear stress criterion – Tresca

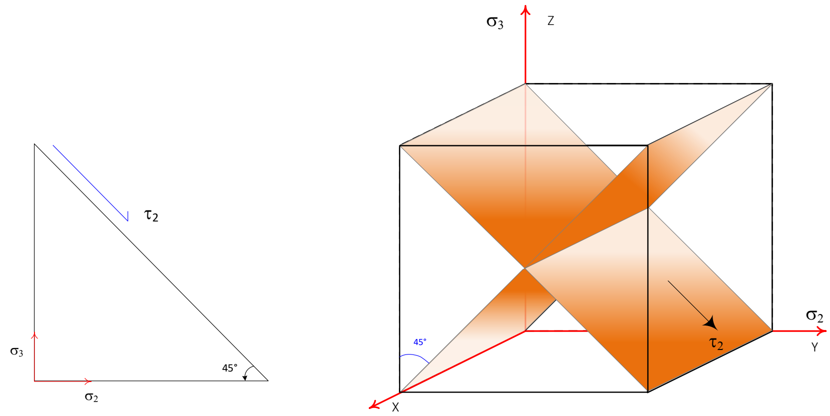
Given that tubulars are made of ductile material and yield is the design limit, failure will occur due to shear stress. Often referred to as the Tresca criterion, the maximum shear stress occurs when τ_{max} exceeds a critical value.

$$\tau_1 = \frac{\sigma_2 - \sigma_3}{2}, \tau_2 = \frac{\sigma_3 - \sigma_1}{2}, \tau_3 = \frac{\sigma_1 - \sigma_2}{2} \qquad \text{\{A-15\}}$$

Developing trigonometric expressions for the shear stress yields the maximum in-plane shear stress:

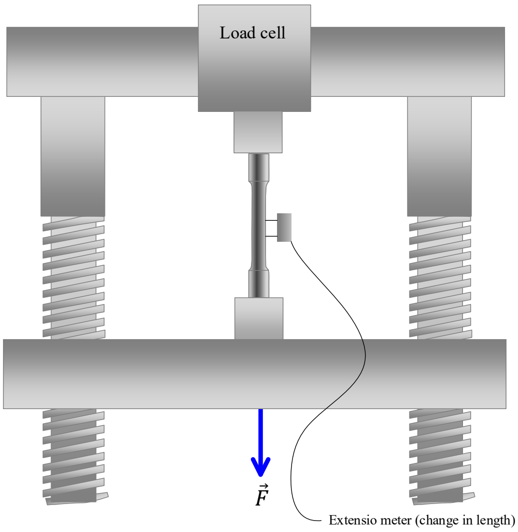
$$\tau_{max} = \sqrt{\left(\frac{(\sigma_x - \sigma_y)}{2}\right)^2 + \tau_{xy}^2} \qquad \{A\text{-}16\}$$

It follows from eq. {A-16}, that the maximum shear stress occurs in a plane 45° to the principal stresses. A stepwise derivation of these equations can be seen in the above-mentioned chapter. A simple visualization of the Tresca criterion can be seen in Appendix figure A-4.



Appendix figure A-4 - Example of maximum shear stress criterion.

Yield is often determined in uniaxial tensile testing as shown in Appendix figure A-5. It will produce a curve as shown in Figure 4-6. The point of yield stress is determined for tested material and can be used to calculate failure in materials such as tubulars.



Appendix figure A-5 - Tensile testing jig.

For a material to fail, the critical value τ_{max} equals yield (σ_y). In uniaxial testing, $\sigma_1 = \sigma_y$ and $\sigma_2 = \sigma_3 = 0$.

$$\sigma_y = \tau_{Max} = \left[\tau_1 = \left|\frac{\sigma_2 - \sigma_3}{2}\right|, \tau_2 = \left|\frac{\sigma_3 - \sigma_1}{2}\right|, \tau_3 = \left|\frac{\sigma_1 - \sigma_2}{2}\right|\right] \qquad \{A\text{-}17\}$$

Inserting:

$$\tau_{Max} = \left[\tau_1 = 0, \tau_2 = \left|\frac{0 - \sigma_y}{2}\right|, \tau_3 = \left|\frac{\sigma_y - 0}{2}\right|\right] \qquad \{A\text{-}18\}$$

And therefore

$$\tau_{Max} = \frac{\sigma_y}{2} \qquad \{A\text{-}19\}$$

To develop visualization of the shear criterion, it is convenient to set the one principal stresses to zero, i.e. $\sigma_3 = 0$.

$$\sigma_y = \tau_{Max} = \left[\left|\frac{\sigma_2}{2}\right|, \left|\frac{-\sigma_1}{2}\right|, \frac{\sigma_1 - \sigma_2}{2}\right] \qquad \{A\text{-}20\}$$

With Eq {A-19}

$$\frac{\sigma_y}{2} = \left[\left|\frac{\sigma_2}{2}\right|, \left|\frac{-\sigma_1}{2}\right|, \frac{\sigma_1 - \sigma_2}{2}\right] \qquad \{A\text{-}21\}$$

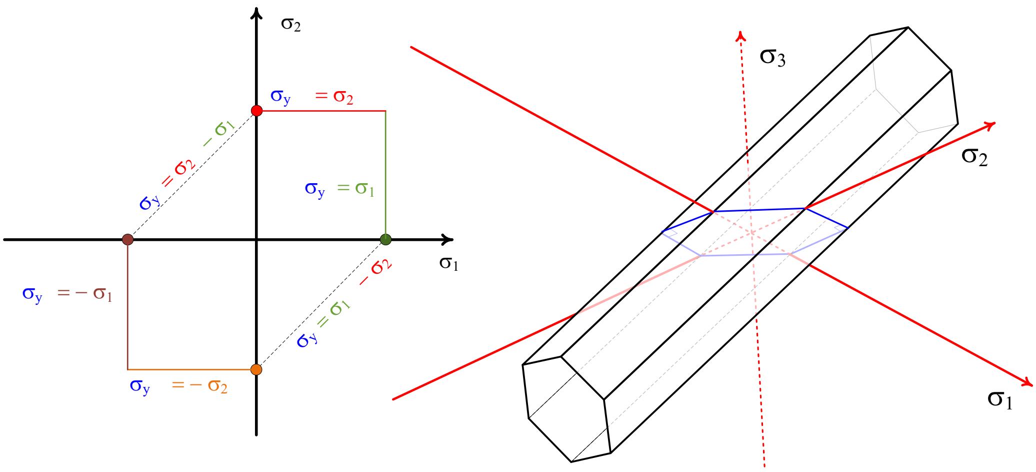
Arriving at

$$\sigma_y = [|\sigma_2|, |\sigma_1|, |\sigma_1 - \sigma_2|] \qquad \{A\text{-}22\}$$

Expanded

$$\sigma_y = \pm\sigma_1, \ \sigma_y = \pm\sigma_2 \ and \ \sigma_y = \pm[\sigma_1 - \sigma_2] \qquad \{A\text{-}23\}$$

Plotting eq. {A-23}, results in Appendix figure A-6.



Appendix figure A-6 - Plotting shear stress / Tresca criterion: 2D and 3D.

The maximum shear stress criterion is used in the Klever & Tamano collapse calculations modified by the API task force who developed the most accurate calculations at current. For more information, see ISO 10400.

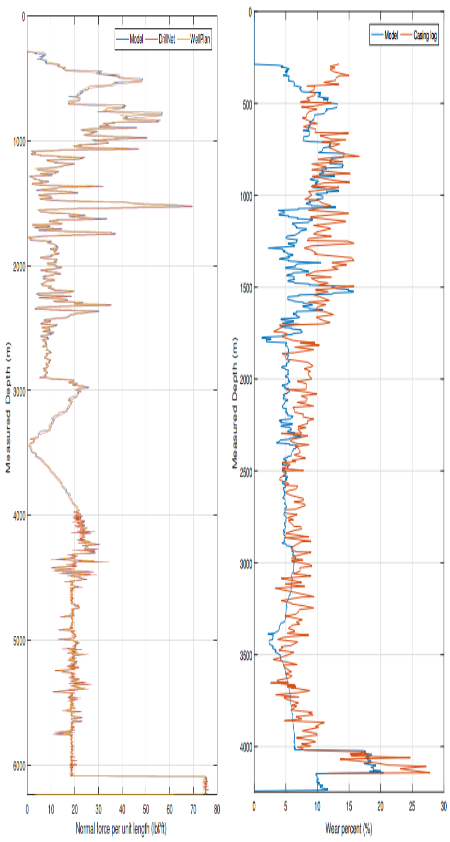
Appendix B Improved engineering and understanding

The conducted research investigated several industry practice calculations for different engineering methods often used in well construction. Part of the work was to compare the current calculations to the latest and most accurate models published.

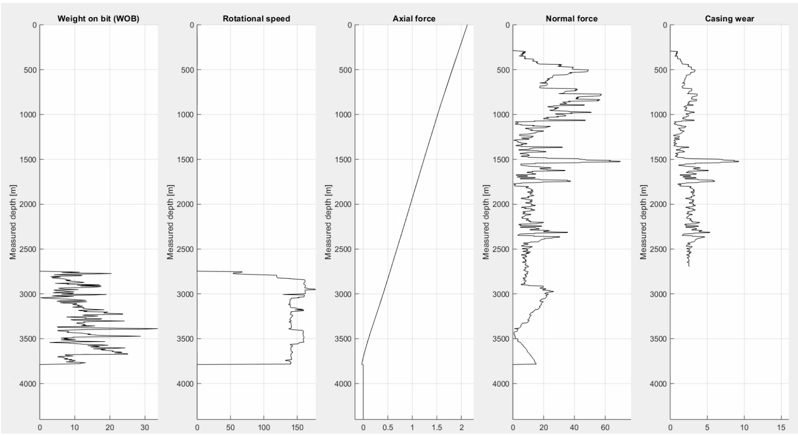
Appendix B.1 Automated casing wear

Casing wear was initiated as part of the research but later "outsourced" in a separate PhD. The background for the research can be summed up to:

1. The base work developed a prototype software producing wear simulations as function of planned activity. I.e. wear prediction from planned drilling parameters produced the same results as with professional software do, see Appendix figure B-1
2. From wear tests of Chrome casing it was discovered that the formulas used in casing wear are not valid. Chrome material does not have the "contact pressure threshold" which is embedded in casing wear prediction today.
3. Because errors in casing wear often have been user related, the wear prediction should be fully automated. This should include automated update during operations with forecasting of end results, see Appendix figure B-2 Also, the prototype casing wear application should fit within the fully automated software environment.



Appendix figure B-1 – Left: Normal force with string at TD for well X. Right: Wear percent form model and casing log

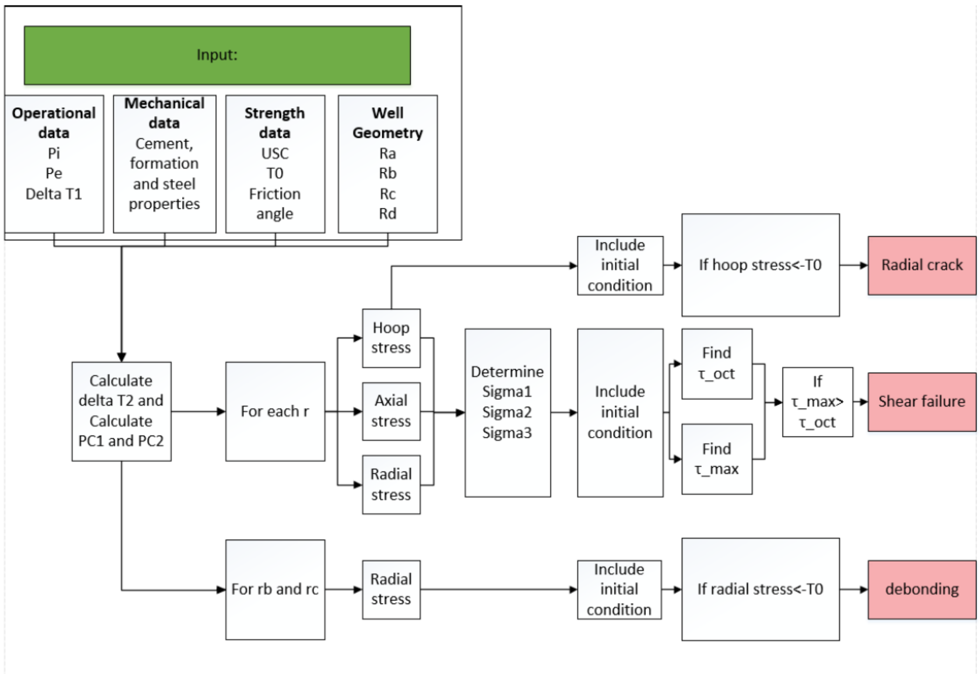


Appendix figure B-2 - Casing wear prototype forecasting wear based on real time data.

The research within casing wear is evaluating formulas for wear of chrome materials using available test data. Casing wear is discussed further in (Brechan(6), 2018).

Appendix B.2 Casing pressure limitation to avoid cement sheath failure

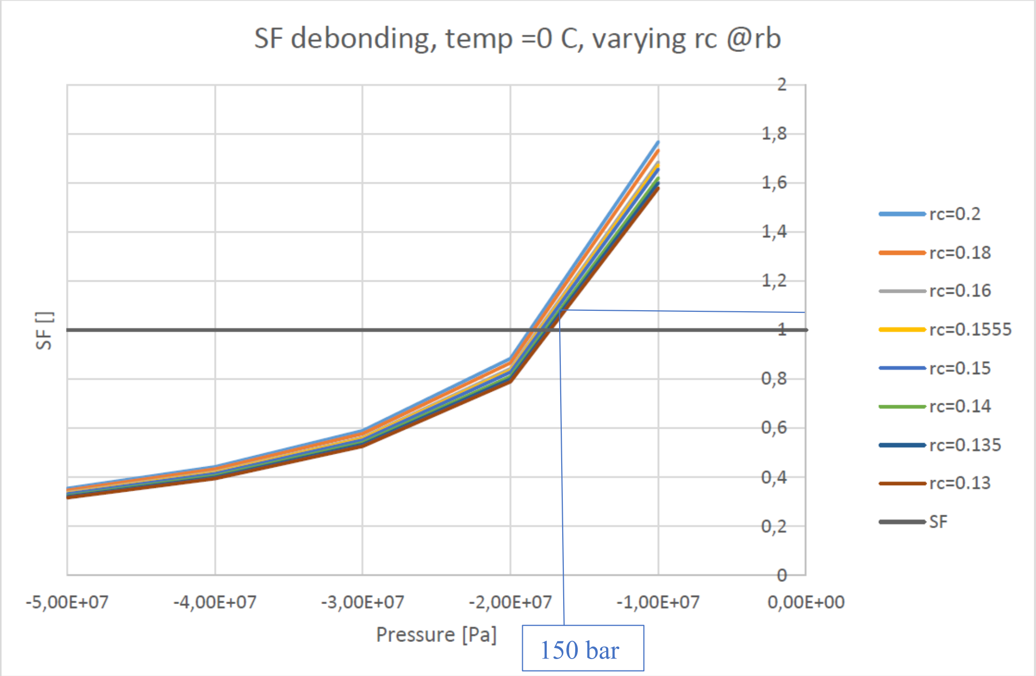
Cement sheath failure is a problem in production. In many cases, the root cause of sustained casing pressure is a damaged cement sheath. A calculator protecting the cement is an important integrity feature. A calculator for considering different types of cement sheath failure as a function of pressure and other possible variables is designed to take part of the automated application for well integrity evaluations. The full flow chart for the different types of possible failure of a cement sheath is shown in Appendix figure B-3 and examples of simulations for maximum pressure test of casing to protect the cement sheath against failure is shown in Appendix figure B-4



Appendix figure B-3 - Flowchart of calculations in the cement model (Bustgaard, 2015).

Where:

P_i is internal pressure
P_e is external pressure
UCS is unconfined compressive strength
T_0 is the uniaxial tensile strength
T_1 is the temperature change at the casing
T_2 is the temperature change at the cement
T_{geo} is the temperature change in the formation
ϕ is the friction angle in the Coulomb criterion
r_a is the inner radius of the casing
r_b is the outer radius casing/inner radius cement
r_c is the outer radius cement/inner radius formation
r_d is the outer radius formation
P_{C1} is the contact pressure at r_b interface
P_{C2} is the contact pressure at r_c interface
σ_1 is the principal stress 1
σ_2 is the principal stress 2
σ_3 is the principal stress 3
τ_{oct} is the octahedral stress



Appendix figure B-4 - Pressure testing of casing - safety factor (SF) towards debonding (Bustgaard, 2015).

Example:
9 5/8” casing in 12 ¼” hole ≈ 1.28

Reading off the graph gives 150 bar pressure limitation to avoid damage to the cement sheath.

Appendix B.3 Fracturing

Fracturing is a large-scale operation repeated daily all over the world. Software for modeling frac design and safe operational parameters are available, but the planning process follows much the same manual steps driven by humans as planning and operations in well construction, maintenance (intervention) and integrity disciplines. The rig count for north America in writing moment exceeds 1000 onshore operations, with a majority of well designs in the category of shale fracs.
The purpose of the developed frac model is to investigate the possibility of making an automated tool for planning and operations of fracturing and integrity analysis. Digital procedures automatically updated with any mini-frac data can be helpful and reduce the administrative load on the highly mobile and equipment heavy frac operations.
Two models for fracturing designs exist, developed from theories of Perkins-Kern-Nordgren (PKN) and Khristianovic-Geertsma-de Klerk (KGD). The below exemplified calculations are based on the KGD method. It is simulated to be drilled along the maximum horizontal stress, thus fracture growth will propagate parallel to the wellbore. Appendix table B-1 displays the simulated frac pad and carrier fluid.

Appendix table B-1 - Simulated frac fluid.

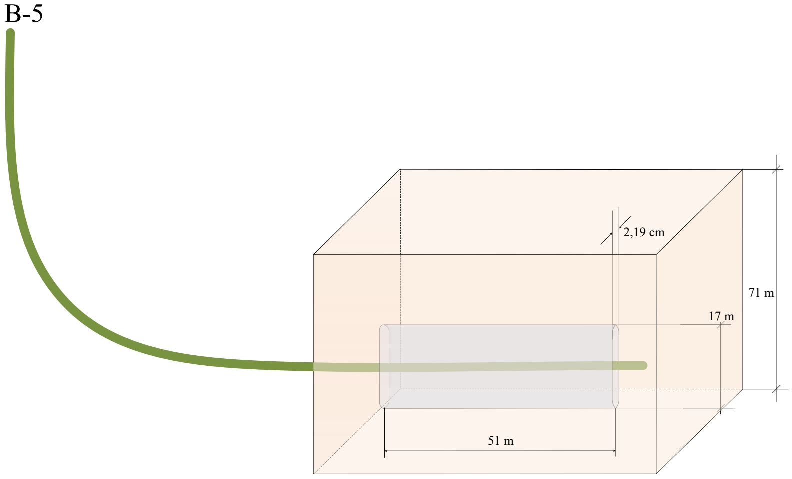
Fracturing fluid	DSC HEC Gel
Flow behavior index, n	0.40
Consistency index, K	$4\ Pa\ s$
Total compressibility; fracture system, $c_{t,f}$	$3 \cdot 10^{-9}\ Pa^{-1}$
Density (@ 25°C) ρ_{frac}	$1.09\ g/cc$

The input frac geometry is given by the Subsurface team based on reservoir simulations. The conductivity of the frac should not restrict the flow of reservoir fluids.

Appendix table B-2 - Frac geometry input.

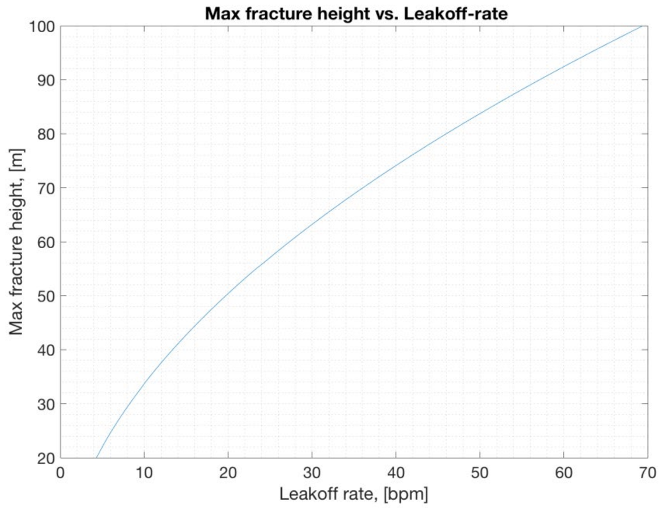
Fracture height, h_f	51 m
Fracture half-length, x_f	2 x 17 m
Average fracture width at end of inflation stage, $\bar{w}_{infl}$	0.0329 m
Final average fracture width, $\bar{w}_e$	0.0219 m

This geometry has a fracture half-length $x_f = h_f/3$ which is suitable for the 2D KGD calculations and a bit out of range for the PKF calculations. A visualization of the frac can be seen in Appendix figure B-5



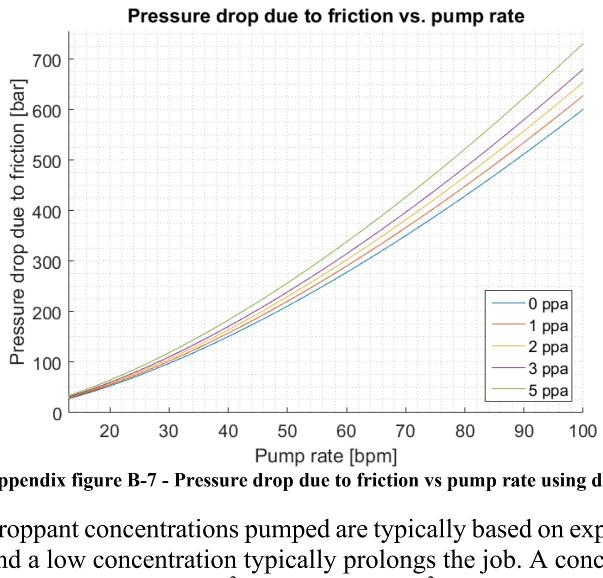
Appendix figure B-5 - Designed frac geometry using 2D prototype frac application.

Increasing the net pressure of the frac fluid will increase the leak-off to the reservoir. This will be controlled by filter loss design and limiting the maximum injection rate. It follows that a higher pump rate yields larger frac area, i.e. more interface between wellbore and reservoir.
A feasible pump rate was simulated to see the consequential height, see Appendix figure B-6 The treatment duration increases significantly when pump rate of the inflation stage and steady packing stage are close. Applying a higher pump rate during the inflation stage than the steady packing stage reduces the total time of the pumping operation and consumption of frac fluid.



Appendix figure B-6 - Frac height vs leak off associated with pump rate Kornberg, 2016).

Increasing the pump rate raise the friction pressure exponentially assuming turbulent flow, see Appendix figure B-7. The pump pressure will have a boundary towards the burst limitation of the exposed well construction. An injection rate of 45 bpm during the inflation stage was chosen to obtain descent fracture dimensions, while avoiding excessive pressure drop and treatment time.



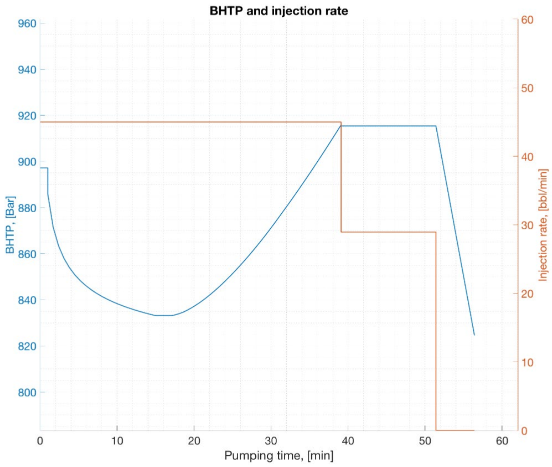
Appendix figure B-7 - Pressure drop due to friction vs pump rate using different proppant concentrations (Kornberg, 2016).

Proppant concentrations pumped are typically based on experience. Too much may plug perforations and a low concentration typically prolongs the job. A concentration of 8 lb/ft^3 is a middle of what is found as high (12 lb/ft^3) and low (5 lb/ft^3) in the literature (Hannah, 1994). The properties of the proppants simulated in the frac design can be seen in Appendix table B-3 - Proppant properties in presented simulation.

Appendix table B-3 - Proppant properties in presented simulation.

Proppant properties	Mesh: 20/40
Proppant density, ρ_{prop}	2700 kg/m3
Porosity of proppant pack, ϕ_{prop}	20%

Pressure[29] vs time can be seen in Appendix figure B-8 The Bottom Hole Treating Pressure (BHTP) during the inflation stage exceeds the breakdown pressure from the XLOT.



Appendix figure B-8 - BHTP (blue) and pump rate (red) as a function of time (Kornberg, 2016).

As proposed in the literature, proppant loading is carefully increased in steps during the stimulation (Smith, 2015), where proppant loading is low and slowly increasing for the majority of the frac and pack treatment, and increases rapidly in the end. The detailed pump schedule can be seen in Appendix table B-4.

Appendix table B-4 - Pumping schedule for frac treatment.

Operation	Fluid	Duration	Rate	Volume	BHTP
		[min]	[bpm]	[m^3]	[bar]
Displace	Brine	178.0	20	566.0	-
Pump	Acid	6.0	25	23.9	425
Pump	Pad	15.0	45	35.8	888
Pump	0.5 PPA 20/40 PP	2.1	45	15.0	833
Pump	1.0 PPA 20/40 PP	5.5	45	39.4	844
Pump	1.5 PPA 20/40 PP	5.5	45	39.4	863
Pump	2.0 PPA 20/40 PP	5.5	45	39.4	888
Pump	2.5 PPA 20/40 PP	5.5	45	39.4	916
Pump	3.0 PPA 20/40 PP	2.0	29	9.0	916

[29] Pumping viscous proppant laden carrier fluid will have some pressure loss over the perforations. It is a risk of bridging out over the perforations, so the perforation design is important. Recommended minimum for 6ppg proppant concentration is 0.2 inches diameter perforation (Gitjenbeek, 2011) which is used in the simulations.

Operation	Fluid	Duration	Rate	Volume	BHTP
		[min]	[bpm]	[m^3]	[bar]
Pump	4.0 PPA 20/40 PP	2.5	29	11.4	916
Pump	5.0 PPA 20/40 PP	2.5	29	11.4	916
Pump	6.0 PPA 20/40 PP	4.9	29	22.7	916
Pump	Flush	17.9	29	82.5	790
Produce	Wellbore fluid	120.0	10	190.8	398

Appendix B.4 Drilling optimization application

Application for drilling optimization can provide two important aspects:

- Provide realistic and optimal drilling parameters in planning for simulations and development of designs
- Ad hoc real time analysis providing:
  - (Contribution to) Boundaries for safe operation
  - Optimal drilling parameters

The application identifies bit dysfunction and drilling inefficiency from expected responses in Mechanical Specific Energy (MSE) and operating parameters:

$$\text{MSE} = \frac{4 \cdot WOB}{\pi \cdot \emptyset_{bit}} + \frac{480 \cdot TQ \cdot \omega}{ROP \cdot \emptyset_{bit}} \qquad \{B\text{-}1\}$$

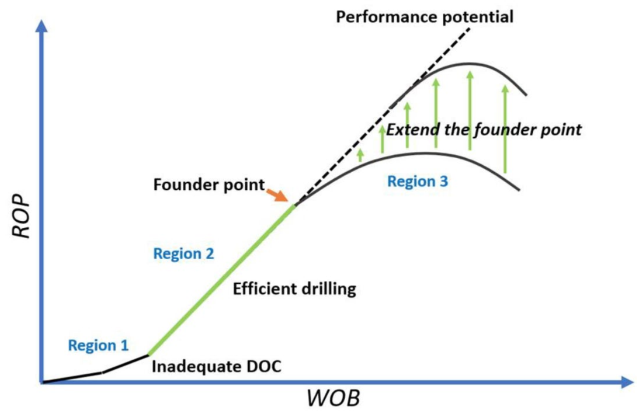
Where:
MSE is Mechanical Specific Energy [Pa]
WOB is Weight on Bit [N]
TQ is Torque [Nm]
ω is Rotations per Minute [1/min]
ROP is Rate of Penetration [m/hr}
$\emptyset_{bit}$ is Hole Diameter [m]

Appendix figure B-9 shows the drill off curve and its regions.

Region 1 has a low depth of cut (DOC) which is inefficient drilling. Low DOC causes a low rock volume to be removed and bit whirl often occur in these conditions since cutters are not appropriately buried. High MSE indicates large amounts of energy put into the system dissipated elsewhere, e.g. vibrations.

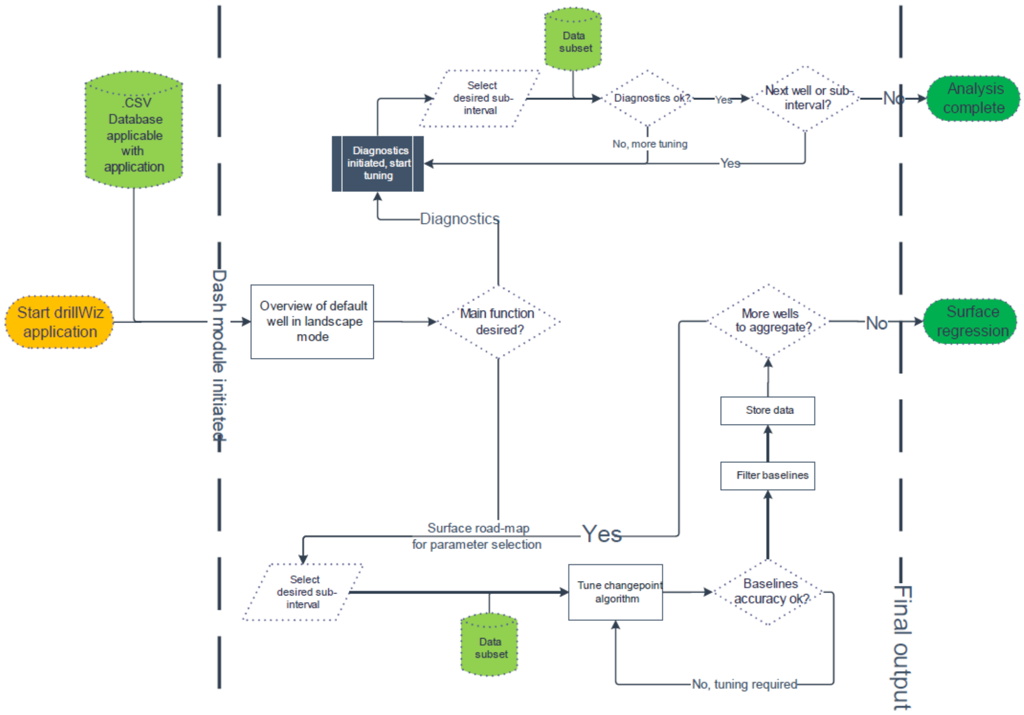
Region 2 is more efficient drilling. Adequate DOC constrains lateral bit movement which prevents bit whirl. The most effective use of energy takes place in this region, i.e. proportional relation between energy input and ROP. This region ends in the founder point, see Appendix figure B-9

Region 3 is above the most effective drilling. WOB above the founder point produce bit dysfunction and poor relation between energy put in versus increase in ROP. Above all, bit dysfunction may severely damage the bit and BHA, resulting in a trip due to bit or tool failure.



Appendix figure B-9 - Drill off curve (Berge-Skillingstad, 2019).

Analyzing and baselining trends in MSE will conveniently identify which region of the drill-off curve the bit is being operated in. Real-time MSE surveillance facilitates a continuous detection of changes in drilling efficiency which allows for an optimum selection of drilling parameters by sufficient parameter exploration or so-called "step-tests". In other words, MSE will indicate if a change in a drilling parameter is moving you closer to, or further away, from the maximum expected performance. Post-drill MSE analysis may provide quantitative data to identify drilling inefficiencies and bit dysfunction in historical reference wells, enabling a cost-justification process to propose changes in the current system to extend the founder point of the next well (Dupriest, 2005). Extending the founder point which onsets a bit dysfunction in any well, may improve drilling performance and BHA tool and bit longevity considerably.

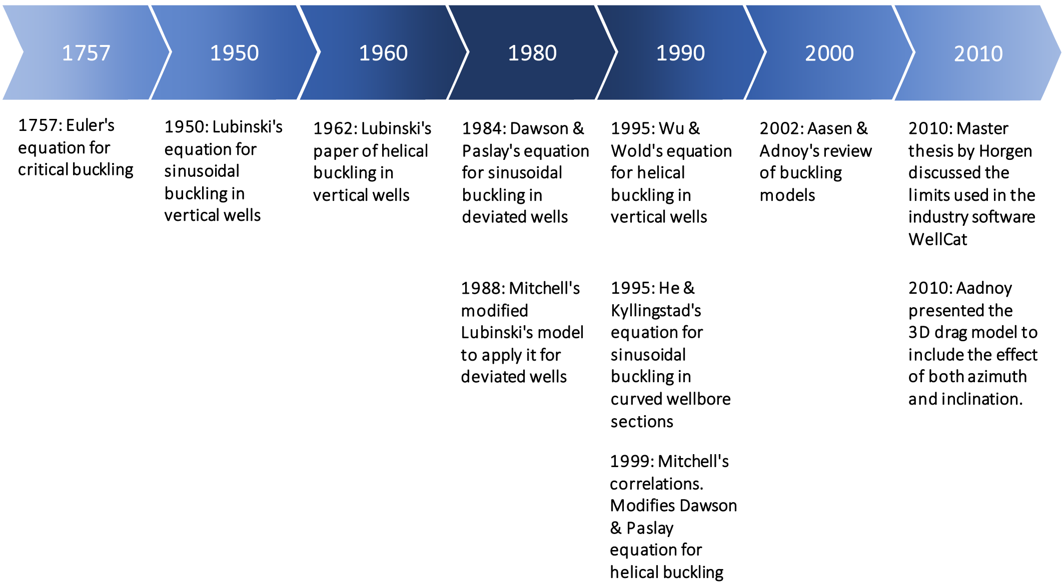


Appendix figure B-10 – Architecture of the drillWiz (Berge-Skillingstad, 2019)

Appendix B.5 Application for buckling

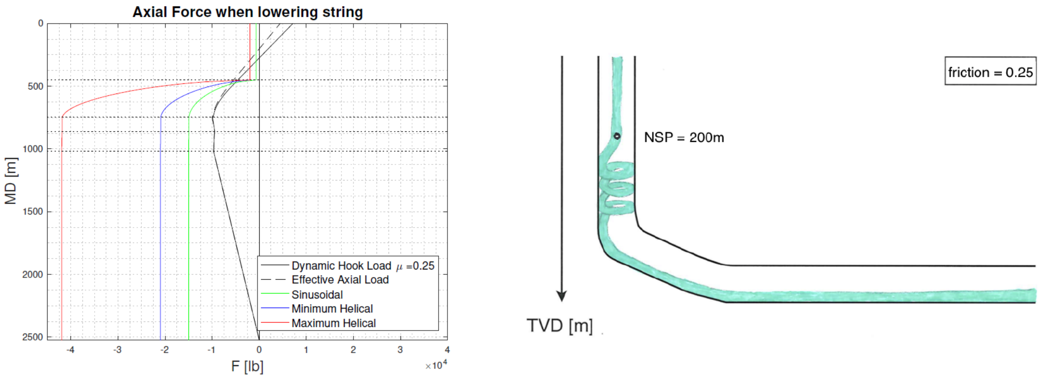
After a comprehensive study of the theoretical foundation behind buckling analysis, the most acknowledged theories in critical buckling limits were programmed into a prototype. Buckling is an important integrity consideration for casing and tubing design, drilling, coiled tubing and snubbing. The total evaluation of the integrity is complex. The more advanced theories are not suitable for a software environment planning regular well construction and intervention. Theories of buckling have evolved, and important contributions have been added recently, see Appendix figure B-11. Simplifications through assumptions are required in today's models. Analysis of operations with drill pipe or coiled tubing are direct calculations, but for well construction requires a buckling model combining stresses locked in during installation of the casing and tubing with operational cycles such as production loads before final critical buckling analysis are made. The prototype proposes a critical buckling ratio, which is an approach useful to compare tubing qualities. The model accounts for dog leg variations in all well sections and predicts lock-up in the string. It integrates calculations of axial forces, the packer force and permanent corkscrewing. An initial installation strategy can also be chosen by implementing a variation of slack-off or pickup forces.

Two models were developed:
The first model represents a scenario where the tubing is installed. Buckling induced by drag forces are visualized through buckling limits with actual forces. Lock-up scenarios are then predicted.
The second model was built to compare with the first. It is similar to the buckling analysis used in the industry software analyzed by "Horgen", see Appendix figure B-11 Both models consider vertical and deviated wells.

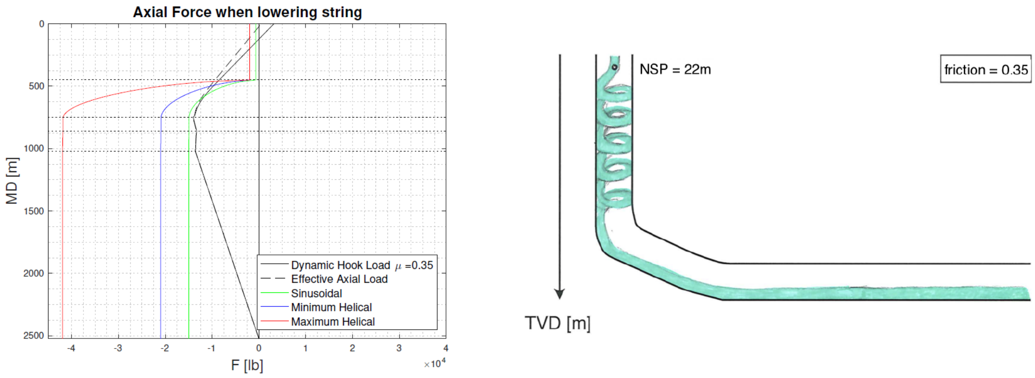


Appendix figure B-11- Timeline of some developments in buckling theory.

The models were tested and compared using the production scenarios of the tubing for a real case with a shallow, horizontal well. Appendix figure B-12 and Appendix figure B-13 shows the buckling limits during installation as a function of friction factor.

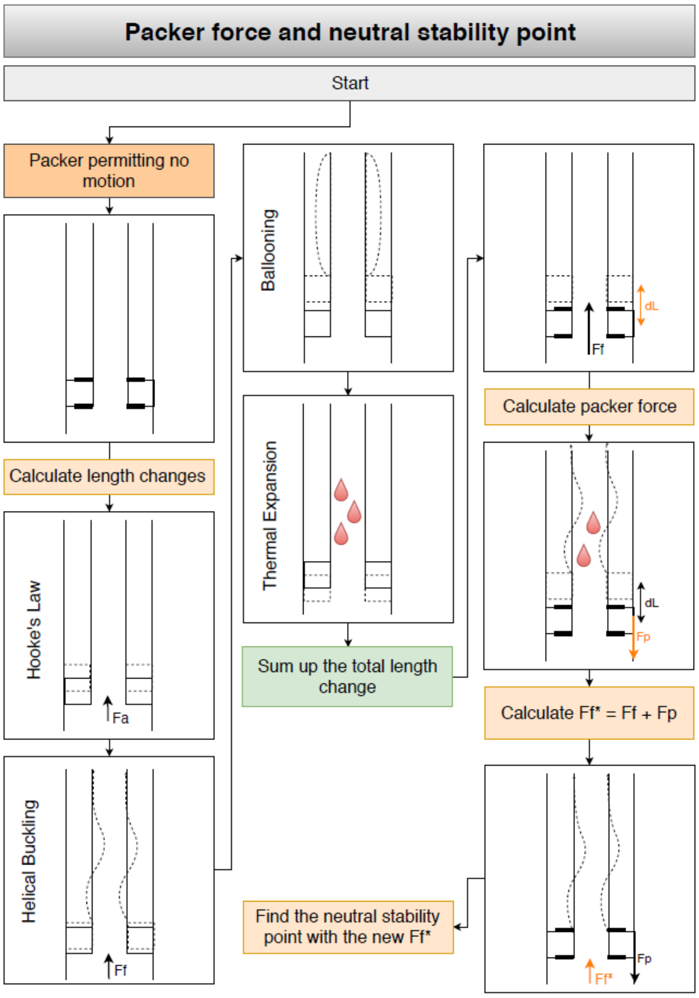


Appendix figure B-12 - Buckling during installation with friction = 0.25. NSP: Neutral Stability Point (Remmen, 2018)



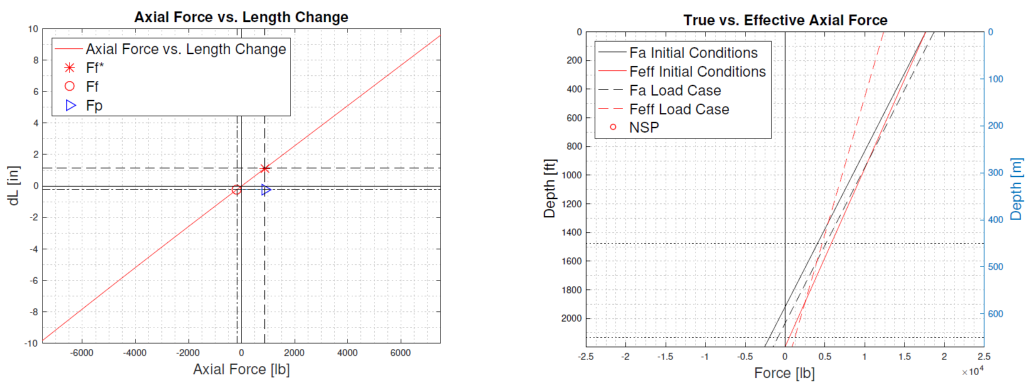
Appendix figure B-13 - Buckling during installation with friction = 0.35 (Remmen, 2018).

Appendix figure B-14 shows the flow diagram applied to analyze the tubing forces and final buckling.



Appendix figure B-14 – Software decision process for buckling in tubing (Remmen, 2018).

Appendix figure B-15 show diagrams from the developed buckling application.



(a) $F_f^* > F_f$, thus tensile packer force

(b) Neutral stability point due to shut-in

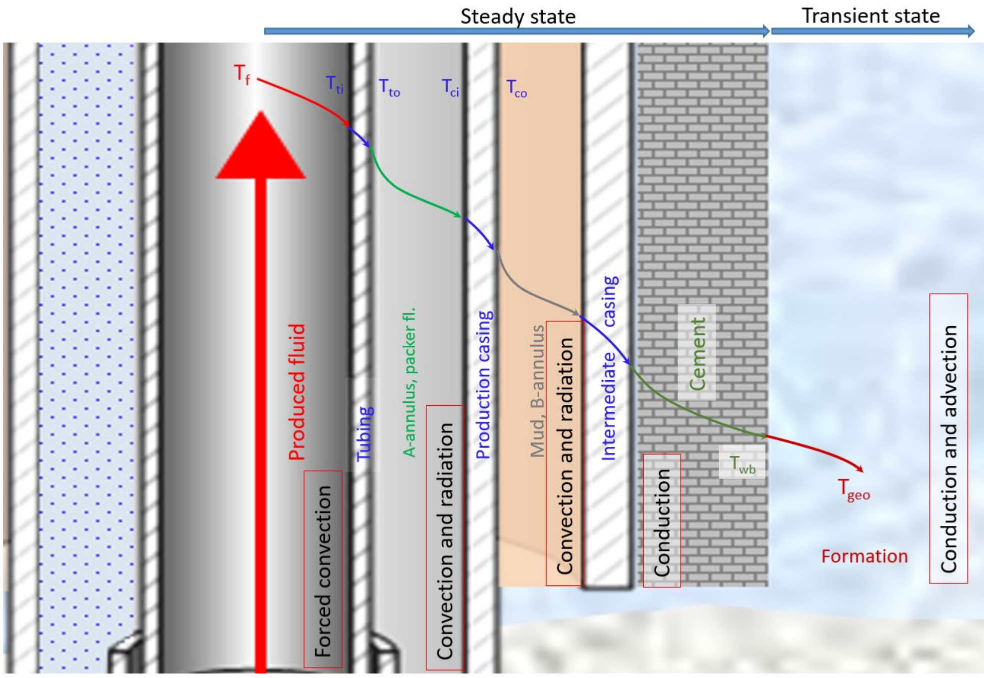
Appendix figure B-15 - Axial force (Remmen, 2018).

Appendix B.6 Temperature model

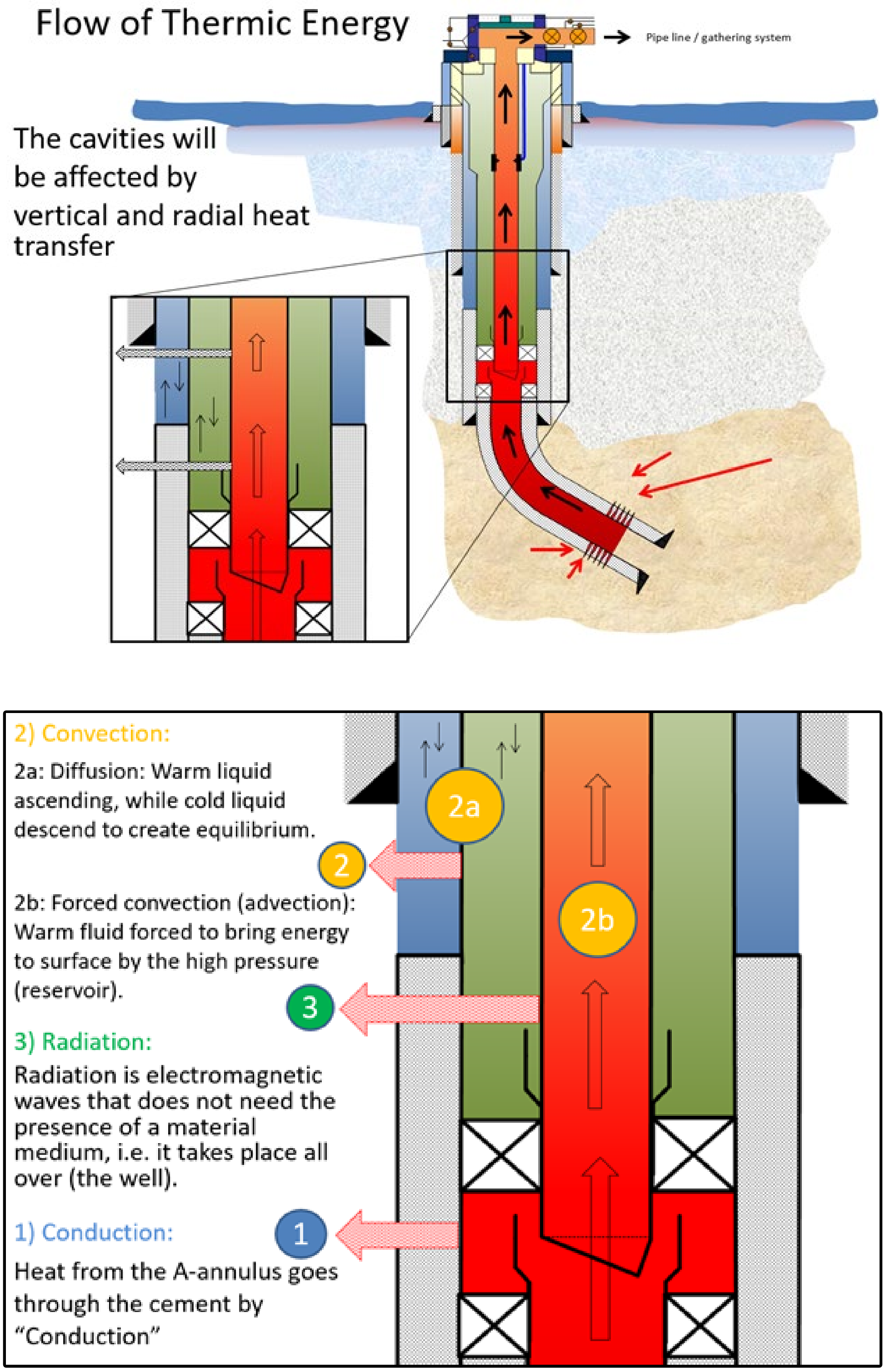
The model developed was limited to producing wells. A separate model will have to be built for injectors, which will be the same equations but with reversed flow. The model builds on of the work of Hasan and Kabir – (Hasan, 1991). Their collected theories are based on the diffusivity equation and the "flowing fluid equation" by Sagar, Doty and Schmidt for steady state. Combined with Newton's law of cooling and the definition of dimensionless temperature, Hasan and Kabir found an expression for the temperature of the flowing fluid as a function of energy transfer to the formation. The three major heat transfer mechanisms in a producing well are conduction, convection and radiation. These are built into one mechanism for a small increment of the well and the iterative approach stepwise calculates the temperature in the well starting at the reservoir.

This first base model has several simplifications. It assumes steady-state fluid flow in the wellbore and heat transfer in the wellbore, but transient in the formation. This prototype model has been programmed so changes can be easily made. This version presumes no vertical heat exchange, homogenous properties for group materials such as steel (casing, liner and tubing), cement, annular fluids (mud and/or brine). The main theories and heat exchange mechanisms are visualized in Appendix figure B-16 and Appendix figure B-17. Some effects derived from thermal change in wells:

- Annular fluid expansion
- Thermal expansion of pipe (collapse, burst, buckling, etc.)
- Temperature dependent yield

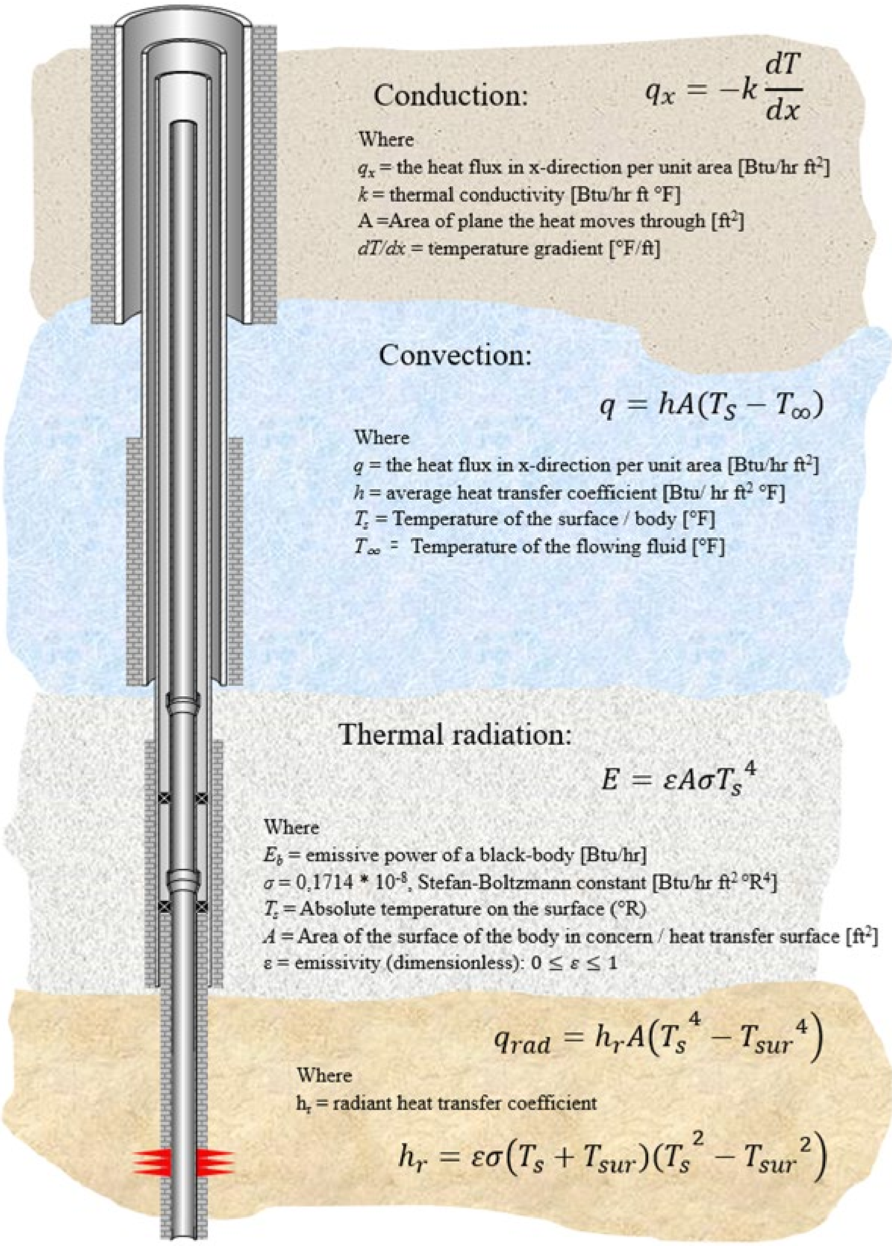


Appendix figure B-16 - Wellbore heat exchange mechanisms



Appendix figure B-17 - Radiation, Convection and Conduction.

A more detailed overview can be seen in Appendix figure B-18.



Appendix figure B-18 - Summary of heat transfer mechanisms.

Below are results from the initial model, see Appendix table B-5. The comparison was conducted using water properties, all other input being the same. The model differs with 9 ºF from the industry model. The result of the multi-purpose temperature model programmed gave a fluid temperature of 0,4 ºF below the industry model. Data from producing wells have been acquired, but the prototype has so far not been run or calibrated with these data. The multipurpose model is far more complex in input and handling of variables, there are few remaining calculations that needs to be looked at following analysis of the data from the producing wells. The results from the multipurpose model can be seen in Appendix table B-6.

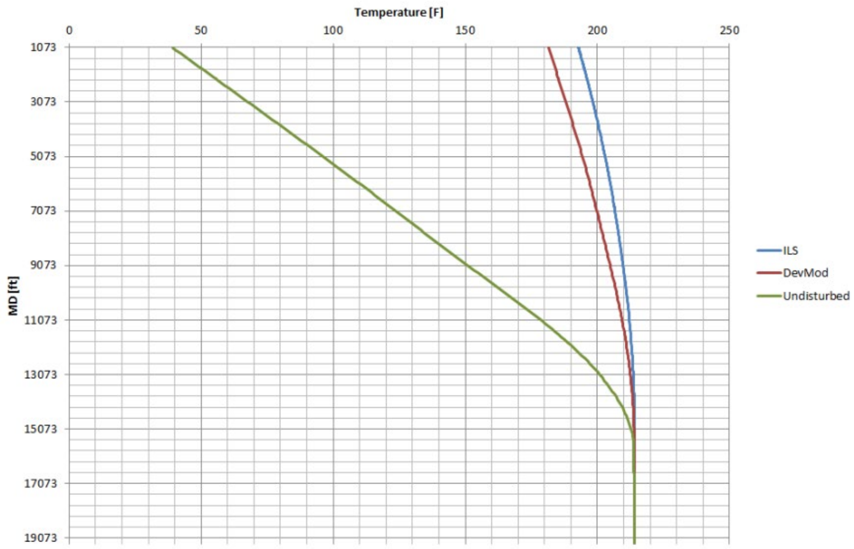
Appendix table B-5 - Initial model.

MD (m)	TVD (m)	INC (deg)	Hdep(m)	MD (ft)	TVD (ft)	INC (rad)	T_geo (F)	U_to	T_f (F)	T_co_9	t_co_13	T_wb	t_co9prev	t_co13_prev	P (bar)
327,00	327,00	0,00	0	1072,8	1072,8	1,57	39,20	2,28	191,87	183,84	173,44	131,86	183,84	173,44	171,1
330,00	330,00	0,00	0	1082,7	1082,7	1,57	39,34	2,28	191,89	184,07	173,66	132,06	184,07	173,66	175,2
360,00	360,00	0,00	0	1181,1	1181,1	1,57	40,75	2,28	192,11	184,34	174,00	132,72	184,34	174,00	176,8
390,00	390,00	0,00	0	1279,5	1279,5	1,57	42,16	3,29	192,34	184,07	173,12	148,20	184,07	173,12	178,5
420,00	420,00	0,00	0	1378,0	1378,0	1,57	43,56	3,29	192,57	184,35	173,48	148,75	184,35	173,48	180,1
450,00	450,00	0,00	0	1476,4	1476,4	1,57	44,97	3,29	192,80	184,63	173,83	149,30	184,63	173,83	181,8
480,00	480,00	0,00	0	1574,8	1574,8	1,57	46,38	3,28	193,03	184,92	174,19	149,84	184,92	174,19	183,4
510,00	510,00	0,00	0	1673,2	1673,2	1,57	47,79	3,28	193,26	185,20	174,54	150,39	185,20	174,54	185,0
540,00	540,00	0,00	0	1771,7	1771,7	1,57	49,19	3,28	193,49	185,48	174,89	150,94	185,48	174,89	186,7
570,00	570,00	0,00	0	1870,1	1870,1	1,57	50,60	3,27	193,71	185,76	175,25	151,48	185,76	175,25	188,3
600,00	600,00	0,00	0	1968,5	1968,5	1,57	52,01	3,27	193,94	186,04	175,60	152,03	186,04	175,60	190,0
630,00	630,00	0,00	0	2066,9	2066,9	1,57	53,42	3,27	194,16	186,32	175,95	152,58	186,32	175,95	191,6
660,00	660,00	0,00	0	2165,4	2165,4	1,57	54,82	3,26	194,39	186,51	176,21	153,05	186,51	176,21	193,3
677,00	677,00	0,00	0	2221,1	2221,1	1,57	55,62	3,26	194,52	186,64	176,38	153,34	186,64	176,38	194,2
690,00	690,00	0,17	0,02	2263,8	2263,8	1,57	56,23	3,26	194,61	186,88	176,66	153,67	186,88	176,66	194,9
720,00	720,00	0,57	0,21	2362,2	2362,2	1,56	57,64	3,26	194,84	187,17	177,03	154,24	187,17	177,03	196,5
750,00	750,00	0,96	0,61	2460,6	2460,6	1,55	59,05	3,26	195,06	187,45	177,39	154,80	187,45	177,39	198,2
780,00	779,99	1,36	1,22	2559,1	2559,0	1,55	60,45	3,26	195,28	187,74	177,76	155,36	187,74	177,76	199,8
810,00	809,98	1,75	2,04	2657,5	2657,4	1,54	61,86	3,64	195,50	188,17	178,48	161,06	188,17	0,00	201,5
840,00	839,96	2,15	3,06	2755,9	2755,8	1,53	63,27	3,64	195,72	188,45	178,84	161,57	188,45	0,00	203,1
870,00	869,94	2,54	4,29	2854,3	2854,1	1,53	64,67	3,64	195,93	188,73	179,20	162,09	188,73	0,00	204,7
900,00	899,90	2,94	5,72	2952,8	2952,4	1,52	66,08	3,64	196,15	189,00	179,56	162,60	189,00	0,00	206,4
930,00	929,86	3,34	7,36	3051,2	3050,7	1,51	67,48	3,64	196,36	189,28	179,91	163,11	189,28	0,00	208,0
960,00	959,80	3,73	9,21	3149,6	3149,0	1,51	68,89	3,64	196,57	189,55	180,27	163,63	189,55	0,00	209,7
990,00	989,73	4,13	11,27	3248,0	3247,1	1,50	70,29	3,63	196,79	189,83	180,62	164,14	189,83	0,00	211,3
1020,00	1019,64	4,52	13,53	3346,5	3345,3	1,49	71,70	3,63	197,00	190,10	180,97	164,65	190,10	0,00	212,9
1050,00	1049,54	4,92	16	3444,9	3443,4	1,48	73,10	3,63	197,21	190,37	181,33	165,16	190,37	0,00	214,6
1080,00	1079,42	5,31	18,67	3543,3	3541,4	1,48	74,50	3,63	197,42	190,64	181,68	165,66	190,64	0,00	216,2
1110,00	1109,28	5,71	21,56	3641,7	3639,4	1,47	75,90	3,63	197,63	190,91	182,03	166,17	190,91	0,00	217,8

Appendix table B-6 - Multipurpose Temperature model.

A	B	C	D	E	F	G	H	I	J	K	L
Depth	Depth	Inc	H_Depart	Depth	[mTVD]	Inc	GeoT	U_tubing	Fluid Temp	9 5/8" temp	13 3/8" temp
[mMD]	[mTVD]	[deg]	[m]	[mFt]	[mFT]	[Rad]	[degF]				
0	0	0	0	0	0	0	0				
327,00	327,00	0,00	0	1072,8	1072,8	1,57	39,20	2,442814	191,489624	16,5581055	0
330,00	330,00	0,00	0	1082,7	1082,7	1,57	39,34	2,442964	191,512421	16,5654812	0
360,00	360,00	0,00	0	1181,1	1181,1	1,57	40,75	2,441678	191,739899	16,4654007	0
390,00	390,00	0,00	0	1279,5	1279,5	1,57	42,16	3,415685	191,966568	183,642059	173,4885712
420,00	420,00	0,00	0	1378,0	1378,0	1,57	43,56	3,688725	192,199158	172,96814	164,3174133
450,00	450,00	0,00	0	1476,4	1476,4	1,57	44,97	3,287686	192,433197	184,283554	173,4753113
480,00	480,00	0,00	0	1574,8	1574,8	1,57	46,38	3,296134	192,662949	184,558807	173,8967285
510,00	510,00	0,00	0	1673,2	1673,2	1,57	47,79	3,677567	192,891953	174,109619	165,6228638
540,00	540,00	0,00	0	1771,7	1771,7	1,57	49,19	2,706422	193,123352	196,784195	181,7563934
570,00	570,00	0,00	0	1870,1	1870,1	1,57	50,60	3,395637	193,344589	185,34343	175,5818481
600,00	600,00	0,00	0	1968,5	1968,5	1,57	52,01	3,667132	193,571976	175,142502	166,8279724
630,00	630,00	0,00	0	2066,9	2066,9	1,57	53,42	3,268257	193,80072	185,973419	175,5964203
660,00	660,00	0,00	0	2165,4	2165,4	1,57	54,82	3,276	194,02533	186,153854	175,9253693
677,00	677,00	0,00	0	2221,1	2221,1	1,57	55,62	3,658108	194,152283	175,990677	167,8321228
690,00	690,00	0,17	0,02	2263,8	2263,8	1,57	56,23	2,691823	194,250519	197,673248	183,2275848
720,00	720,00	0,57	0,21	2362,2	2362,2	1,56	57,64	3,295767	194,467697	186,797394	176,8619995
750,00	750,00	0,96	0,61	2460,6	2460,6	1,55	59,05	2,68965	194,690109	198,034378	183,8374329
780,00	779,99	1,36	1,22	2559,1	2559,0	1,55	60,45	3,663064	194,905396	187,177551	179,6027679
810,00	809,98	1,75	2,04	2657,5	2657,4	1,54	61,86	6,323125	195,128845	188,747025	178,1307373
840,00	839,96	2,15	3,06	2755,9	2755,8	1,53	63,27	6,318694	195,356842	189,028259	178,5003967
870,00	869,94	2,54	4,29	2854,3	2854,1	1,53	64,67	6,314204	195,584229	189,307785	178,8686218
900,00	899,90	2,94	5,72	2952,8	2952,4	1,52	66,08	6,306555	195,81012	189,588715	179,232666
930,00	929,86	3,34	7,36	3051,2	3050,7	1,51	67,48	6,30195	196,035507	189,86673	179,5995026
960,00	959,80	3,73	9,21	3149,6	3149,0	1,51	68,89	6,297626	196,259537	190,143036	179,9653473
990,00	989,73	4,13	11,27	3248,0	3247,1	1,50	70,29	6,294435	196,482712	190,418518	180,3324585
1020,00	1019,64	4,52	13,53	3346,5	3345,3	1,49	71,70	6,289043	196,704651	190,693527	180,6954956
1050,00	1049,54	4,92	16	3444,9	3443,4	1,48	73,10	6,283703	196,925858	190,967575	181,0578003
1080,00	1079,42	5,31	18,67	3543,3	3541,4	1,48	74,50	6,278238	197,145935	191,240097	181,4186401
1110,00	1109,28	5,71	21,56	3641,7	3639,4	1,47	75,90	6,270188	197,364944	191,512772	181,7753906

Appendix figure B-19 show a diagram produced by the developed application for multipurpose temperature simulations for producing wells.



Appendix figure B-19 – Multipurpose model producing 2-phase fluid (ILS = Industry Leading model, DevMod = developed model)

Appendix B.7 Other

Many calculations investigated will not be discussed in detail. E.g. kick tolerance (see Figure 3-16), conversion between different coordinate types and map reference systems (positioning and positioning uncertainty), Wellhead growth and others. Annular Fluid Expansion (AFE) and automated monitoring and risk analysis of well integrity are briefly discussed below.

Appendix B.7.1 Annular Fluid Expansion (AFE)

Trapped fluid will expand when heated and vice versa for cooling. This can result in a pressure build up:

$$\Delta P = \frac{V - V_0}{V_0 C} \quad \{B\text{-}2\}$$

Where:

- V is the expanded volume
- V_0 is the initial volume
- ΔP is the pressure change in the annulus
- C is the compressibility of the fluid

The temperature effect volume of a fluid can be expressed as:

$$V = V_0(1 + C_T \Delta T) \quad \{B\text{-}3\}$$

Where:

- C_T is the coefficient of thermal expansion
- ΔT is the temperature change

Combining equation {B-2} and {B-3}:

$$\Delta P = \frac{C_T \Delta T}{C} \quad \{B\text{-}4\}$$

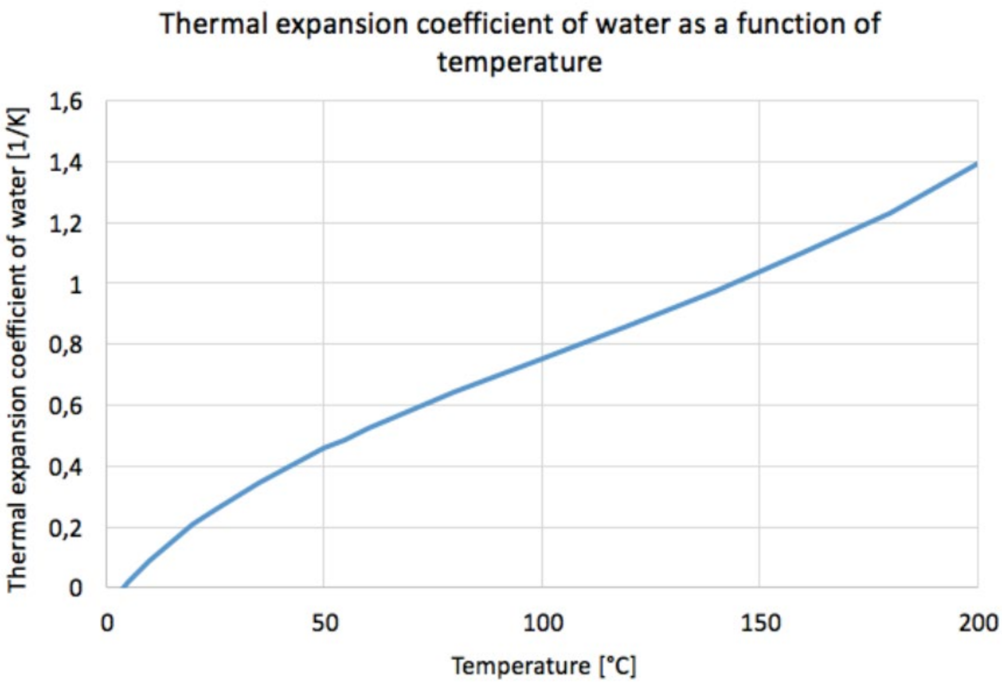
ΔT can be determined from the temperature model discussed above.

The thermal expansion coefficient and compressibility of a fluids are non-linear functions of the pressure and temperature properties. The values vary for water-based and oil-based fluid. Appendix table B-7 lists general thermal expansion and compressibility values.

Appendix table B-7 - Thermal expansion and compressibility values (Moe, 2000).

Fluid type	Thermal expansion [R^{-1}]	Compressibility [psi^{-1}]
Water-based	2.5×10^{-4}	2.8×10^{-6}
Oil-based	3.9×10^{-4}	5.0×10^{-6}

The thermal expansion coefficient of water as a function of temperature is not linear, see Appendix figure B-20.



Appendix figure B-20 - Thermal expansion coefficient of water as a function of temperature.

A change in temperature can also influence the density of the fluid. This will not be discussed further here.

Appendix B.7.2 Well integrity

Automated analysis of standard surveillance data from wells such as temperatures, pressures, flow rates, sand production, fluid composition, etc., can be analyzed by an application which develops a risk status should integrity be compromised. Evaluations of each barrier element is possible in the described object-oriented environment. History and performance of each component can take part of the automated evaluations, which are carried out in context of exposure to people, environment, installation / material damage – i.e. risk consequence factors. These can be:

- Installation type
    - Onshore: remote / urban
    - Fixed platform concepts (dry XTs)
    - Floating production units (subsea development)
    - Tension leg platforms and deep draft floaters
    - Satellite fields with tie-back to installation
- Installation activity (manned/unmanned)
- Type of x-mas tree (dry/wet)
- Well type
    - Free flowing production well
    - Production well with artificial lift
    - Injection well
- Well position on seabed relative to the production unit
- Well concentration
- Water depth
- Multiple failures
    - Barriers
    - wells
- Formation strength (adequate or low)
- Type of well leakage
    - Internal: leakage to closed system.
    - External: leakage outwards in the well with potential of reaching seabed/surface
- Leakage characteristics, ref API RP 14B
- Reservoir/injection pressure (relative to hydrostatic): flow potential
    - ≤ Normal (≤ Hydrostatic)
    - Abnormal (> Hydrostatic)
    - Abnormal high (>> Hydrostatic)
- Energy source
    - Reservoir
    - Injection
    - Gas lift
- Well leakage fluid (o/w/g)
- Ability to access the well
- Escalation factors
    - Corrosion/erosion
    - Well kill/recoverability
    - Mechanical/pressure loads
    - Well release

Part of the planned integrity work is automated updates of well barriers as physical changes from initial well construction to final P&A. A powerful visualization of barrier envelopes with each element and their history can improve the understanding of the integrity of the well and asset.
Another important feature with the WOS connected to the standard surveillance data from wells is an automated update of the integrity of each barrier envelope according to the company governing documentation. Integrity is based on tubular design with involved equipment, cement design and formation strength. The WOS can run the load cases and update the integrity should the real time data be outside the range of input data in the original design.

Appendix figure B-21 shows an initial version of the prototype integrity risk evaluation tool.

Energy			Fill in	
	fi (1=yes)	wi	Wj	fi*wi*Wj
Energy source			3	
Injection		6		0
Gas lift		8		0
Reservoir		10		0
Reservoir/injection pressure			10	
Normal		1		0
Abnormal		5		0
Abnormal high		10		0
Flow potential from reservoir			10	
None		1		0
Some		2		0
Medium		5		0
High		10		0
Leakage fluid (mainly)			10	
Water		1		0
Ouil		5		0
Condensate		8		0
Gas		10		0
Σ Energy factors				0

Surroundings			Fill in	
	fi (1=yes)	wi	Wj	fi*wi*Wj
Type of installation			5	
Subsea		1		0
Subsea below platform		5		0
Platform		10		0
Isntallation activity			5	
Manned facitily / location		10		0
Unmanned facitlty/location		1		0
Water depth			3	
Deep (>300 m)		1		0
Medium (100 - 300 m)		5		0
Shallow (<100 m)		10		0
Σ Surrounding factors				0

Barrier			Fill in	
	fi (1=yes)	wi	Wj	fi*wi*Wj
Leakage path			10	
Inside well (internal)		3		0
Inside to next casing		5		0
Inside to environment		10		0
Potential leak rate			10	
Low leak rate (API RP 14B)		2		0
Medium leak rate (> API RP 14B)		5		0
High leak rate / blowout		10		0
Escalation factors (none or several)			5	
Corrosion (erosion in well)		4		0
Mechanical pressure loads > design		8		0
Unacceptable HC storage in well		10		0
Challenge relating to normalization / well kill		10		0
Σ Barrier factors				0

Appendix figure B-21 - Automated well integrity risk assessment tool (Størseth Møller, 2019).

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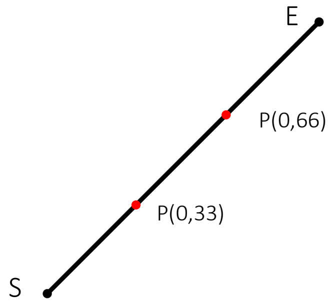
Appendix C Bézier curves in well trajectory design

The trajectory planning in the "initial planning" is made with Bézier curves. Compared with traditional cubic functions and other methods, Bézier curves provides a flexible and easy base for an application developing automated well paths. Appendix figure C-1 shows a 1st order curve.



Appendix figure C-1 - 1st order Bézier curve is a line.

Any point P on a Bézier curve can be expressed by the parameter k, where k ∈ [0,1].

$$\frac{P-S}{E-S} = \mathrm{k} \qquad \{C\text{-}1\}$$

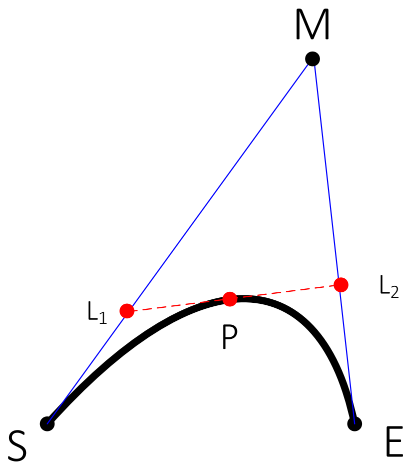
Rearrange

$$\mathrm{P} = (1-\mathrm{k})\mathrm{S} + \mathrm{kE} \qquad \{C\text{-}2\}$$

Where:

- P = point coordinate of a Bézier curve
- E = ending point of a Bézier curve
- S = starting point of a Bézier curve
- k = independent parameter of a Bézier curve

The 2nd order Bézier curve builds on the calculations for the 1st order curve by adding a support point M, see Appendix figure C-2.



Appendix figure C-2 - 2nd order Bézier curve is a 2D well path.

The 2nd order Bézier curve is supported by two 1st order curves, SM and SE, and a third 1st order curve marks the main point “P” on the second order curve.

$$\frac{L_1 - S}{M - S} = \mathrm{k} \tag{C-3}$$

$$\frac{L_2 - M}{E - M} = \mathrm{k} \tag{C-4}$$

Rearrange

$$L_1 = (1 - \mathrm{k})\mathrm{S} + \mathrm{kM} \tag{C-5}$$

and

$$L_2 = (1 - \mathrm{k})\mathrm{M} + \mathrm{kE} \tag{C-6}$$

The third curve:

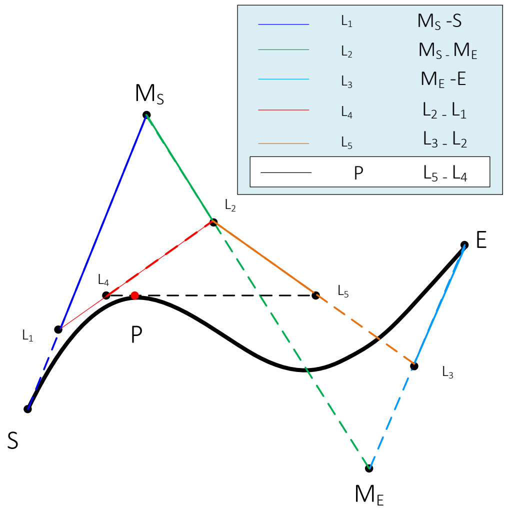
$$\frac{P - L_1}{L_2 - L_1} = \mathrm{k} \tag{C-7}$$

$$\mathrm{P} = (1 - \mathrm{k})L_1 + \mathrm{k}L_2 \tag{C-8}$$

Combining {C-5}, {C-6} , and {C-8}:

$$\mathrm{P} = (1 - \mathrm{k})^2 S + 2(1 - \mathrm{k})\mathrm{kM} + k^2 E \tag{C-9}$$

A 3rd order curve can be seen in Appendix figure C-3.



Appendix figure C-3- 3rd order Bézier curve is a 3D well path.

L_4 and L_5 follows are deducted analogue to equation {C-9}:

$$L_4 = (1 - \mathrm{k})^2 \mathrm{S} + 2(1 - \mathrm{k})\mathrm{k}M_S + k^2 M_E \tag{C-10}$$

and

$$L_5 = (1 - \mathrm{k})^2 M_S + 2(1 - \mathrm{k})\mathrm{k}M_E + k^2 \mathrm{E} \tag{C-11}$$

It follows that point P on a 3D Bézier curve has the following coordinates:

$$\mathrm{P} = (1 - \mathrm{k})L_4 + \mathrm{k}L_5 \tag{C-12}$$

Combining {C-10}, {C-11}and {C-12}:

$$P(k) = (1-k)^3 S + 3(1-k)^2 k M_S + (1-k) k^2 M_E + k^3 E \qquad \{C\text{-}13\}$$

Using Bézier curves to design well paths in 3D space require additional computations. Looking at the input in well path design, the known input is WH and target coordinates. Often, the targets in the reservoir have a preferred inclination I and azimuth θ through the target. See Appendix table C-1 for an overview of input parameters.

Appendix table C-1 - Input parameters for 3D Bézier curves.

Description	Bézier	Variables
WH / start coordinates	S	NS, EW and TVD
Inclination and azimuth in WH		I_s and θ_s (respectively)
Target coordinates	E	NS, EW and TVD
Inclination and azimuth in target		I_E and θ_E (respectively)

Comparing Appendix table C-1 and equation {C-13}, the required input missing are the coordinates for the control points M_S and M_E. In a cartesian system, it is possible to define a unit tangent vector in any point along the well path as:

$$t = (\cos I, \sin I \cos\theta, \sin I \sin\theta) \qquad \{C\text{-}14\}$$

The two control points becomes:

$$M_S = S + d_S t_S \qquad \{C\text{-}15\}$$

and

$$C_E = S + d_E t_E \qquad \{C\text{-}16\}$$

Where:

d_S is the distance from S to M_S
d_E is the distance from E to M_E
t is the unit tangent vector

The unit tangent vectors are:

$$t_S = (\cos I_S, \sin I_S \cos\theta_S, \sin I_S \sin\theta_S) \qquad \{C\text{-}17\}$$

$$t_E = (\cos I_E, \sin I_E \cos\theta_E, \sin I_E \sin\theta_E) \qquad \{C\text{-}18\}$$

There are two free scalar parameters which can be used to manipulate the shape of the well-path for e.g. T&D optimization, etc.

Length of well path can be approximated to:

$$L(k_i) = \sum_{k=1}^{n} \sqrt{(\Delta TVD_i)^2 + (\Delta NS_i)^2 + (\Delta EW_i)^2} = \sum_{i=1}^{n} \Delta L_i \qquad \{C\text{-}19\}$$

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Appendix D Article abstracts

Only a collection of the abstracts of the articles produced is enclosed due to the comprehensive number and total size of the work. The articles are introduced in the sequence they were presented in the different conferences.

Appendix D.1 SPE-189403 Well Integrity - next developments

Step changes in the area of Well Integrity is often based on HSE, production regularity and intervention cost. Well Integrity is a relatively new area of expertise, where small and larger quantitative and qualitative improvements can be expected. With change in technology comes procedural changes. With more significant improvements comes organizational changes. This paper shed some lights on some improvements in the pipeline for future Well Integrity Management.

Some step changes are more evident as new equipment are qualified. Other improvements may be more intangible, like procedural or organizational changes. An overview has been made per phases a well is subjected to, in an approach to understand where it is likely to see progress in the area of Well Integrity. The overview follows a typical life cycle of a well to map out the processes and work where a well's barriers, integrity and containment are either planned, established or active.

One important issue learned from making an overview of the Well Integrity activities through the life cycle of a well is how the work is divided between different groups in an organization with different responsibility and Key Performance Indicators (KPIs). Updating and reporting integrity status, providing performance and reliability data across lines is in itself a challenging task.

The Integrity of a well is often tied to the capacity to contain fluids. The processes which happen on the outside of the barrier envelopes are also important. It can be gas migration leading to sustained casing pressure, exposure to mobile corrosive fluids, subsidence or formation collapse. Traditionally, monitoring pressure in the production annulus has been the main indicator of integrity and source of information. Many operators acknowledge that monitoring the other annular pressures are important and have long desired automatic surveillance of the next annulus.

Appendix D.2 OTC-28481 Well Integrity Risk Assessment - Software Model for the Future

Risk is a topic reaching over many layers in an organization and its structure. From operator and asset level to individual wells and operations. The oil and gas industry's joint consensus of primary focus is safe and effective production. This is reflected in the growing efforts in the area of Well Integrity. The essence of Well Integrity is "containment" and the essence of a Well Integrity Risk Assessment (WIRA) is to demonstrate containment capacity in a scenario where barrier elements fail to meet industry standards and requirements. Risk assessments often adhere to guidelines in ISO 16530 part 1 "Life cycle governance" and part 2 "Well integrity for the operational phase". Following the practice outlined in these standards, understanding the risk starts with a procedure for identifying the risk level of the individual wells and then goes on to evaluate the impact to – and the total asset risk level.

When a parameter indicates a weakness in a barrier, the general procedure is to investigate until the source is identified and the associated risk is understood. In many cases, the error indicator, troubleshooting procedure, and final risk assessment is triggered by a failure known and familiar to the many experienced Well Integrity organizations operating wells. These organizations are processing vast amounts of data to understand the Well Integrity, the risk at single well level and asset level associated by producing one or more wells with deviating behavior. Software exists to support the daily efforts in Well Integrity, but a digitalization process can make a step change. The basis of a new Life Cycle Well Integrity Model (LCWIM) has been developed. Risk assessment support as function of the integrity indicators is one of the features planned for the LCWIM. The scope of this paper is to outline how risk assessment processes often are performed in Well Integrity and establish the key components in a plan for an autonomous process, where the LCWIM generates the risk assessment based on the signals transmitted from the well.

Appendix D.3 SPE-189395 Well Integrity Model - Klever & Tamano Collapse

Better understanding of collapse resistance of casing and tubing can unlock significant value in support of Asset Life Extension (ALE), support routine Well Integrity assessments in every-day work and save significant cost by omitting costly oversized designs. Many operators still use the traditional API collapse model, which were accurate for tubulars produced 50 years ago but now underestimate collapse resistance and predicts typically 80 – 85% of the real collapse pressure. Adding to the excess dimensioning is the standard procedure of applying a safety factor to this prediction.

Early 2000, a joint API/ISO Work Group 2b (WG2b) under the Steering Committee 5 (SC5) for tubular goods reviewed casing and tubing performance property equations. ISO/TR 10400:2007, equivalent to API TR 5C3, presents the results from the extensive testing, and the Klever and Tamano (K&T) model for collapse prediction was found to be most accurate. Building on the test data from WG2b/SC5 group, a model was made for collapse pressure prediction of tubulars – hereafter referred to as the “Ultimate Limit Strength (ULS) model”, where the simulation result is a prediction of tubular failure. Its predictive accuracy is calibrated with a complete set of data from 113 actual collapse tests offered by the Drilling Engineering Association (DEA). The ULS model was used to predict collapse strength of 9 5/8 inch 53.5 ppf, P-110 casing, using parameters with probability density functions (PDF) for the relevant type of pipe, e.g., quenched & tempered (Q&T), hot rotary straightened (HRS). The PDFs for each input parameter were obtained by measurements of the 113 samples and compared with the PDFs obtained by the WG2b/SC5 group. Random value generators in a mathematical spreadsheet allowed for Monte Carlo simulations to output 100 000 collapse strength predictions for the 9 5/8 inch casing in question. With confidence level of 97.5%, the basic strength was 9900 psi using PDFs from the DEA data set. Using ensemble PDFs, the basic strength was 9500 psi – 19.5% greater than API’s standard rating of 7950 psi.

Performing casing and tubing design, the industry practice is to develop load cases to identify the design limiting loads for the well. Once identified, the pipe selected needs to be investigated for factors reducing the collapse capacity further, e.g. axial / triaxial loads and wall loss from wear and tear. Axial loading is accounted for in the ULS model through the theories of Klever & Tamano. Aspects briefly discussed and not fully incorporated in the prototype ULS model are the linear derating factors considering imposed ovality, casing wear and experimental formulas derived for increased collapse strength of pipe in compression. These were conservatively approximated by polynomial curve fitting of an alternative formulation of yield collapse strength and tried in a version of the prototype model.

Appendix D.4 OTC-28988 New standard for Standards

Digital well planning, construction and maintenance have a lot of potential for cost reduction and improved HSE. Developing a software model to replace many of the tasks performed by humans can reduce administrative tasks and enables more focus on the quality of plans and operations. One single model to overlook engineering and activity through the life cycle of wells from the planning phase, through construction, production, maintenance to the final plugging unlocks many potential improvements. One possible feature for a Life Cycle Well Integrity Model (LCWIM) is to embed industry standards to supply guidance and recommendations during the life cycle of a well. Changing the format of standards so both computers and humans understand their content can benefit the planning and operational phases of well construction, intervention, production and finally plugging.
Typically, standards are used broadly in the planning phase. However, in the later phases of the life cycle of the well, it is often more difficult to accommodate both changes in operations and updates to industry standards. Embedding the industry “best practice” into software for planning well construction and maintenance, can prevent potential human errors and ensure an appropriate well construction. Having standards as “digital eye” on the engineering and well construction parameters can help to ensure safer operation and help to ensure that no regulations are overseen due to human error.
Standards can be considered a collection of experiences gathered over decades in the industry, and they represent the common ground for description of methods and procedures for safe and sustainable operations. When digital well planning gradually replaces the traditional manual planning processes, the vast experience of standards can support engineers more actively and directly compared to text documents. This paper describes an approach to merge the digital version of a standard into the LCWIM so it actively provides relevant information to ongoing operations similar to a help function. The user would experience this as “relevant information” by just a mouse-click. The method of choice elaborated in this article shows a life cycle standard in the shape of an active support module to the LCWIM. The reasons behind the selected approach is twofold: (1) LCWIM is a life cycle tool, which incorporates life cycle standards to support all activities in all phases, (2) Standards support LCWIM by verifying that tests and procedures are in compliance.
The focus of this paper is to demonstrate how a life cycle standard like the NORSOK D-10 Rev. 4, June 2013 can be completely digitalized to take an active part in planning and operations. The scope is limited to section 5.6 “Casing design” with elaboration of section 5.6.3 “Load cases” to stepwise show one way the standard can become interactive.

Appendix D.5 SPE-191341 MWD Wellbore Surveying – Sensitivity Analysis of Survey Errors as a Function of Hole Inclination and Compass Direction

(2^{nd} author if the article)
Measurement While Drilling (MWD) is a common survey tool used in wellbore positioning. The industry often uses the Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA) error models for estimating the Wellbore Position Uncertainty (WPU). However, the model’s sensitivity to direction and nature of trajectory has not been discussed in detail. In this paper, a software model has been developed to better understand the influence of the individual error sources on measurement and position uncertainty in various drilling directions and hole sections.
Most operators have classified accurate wellbore positioning and directional design as one of the pillars of safety. It is commonly known that measurement accuracy of frequently used MWD instruments decreases with increasing hole inclination. Survey accuracy is also

influenced by North to East direction. This work provides a detailed understanding of the behavior and contribution of each survey error source and screens the error terms contributing most towards WPU. Visualizing the contribution of each error source as a function of well path direction and inclination will support the understanding of position uncertainty of individual wells.

The results in this paper are based on analysis of the ISCWSA Non-mag error model. It has been observed that some errors are most dominant in the North/South drilling direction while others are most dominant in the East/West direction. Similarly, some error sources are most effective in the vertical hole section and least effective in the build-up or horizontal sections. This process continues for all different error sources in various hole sections and drilling directions. Therefore, this paper has summarized the most important error sources for the vertical, build-up and horizontal sections of the three wells, i.e. North/South (NS), North/East (NE) & East/West (EW). The visualization of error sources will provide a more focused approach towards ultimately reducing the WPU.

The work in this paper is a part of a new digital well planning and well construction software tool. The working title of this software is Life Cycle Well Integrity Model – LCWIM.

Appendix D.6 OTC-28772 Digital Well Planning - New Cost Saving Well Construction and Life Cycle Well Integrity Model

A new generation software for well construction and maintenance is under development. The working name is Life Cycle Well Integrity Model (LCWIM) as its main focus is to support work with wells and fields from the planning stage to final P&A. LCWIM is a systematization of a fully digitalized software model that can provide many advantages for the industry. This paper focusses on four main objectives: Firstly, reduction of workload and direct human involvement by replacing many tasks in well construction and well integrity engineering by automatization. The goal is to shift the focus of humans towards supervision of computerized processes. Secondly, a modern software architecture should provide a fluent interlink between all stakeholders to provide and share information. A fully digitalized module should reduce repetitive tasks. Building on the architecture and metadata of LCWIM, future digitalization projects in e.g. administrative routines such as invoicing can be linked to establish a work process dominated by computerized events which are supervised by humans. Thirdly, the model will store all relevant data pertaining to a well through its life cycle, providing a potent self-service information hub that is easy to use for all disciplines. Fourthly, the scope of the LCWIM is to improve HSE and significantly reduce non-productive time in three ways: (1) interactive experience transfer, (2) embedding of interactive standards and governing documentation to support planning and operation, (3) elevation of personnel out of direct involvement into a supervisory role to reduce human error.

Access and availability favor a cloud-based solution. With increasingly more data and information to process, a modern software will require significant processor capacity that is scalable according to the number of users. By combining the capacity of both servers and local computers, the software can provide advanced calculations and graphical representations at interactive response times.

Appendix D.7 OTC-28300 Interactive Experience and learning Model Can Reduce Non-Productive Time (NPT)

Digitalization is believed to increase efficiency and operational safety while reducing cost. While many initiatives are directed towards automatization of the drilling process, there are other areas that potentially can provide additional cost reductions in the same order of magnitude or more. Founded in the emerging era of digitalization is a new Life Cycle Well Integrity Model (LCWIM) which will change work processes and roles of involved personnel. The model will support work from the planning phase through to the final plugging and abandonment (P&A) of wells. The philosophy used during the systemization of the LCWIM entails reduction of direct human involvement through digitalization and automation. This can reduce the aspect of human error and focus the efforts of each employee towards the performance aspects of their work. An area where the benefits from this philosophy may be most evident is handling of experiences and improvement. The new work process will allow personnel to establish an experience using the interactive section in the LCWIM. The software would then propose the content of the experience in subsequent planning and well construction work – where relevant. Some other areas where the LCWIM applies this philosophy are in the digitalization and embedding of standards and operational procedures.

The oil and gas industry is constantly battling costly NPT in well construction and the production phase. Since the 90ies, there have been many initiatives to reduce NPT. The literature offers many technical improvements that eliminate specific errors and failures in the Well Construction phase, company internal campaigns and methods to focus on the most frequent time thieves, and proactive campaigns to boost performance. Digitalization may provide a step change in the fight against failure in planning and operations by the support of an interactive software built with learning features.

The background for the change in work process is maybe best stated by a proverb possibly attributed incorrectly to Albert Einstein: “Computers are incredibly fast, accurate, but stupid. Humans are incredibly slow, inaccurate, but brilliant. Together they may be powerful beyond imagination”. A software is not likely to be as brilliant in problem-solving as humans, but it can accumulate and apply all human intelligence implemented over time for every relevant planning and operational situation. Reaching the software’s design target ability to adapt to any type of well design and operational situation, the LCWIM can be a considerable tool for increasing safety and reducing NPT.

Appendix D.8 SPE-191299 Work Process and Systematization of a new Digital Life Cycle Well Integrity Model

This paper outlines an extract of a software model for digitalization of the processes supporting upstream activities for onshore and offshore fields. Digitalization in this context means full automation of planning and a step change in the daily well integrity work. The planning process will produce digital programs and procedures understandable to humans and computers. The software comprises building blocks for every engineering calculation. These are interlinked and constructed such that their planning capacity can be improved by the users. Today, humans drive every step in engineering and planning. Digital well planning and operations will shift the role of humans towards feeding the planning process with experiences in digital format. Changing from text-based learning to digital experience will improve planning and operations. Digitalization can also provide digital standards, governing documentation and automate administrative routines such as invoicing.

Visualization of wells, their components, barrier envelopes and elements from plan to “as installed” will form a 3D interactive interface where users of different roles can retrieve information and see relevant engineering, modelling and integrity status. The software is planned to be cloud based and exploit local graphics hardware for optimal performance and response.

This article gives an introduction to the planned functionality of a new Digital Life Cycle Well Integrity Model (LCWIM) which is under development. In addition to an overview of the functionality, digitalization is exemplified by automation of one of the LCWIM modules, namely casing wear prediction. The LCWIM will produce digital programs and procedures, which is a foundation for the next step in digitalization: automation of the drilling process. The focus of this paper is to depict a digital work process concerning well planning giving input to the operational phase and well integrity.

Appendix D.9 OMAE2019-95534 Next generation well design and integrity digital tools – boosting drilling systems automation (DSA)

The first of the next generation applications for well planning and operational support is under development. All aspects of construction, integrity, intervention and final plugging of wells are supported and fully automated into digital programs and procedures. Expanding the scope of software support entails a change from current practice of simulating all activity upfront to keep the model active and updated to supply all integrity data through production and final plugging of the well.
The software is built to carry executable experience. These "digital experiences" range from the single event type often noted during operations, to complex sets of instructions in governing documentation. Experiences act as rules for how the software select methods outlined in activity plans and how these plans are executed by the equipment on drill floor. Any activity plan, e.g. drilling, completion, intervention or plug and abandonment (P&A), will be established using the entire company portfolio of experience regardless of the capacity and experience of the planning team.
Engineers working with the next generation software will focus on ensuring the quality of the produced digital procedures. The software will handle administrative routines, such as invoicing and logistics, which will free up capacity for engineers. The user threshold of the next generation software will be low for any person familiar with the daily operational reporting system.

Appendix D.10 OMAE2019-95819 Improved model for tubular burst

Modern casing design can reduce significant amounts of CO2 and considerable cost per well. Collapse design was modernized by ISO/API Technical committee 67, Sub Committee 5, Work Group 2b (ISO/API TC67/SC5/WG2b). Modernization of burst design has so far not had the same focus and only minor changes have been made. A new burst design model has been developed to add to the collapse prediction for a complete environmental and cost effective well design tool. It is based on the theories of Lubinski and presents designs using "exact von Mises ellipsis" together with the Klever and Stewart ductile rupture model.
This paper presents the model developed for burst design and the improvement compared to current industry practice. Inspired by the current most accurate collapse prediction model, the modified burst model (prototype) is the first to consider actual wall thickness to predict a more accurate internal yield of OCTG (Oil Country Tubular Goods). Investigations show that the standard 12.5% wall thickness reduction for manufacturing tolerances may be obsolete. ISO 10400 offers physical measurements and statistics of tubular properties. Following the principals by WG2b applied with the Klever & Tamano collapse prediction, there is a set of data to be used for a specific batch of tubulars or they are deducted through large quantum of measurements; ensemble Probability Density Function (PDF). The value proposed as "ensemble PDF" for wall thickness is based on more than 10 000 measurements of tubulars from 11 vendors distributed over Electrical Weld (EW) and quenched and tempered (Q&T) qualities of miscellaneous sizes and grades. The batch specific value proposed is based on more

modest numbers of specimens from 4 sources but offers "minimum measured wall thickness" for all the samples. Adding to the confidence of the final design is the automated ductile burst calculation, which is one of the latest contributions to burst modeling in the industry. It is a useful aid for the design engineer to know the potential failure mode and the limit before loss of integrity. However, burst is limited to yield because exceeding this limit may lead to loss of the pipe's effective diameter and eventually loss of integrity. Therefore, the ductile burst prediction is proposed as a visual aid only.

Appendix D.11 SPE-195628 Digital well planning, well construction and life cycle well integrity: the role of digital experience

Automation is about to bring major changes to the work process for well planning. The next generation well planning tools will take the steps to higher levels of automation, which can provide step changes in quality of the planning, safety aspects in operations and reduce time and cost for planning and operations.

This article discusses the changes that will follow a new standard in well planning and operations. Analysis of the current practices and investigating the potential of a fully automated planning tool leads to a complete re-structuring of the work process. Well planning is a multidisciplinary activity where representatives from the different subsurface disciplines collaborates with the Wells engineers in a compromise-prone process often with multiple iterations due to the differences in objective and understanding. The arrival of cross discipline 3D visualization tools has led to improvements in average duration of planning, but it is still a process depending on the efforts of the participating individuals and their level of experience. In an era where computers are landing passenger planes and the pilot has a verification role, it is time to look at the potential in digitalization for well planning and operations.

Many software developers are familiar with the difficulty in developing a "solution" to a challenge in a complex environment such as well construction and production. Many areas of expertise are involved, and it is easy to end up with a compartmentalized product which is specialized for one area or a specific challenge. Establishing links and communication to all engineering and calculations in Wells, Subsurface and Production (e.g. well integrity data) are a matter of cost and safety. The next generation well planning tools has to incorporate all areas of expertise from planning well construction, through producing wells to final P&A.

The key enabler for automating the well planning process is the digital experience module, which will be the main task and focus for the Wells Teams. With built in experience, the application has rules and enhanced algorithms allowing Subsurface Teams to make accurate well plans and mature optimal well designs without involving the Wells Teams. Subsurface can identify the optimal drainage and well path including anti-collision, future sidetracks, regulations in governing documentation and follow "local best practice". The Wells teams are ultimately responsible and will verify the well path generated by the software and do any required updates.

Appendix D.12 SPE-195604 Well Integrity – Managing the risk using accurate design factors

Wells closed in due to integrity issues compose large volumes of recoverable hydrocarbons. In recent years, there has been advances in the understanding of pipe performance. The understanding of these advances is kept with a few specialists, and the industry standard remains unchanged for most engineers working with well integrity. This paper shed light on these advances and the impact they have to well integrity. A modest estimate for an average well is an upfront saving potential of ~$45,000 USD for tubulars and a reduction of more than 50 metric tons of CO_2 saving of the environment. The larger values, however, is with wells closed in due to integrity marginally under the acceptable. This article shows a hidden design margin. On average, pipe resistance to collapse is ~10 to 25% above the industry standard calculations. And for burst design, the real limit is often more than 7% higher than the industry standard calculations.

Well integrity is a discipline ensuring safe hydrocarbon recovery on behalf of an operator. Every well is scrutinized and every signal outside the set boundaries from a well is ensued until the integrity is understood and a decision can be made to safely produce or to suspend the well. Well integrity is based on performance of the equipment in the barrier envelopes. Pipe is an important element in both the primary and secondary envelopes. Following a better understanding of pipe integrity, a new integrity work flow is proposed. Well Integrity is a relatively young discipline, where guidelines and standards have evolved significantly over the last decade. There are still several important issues to be standardized, such as the minimum integrity information to be defined for a well. Examples are operational parameters such as (assumed) effective hole diameter, cementing parameters (rate, preflush, slurry, etc.) which have an impact to the integrity. Other important information to standardize is the restrictions in pressure testing of casing to avoid damage of the cement sheaths. Finally, this article proposes “information management” as the 4th element in the definition of well integrity. The digitalization wave washing over the industry is about making optimal use of data, which is essential to make good decision in well integrity as much as any other area in the oil and gas industry.

Appendix D.13 Collapse prediction of pipe subjected to combined loads

Prediction of tubular performance has over the last decades improved with models that are more accurate. There is a trend in the oil and gas industry where traditional uniaxial modelling is given less importance and the triaxal consideration is gaining ground. The American Petroleum Institute (API) added a formula to the standard to consider the effect of internal pressure on the collapse strength in the early 1980s. In 2015, API issued an addendum to API Technical Report 5C3 (TR 5C3) where the triaxially based collapse strength method was incorporated. This was a more accurate method of incorporating the effect of internal pressure and axial stress on collapse strength. The validity of the formula was demonstrated by collapse strength tests with simultaneous internal pressure by an API work group – API WG 2370 (Greenip, 2016).

In 2007, API/ISO presented an ultimate strength (ULS) method for predicting collapse. The new calculation, referred to as the Klever & Tamano model, was developed by API/ISO Work Group 2b (WG2b) under the Steering Committee 5 (SC5) for tubular goods. Following 2986 collapse tests of quenched and tempered tubular specimens, the Klever & Tamano (K&T) model has since been presented as the most accurate ULS model for collapse prediction.

This paper compares the collapse prediction performed by the Klever & Tamano model with the 2015 API model using the triaxial collapse tests performed by Greenip for API. Comparison of the K&T (ULS) model and the traditional API (minimum performance) model requires some considerations to establish common ground before the results can be compared. The K&T model builds on a probabilistic estimation of the pipe properties while key components of the API prediction is empirical. The resulting collapse prediction for the entire batch is 3.11% lower than actual for K&T and 20.9% for API. Using two standard deviations, the collapse prediction of K&T is 14.7% lower than actual. Increasing to three standard deviations, the K&T model coincides with the API triaxial model from 2015 for the investigated pipe. No figures reported include any design factors. These results support that slimmer tubular designs can be made exercising detailed control of safety margins to collapse. A generic example shows a reduction of $47,000USD per well for a typical 13 000ft long well in a 8.6 lb/gal (1.03 sg) pressure gradient.

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Appendix E Well Integrity aspects per phase

Appendix table E-1 - Well Integrity aspects in the planning phase (part 1)

Phase	Activity	Process	Tools	Comment	Well Integrity	#
Planning	Establish design limitations	Well Design Pressure(s)	Operational limit / max load	Ref NORSOK D-10 rev4 section 4.3.3.	Foundation for pressure test of primary and secondary envelope	[1]
		Section design pressure	Gas lift: Extended testing of intermediate casing	If tubing is not qualified as barrier	Gas tight threads. Restrictions due to previous annulus integrity	[2]
			Abnormal pressures in shallow formations	Leak path to previous casing	Monitor annular integrity Reinforce annular integrity Extra section	[3]
				P&A considerations	Strength of exposed formations	[4]
	Establish design requirements	Tubing size	Reservoir Engineering	Number of wells and plateau production	Surveillance data handling and capacity	[5]
		Casing program	Number of sections	Formation pressures and stability	Annuli properties: • Monitoring • Vented or closed • Consequence of leak to next annulus	[6]
			Size of reservoir section and production casing/liner	Reservoir Engineering and tubing size limitation		
			Secondary barrier envelope	Internal integrity (Performance)	Threads, collapse, burst and axial load capacity after corrosion and wear	[7]
				External Integrity (Cement jobs)	• 2 cement jobs towards reservoir • Length and quality of cement job	[8]
				External Integrity (Formations exposed)	• Gas migration capacity • Collapsing shales	[9]
		Primary barrier / Completion equipment	Primary barrier envelope	Corrosive capacity	Alloy selected according to reservoir fluids and temperature. Integrity: monitor annulus	[10]
				Wear prediction	Intervention activity: Pickling, WL/CT/ TTRD interventions	[11]
				Internal integrity (Performance)	Threads, collapse, burst and axial load capacity after corrosion and wear	[12]
				External integrity	Equipment selection: Control lines,	[13]
				Component selection	Reliability and performance data	[14]
				Stress design	Differential temperature and pressures, bending forces and wear kept within design limit	[15]

Appendix table E-2 - Well Integrity aspects in the planning phase (part 2)

Phase	Activity	Process	Tools	Comment	Well Integrity	#
Planning	Establish design requirements	Completion functionality	Gas lift	Older gas lift systems not qualified as barrier	Intermediate casing may be used if formation strength allows	[16]
				Production casing collapse	Max / min pressure scenarios and possible leak to next annulus.	[17]
			Redundancy	Fallback option for valves in barrier envelopes	Wet XT: If valves fails, others behind are certified to take over Gas lift: Missing / failing ASV can be replaced with flanged safety system.	[18]
			Intelligent completion, CIS, DHSV	Leak points	Leak may be internally or externally (to annulus). Special considerations apply for control lines through the production packer.	[19]
				Pressure source	Any system rated higher than WDP needs special consideration	[20]
	Design revision / review	ISO 16530-1:2017 Chapter 6.5 "Well integrity considerations for the basis of design", with verification of barriers as defined in Norsok D-10.				[21]

Appendix table E-3 - Well Integrity aspects in the Well Construction phase (part 1)

Phase	Activity	Process	Procedure / equipment	Comment	Well Integrity	#
Well Construction	Execution	Establish barriers	Position control	Keep low dog legs (DLS)	Excessive wear due to high dog legs	[22]
					Excessive bending forces from high DLS (inadequate residual burst/collapse resistance)	[23]
				Intersecting formation / faults / wells accidentally	Well construction exposed to higher / lower pressures than design (burst / collapse).	[24]
				Well Control	Fracturing up to weak formation / leak paths	[25]
				Poor placement in reservoir	Initial high corrosive water cut	[26]
			Formations / conditions not as outlined in the design phase	Change of/from scope	Management of change Evaluation of impact on final Well Integrity => review steps in planning phase	[27]
			Formation properties	FIT / LOT / XLOT	Formation integrity knowledge for establishing P&A barrier. Part of the envelopes through the production casing/liner	[28]
			Install Casing / liner	Change of depth	Formation strength at shoe	[29]
					Reduced section pressure, MAASP and kick tolerance	[30]
				Seal assembly, flanges, valves and other access points to annulus	Items to be classed as leak paths, tracked for performance and installation procedure documented. Anything not normal to be reported.	[31]
			Annular barrier - Cement	Short (losses)	Possible permeable zones exposed – gas migration – potential for SCP	[32]
					Conductor: potential for WH growth and WH fatigue	[33]
				Lack of bond (inadequate cleaning / spacer composition and rates)	Possible permeable zones exposed – gas migration – potential for SCP	[34]
				Leak test casing/liner after cement is set up	Overload cement sheath – establish cracks and initiate leak paths	[35]
				Poor mud properties	Collapsing shale and particle sagging - whichever comes first - may block annulus from access to formation (max pressure no longer limited to frac at shoe).	[36]
			Equipment / functionality	No pressure monitoring in annulus	Subsea / wet XT: Design intermediate casing according to AFE simulations – run well according to design only	[37]
					Below formation collapse or bridge of sagged barite: Gas migration may take place	[38]

Appendix table E-4 - Well Integrity aspects in the Well Construction phase (part 2)

Phase	Activity	Process	Procedure / equipment	Comment	Well Integrity	#
Well Construction	Execution	Design verification	Update models	Real data to replace planned data to confirm wear, bending stress and residual burst and collapse capacity	Final data and operational limits are essential input for the Well Integrity work	[39]
		Suspension / P&A	Install barriers	Establish deep and shallow barrier	Monitoring of pressures, surveillance (wet XT) and potential time restrictions (e.g. for wells with no pressure monitoring)	[40]
			Preparedness	For Subsea wells: Disconnect due to bad weather	If well is abandoned for a longer period (e.g. damage to rig or WH / BOP) equipment	[41]
	Barrier Verification	Leak testing	Pressure up with fluid in the well	Particle free fluid or standard mud	Flattening trend essential.	[42]
				Duration of leak test	Longer duration can compensate for particles in test fluid	[43]
	Info management	Verification of design and limits	Input for Well Integrity work	Handover certificate	ISO 16530-2:2014 Annex M "Information required of well handover"	[44]
				Deviations from normal design / special limitations	Documented in Deviation System and WIMS.	[45]

Appendix table E-5 - Well Integrity aspects in the Production / Intervention phase

Phase	Activity	Process	Procedure / equipment	Comment	Well Integrity	#
Production / Intervention	Flowing / Injecting	Monitoring Integrity	WIMS	Well Integrity Management System	WIMS populated with operational limits for each well - surveillance of pressures ensures containment	[46]
				Surveillance of all annuli	What is not read digitally, is often entered manually into the WIMS	[47]
				Periodic testing	Valves integrated in barrier envelopes are leak tested periodically	[48]
				Equipment reliability	Input to selection of equipment for new wells and prediction of failure in the future	[49]
			Failure detection	Pressure in annulus deviating from set limits	WIMS raise alarm for breached limit – notification process	[50]
				Trouble shooting	Provide procedures to identify failing barrier element	[51]
			Safe operations – WIMS status	Each well listed with known deviations	Establish and publish risk level for each well	[52]
				Safe field operations	Updated procedures mitigating barrier weakness	[53]
			Overall risk level	Asset total risk level	ISO 16530-1:2017 Annex A, including sub clauses and linked references	[54]
		ALE	Asset Life Extension	Full design review	As described in phase "Planning" – also ref. section 9.10 - ISO 16530-1:2017.	[55]
		Change of scope	Inject ⇔ produce	Change from/to injecting/producing	If accounted for in original design, change status and update operational limits in WIMS. Otherwise, – see comments for ALE above and section 9.10 - ISO 16530-1:2017.	[56]
	WIMS	Update	Regulatory changes	Update WIMS	Changes in regulations may lead to closing or accepting wells with reduced Well Integrity	[57]
	Intervention	Well maintenance	Repair / change valves	Update WIMS, including barrier diagrams	Remove obsolete deviations, restrictions of use and update barrier diagram	[58]
			Plugging / perforation		Track new formations exposed and review well design pressure	[59]

Appendix table E-6 - Well Integrity aspects in the Permanent Plugging phase

Phase	Activity	Process	Procedure / equipment	Comment	Well Integrity	#
P&A	Planning	Permanent abandonment	Well history	Ensure all side tracks are appropriately plugged	Input to program for establishing permanent barrier plugs: • Provide integrity status of well construction. Identify any leak paths • Review status of earlier wellbores from slot (good barriers or potential leak paths)	[60]
	Execution		Program input	Quality of restoration of permanent barriers	• Barrier material selection • Barrier placement and redundancy • Barrier testing and verification • Final documentation	[61]

Appendix F Brief intro to AI

Big Data and Machine learning are two key topics in modern AI. One of the early definitions of machine learning proposed: "field of study that gives computers the ability to learn without being explicitly programmed". Some define big data as: "using computation techniques to uncover patterns, trends, and associations in very large sets of data from various sources and formats.
A third term "cognitive computing" may offer more perspective, see Appendix table F-1.

Appendix table F-1 - AI and cognitive computing

AI		Cognitive Computing
Machine learning, NLP, Neural Networks, Deep learning	Technology	Machine learning, NLP, Neural Networks, Deep learning, sentiment analysis30
Find patterns in big data to learn and either reveal hidden information or deliver solutions to complex problems	Capabilities	Simulate human thought processes to assist humans in finding solutions to complex problems
Automate processes	Purpose	Augment human capabilities
Finance, security, healthcare, retail, manufacturing, government	Industries	Customer service, healthcare, industrial sector

Cognitive computing will not be discussed further here. A short introduction by comparison can be useful the reader with little previous knowledge of big data and machine learning, see Appendix table F-2.

Appendix table F-2 - Big Data and Machine Learning.

Big Data		Machine Learning (ML)
Big data is highly versatile and is used in several applications and purposes. E.g. financial research, customer behavior / sales data etc.	Application of technology	Machine learning is used for chat bot technology, advance recommendation engines (Netflix, Amazon, etc) and it is central in the technology behind self-driving cars.
Big data can extract info from a variety of data formats, i.e. existing or live streamed information, and perform analytics to determine patterns according to the users' queries.	Basis of intelligence	Machine learning is normally trained with a set of data to recognize patterns. These patterns can be used to solve problems in data unknown to the software. ML can be set up to learn.
Big data technology reveals patterns through classifications and sequence of input data	Data analysis	ML is one step ahead by adding learning from the collected data.
Big data technology is developed for large-scale datasets – often so large conventional file handling is a problem due to the volume of data	Input data	ML is often applied to small datasets where over-fitting[31] is the problem.

[30] Computationally identifying opinions expressed in texts
[31] Overfitting means that a model is tuned so "specific" that new data will not be interpreted, analyzed and understood correct by the model.

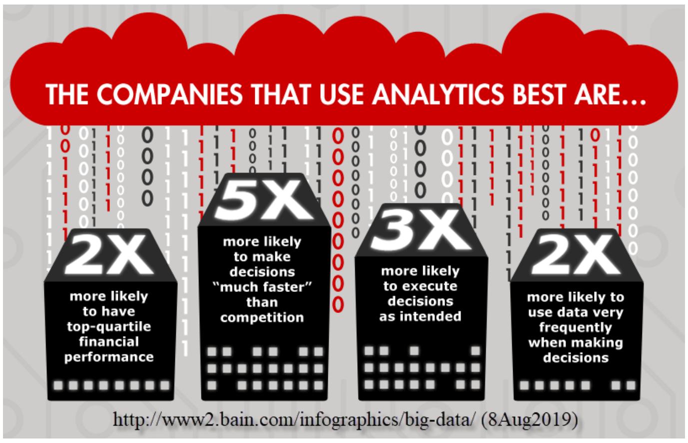
Big Data		Machine Learning (ML)
Purpose of big data is to store large volume of data and find out pattern in data. Business intelligence is made from a large quantity of collected raw data. These analyses can be utilized by organizations to increase their efficiency and take better decisions.	Application in business and industry	Machine learning systems can learn and improve from experience without being explicitly programmed. The tasks for Big data are typically classification, regression and clustering of data. Other applications are image processing, natural language processing, fraud detection, energy production and more.

Appendix F.1 Big data

When managing large and complex data sets in the scale of modern social media applications, conventional software and hardware are no longer viable. The size and variety of data that big data encompasses brings several challenges.

Appendix F.1.1 Introduction

The amount of data produced every year is increasing exponentially. Big data technology can make the information assist health care, crime prevention, research and many other fields. One of the drivers for big data systems is data analysis in business intelligence (BI). Investigating customer behavior is essential, see Appendix figure F-1.



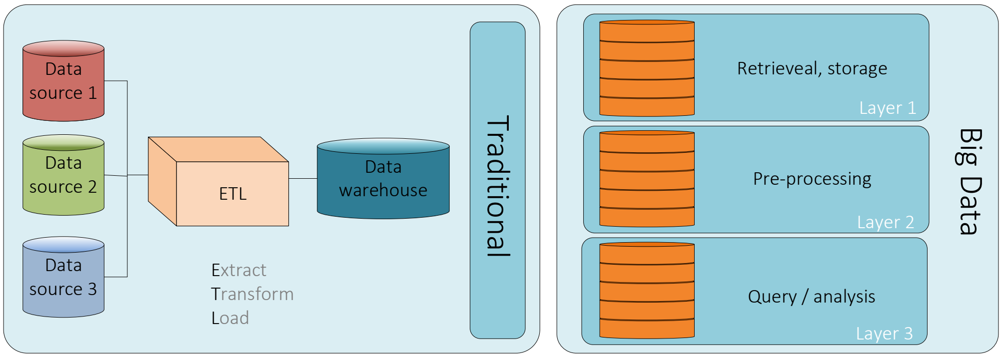
Appendix figure F-1 – Technology in Business Intelligence analyses can also be used in the oil and gas industry.

Appendix F.1.2 Processing of Big data

Many data sources are unstructured, e.g. combining Twitter, Facebook, emails, weather-forecast, news, etc., and need to be organized and stored such that they are easily available. Some of the key technologies in big data are related to those two topics: storing and querying/analysis of multiple large (streams of) data sets. These services rely on connectivity and computational power such as found in cloud-based services with applications such as Apache Hadoop, Microsoft HDInsight, NoSQL (non-SQL, name referring to database not limited to queries in SQL[32]), Hive, Sqoop, PolyBase, Big data in EXCEL and Presto.

[32] SQL - Structured Query Language is used to prepare and run operations in databases with structured data.

Traditional processing of queries follows the Extract, Transform, Load (ETL) process in data warehousing, see left picture in Appendix figure F-2. ETL Software helps in Data extraction, Data Transformation and Data Loading. The software is used to combine data from multiple sources into a single programming solution.



Appendix figure F-2 - Data processing.

(Enterprise) data warehousing (DW) are systems used for reporting and data analysis in business intelligence. DWs are central repositories of integrated data from one or more type of source or application (disparate formats).

Big data processing is typically done on large clusters of shared-nothing[33] servers. With the increased volume and sources of data, big data challenges include capturing data, data storage, data analysis, search, sharing, transfer, visualization, querying, updating and information privacy.

In Layer 1 and 2 in Appendix figure F-2, can maybe best be explained by one of the early big data tools: Apache Lucene, which is a full-text, downloadable search library. It can be used to analyze normal text for the purpose of developing an index. The terms in the texts are indexed in maps, i.e. Lucene "remembers" their location. When users are searching for these terms, the software knows all the locations where they are, enabling a fast and efficient search process compared to seeking for the term anew. More modern applications can work with more than text. An example is such as Hadoop that support applications and companies such as Yahoo, eBay, Amazon, Facebook, Twitter, LinkedIn and others.

For applications, scalability is important. A short intro to the significance of this term is as follows:

a) the ability of a computer application or product (hardware or software) to continue to function well when it (or its context) is changed in size or volume in order to meet a user need.
b) the ability of a computer application or product to be moved from a smaller to a larger operating system (and take full advantage of it)

Vertical scaling is limited by the fact that you can only get as big as the size of the server. Horizontal scaling affords the ability to scale wider to deal with traffic. It is the ability to connect multiple hardware or software entities, such as servers, so that they work as a single logical unit.

[33] Shared Nothing and traditional Shared Disk Architectures (SDA): SDAs are write-limited when multiple sources contribute (writes) – they must be coordinated. Shared Nothing Architectures are write limited since each node are in full control of its subset of data.

Appendix F.1.3 Big data application for petroleum

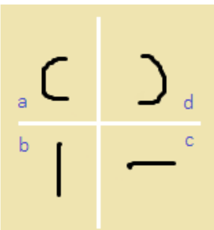
Operators have a vast amount of data in various forms. Limiting the scope to the context of this Thesis, i.e. relevant for planning, construction, intervention, integrity work and P&A of wells, mud logging data from drilling, formation logs, modelling of integrity (casing and tubing design), emails, contracts, rig activity reports, drilling, completion intervention programs, maintenance reports, etc. can all be gathered and analyzed using big data technology. The processing can follow the steps outlined in the right picture in Appendix figure F-2. Some of the possible queries are:

- Failure frequency of components
- Integrity issues cross matched with conditions like fluid composition and temperatures, etc.
- Performance of drilling rigs
- Performance of chemicals for stimulating reservoirs
- What causes the down time in different phases of operations
- What is the technical limit of projects and activities (i.e. hidden down time)
- What are the essential experiences (methods) that may save time to projects
- Etc.

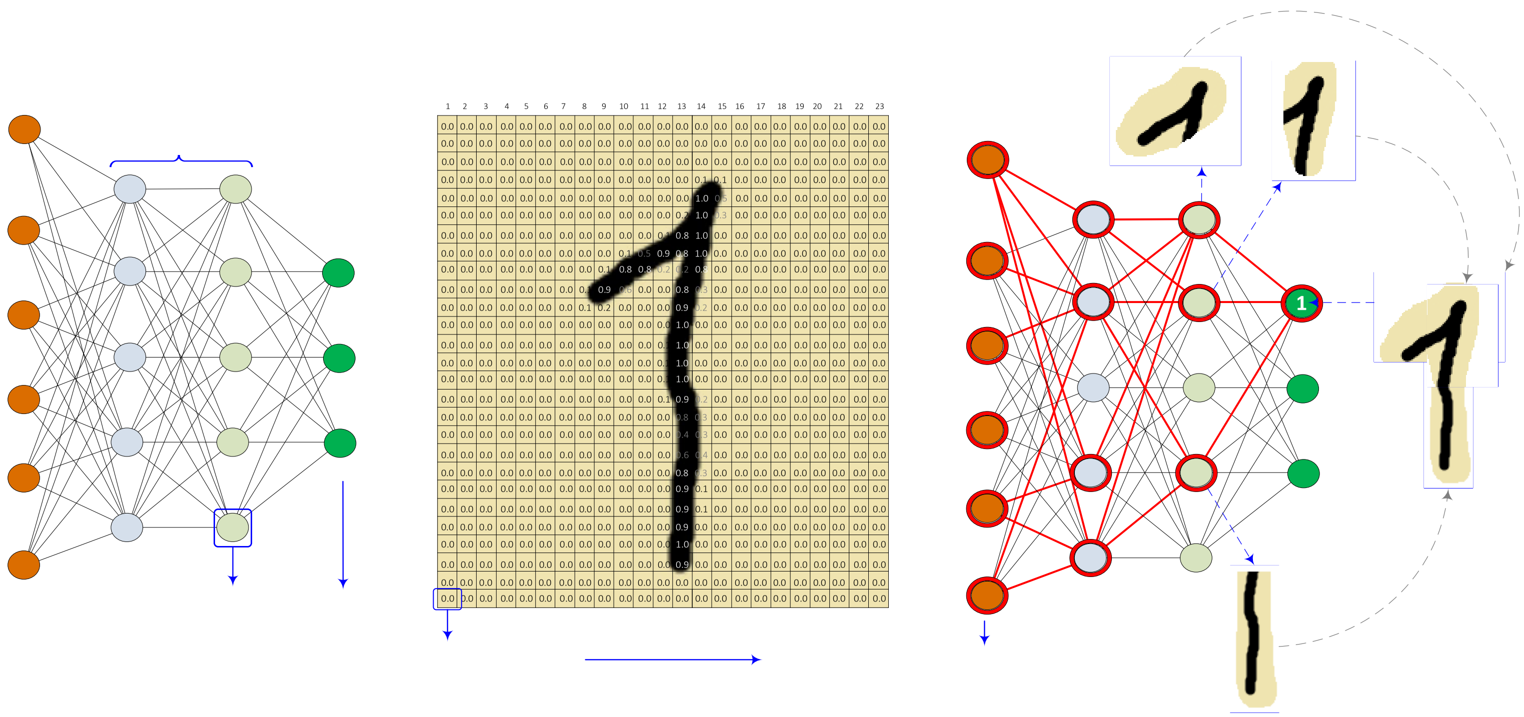
Basically, the answers to many questions that may bring or save value are in the data in ways that "big data" technology can unlock.
https://web.stanford.edu/class/cs102/lecturenotes/Overview102.pdf

Appendix F.2 Machine Learning

Machine learning (ML) is already manifest in many automated tasks and applications. Some areas where ML is applied are: image recognition, speech recognition, medical diagnosis, automated trading with security routines, BI: developing insights into the various associations between the products (consumer behavior), classification, prediction / probabilities, extracting structured information from the unstructured data (e.g. web pages, articles, blogs, business reports, emails, etc), and other fields. Explaining ML in layman's terms using an example of a Convolutional Neural Network (CNN), which are often used to analyze images. Appendix figure F-4 shows an artificial neural network (ANN) with 4 columns (layers).
Each neuron in the layer after the input layer applies the score from the shades of colors. E.g. should some neurons be trained to identify a combination of shades such as in Appendix figure F-3, multiple combinations of these can lead to identification of numbers. In this example, the score from the shades can be degree of brightness, changes from one color to another or another image property – see the numbers in each pixel in the image of the number "1" in Appendix figure F-3.

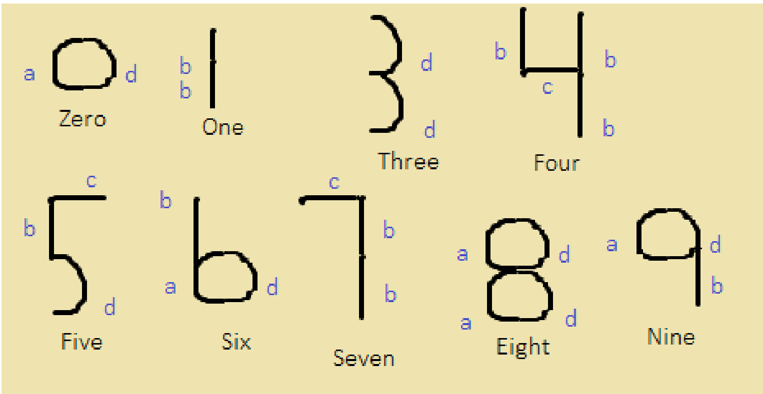


Appendix figure F-3 - Example of shades for recognition.



Appendix figure F-4 - Example of ANN structure with basic data processing.

The shades in the pixel grid are systematically read and the image is then analyzed using a mathematical process. Note that many terms and methods are "old school", but they are often used to give an introduction and build understanding of ML. Note also that the number of parameters (variables) in the example is not adjusted for matrix calculation which is central for ANNs.
One neuron can recognize the shade combination in Appendix figure F-3 a, another neuron can recognize the shades in Appendix figure F-3 b and another can recognize c, etc. The next layer can hold neurons that recognize some combinations of these recognized parts, see Appendix figure F-5, or exclude some combinations due to missing parts.



Appendix figure F-5 - Combination of recognized shades from the previous figure can be interpreted as numbers.

The connection between the neurons in the different layers are controlled by a function. Should a neuron in the first hidden layer be focused on identifying the circular part of numbers, it would give focus to neurons in the input layer holding shade combination in Appendix figure F-3 a and b, while giving less to shade combination in Appendix figure F-3 c and d.
In Appendix figure F-4, the input layer may hold 6 pieces of information i.e. shade combinations such as the 4 in Appendix figure F-3. The neurons dedicated recognition of circular parts of numbers will be activated by a function of the information held in the first neurons:

$$S = \alpha_0 + \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 \quad \{F\text{-}1\}$$

Where:

a_1 through a_6 are activations as given by the shades.

Say that neuron #1 and #2 are holding shade combination in Appendix figure F-3 a and b respectively, these will be given more weight than the rest:

$$S = \alpha_0 w_0 + \alpha_1 w_1 + \alpha_2 w_2 + \alpha_3 w_3 + \alpha_4 w_4 + \alpha_5 w_5 \quad \{F\text{-}2\}$$

Where:

w_1 through w_6 are weights of the activations, and w_1 and w_2 are higher than the rest in the example. Some weight may even be negative.

Often, the sum S in Eq. {F-2} would be set in a function to reduce the span of values to [0,1]. The Sigmoid function {F-3} is an example of this:

$$\sigma(S) = \frac{1}{1 + e^{-S}} \quad \{F\text{-}3\}$$

Should the input layer hold none of the curved parts in Appendix figure F-3, the neuron in the next layer should not be activated. To avoid activation, the sum S in Eq. {F-2} is give a fixed number, e.g. -5.

$$S = \alpha_0 w_0 + \alpha_1 w_1 + \alpha_2 w_2 + \alpha_3 w_3 + \alpha_4 w_4 + \alpha_5 w_5 + bias \qquad \text{\{F-4\}}$$

Where “bias” is the fixed number set to control the activation, in this example set to -5. Should the sum S not overcome the value 5, it means that the connection to this neuron will not be established. It can be said that the network is not confident that the identified piece of shading is not part of a recognizable number. Note that activation of the input layer can be different than the consecutive layers.
When learning the network in Appendix figure F-3 how to recognize numbers, known pictures of numbers are given to the input layer and the connections between the consecutive layers are adjusted until they perform accurate. These adjustments are done by changing the weights and biases for each connection. This is called “supervised learning”.

For neuron N1 in layer 2 in Appendix figure F-3, the activation can be denoted:

$$a_0^{(1)} = \sigma(a_0 w_0 + a_1 w_1 + a_2 w_2 + a_3 w_3 + a_4 w_4 + a_5 w_5 + b_0) \qquad \text{\{F-5\}}$$

For neuron N2 in layer 2 in Appendix figure F-4, the activation can be denoted:

$$a_1^{(1)} = \sigma(a_0 w_0 + a_1 w_1 + a_2 w_2 + a_3 w_3 + a_4 w_4 + a_5 w_5 + b_0) \qquad \text{\{F-6\}}$$

..and so on until the last of the neurons in layer 2 has an activation as expressed in {F-7}:

$$a_4^{(1)} = \sigma(a_0 w_0 + a_1 w_1 + a_2 w_2 + a_3 w_3 + a_4 w_4 + a_5 w_5 + b_0) \qquad \text{\{F-7\}}$$

All equations for activation of the neurons in layer 2 can be expressed in a matrix.

$$\begin{bmatrix} w_0^{(0)} & w_0^{(1)} & w_0^{(2)} & w_0^{(3)} & w_0^{(4)} & w_0^{(5)} \\ w_1^{(0)} & w_1^{(1)} & w_1^{(2)} & w_1^{(3)} & w_1^{(4)} & w_1^{(5)} \\ w_2^{(0)} & w_2^{(1)} & w_2^{(2)} & w_2^{(3)} & w_2^{(4)} & w_2^{(5)} \\ w_3^{(0)} & w_3^{(1)} & w_3^{(2)} & w_3^{(3)} & w_3^{(4)} & w_3^{(5)} \\ w_4^{(0)} & w_4^{(1)} & w_4^{(2)} & w_4^{(3)} & w_4^{(4)} & w_4^{(5)} \end{bmatrix} \begin{bmatrix} a_0^{(0)} \\ a_1^{(0)} \\ a_2^{(0)} \\ a_3^{(0)} \\ a_4^{(0)} \\ a_5^{(0)} \end{bmatrix} + \begin{bmatrix} b_0^{(1)} \\ b_1^{(1)} \\ b_2^{(1)} \\ b_3^{(1)} \\ b_4^{(1)} \\ b_5^{(1)} \end{bmatrix} = \begin{bmatrix} r_0^{(1)} \\ r_1^{(1)} \\ r_2^{(1)} \\ r_3^{(1)} \\ r_4^{(1)} \\ r_5^{(1)} \end{bmatrix} \qquad \text{\{F-8\}}$$

The handling of the values for non-existing neuron 5 in layer 2, marked in red in {F-8} will not be discussed further here. A visualization of this process can be seen in Appendix figure F-6.
The expression is often inserted in the Sigmoid function {F-3}, which results in {F-9}:

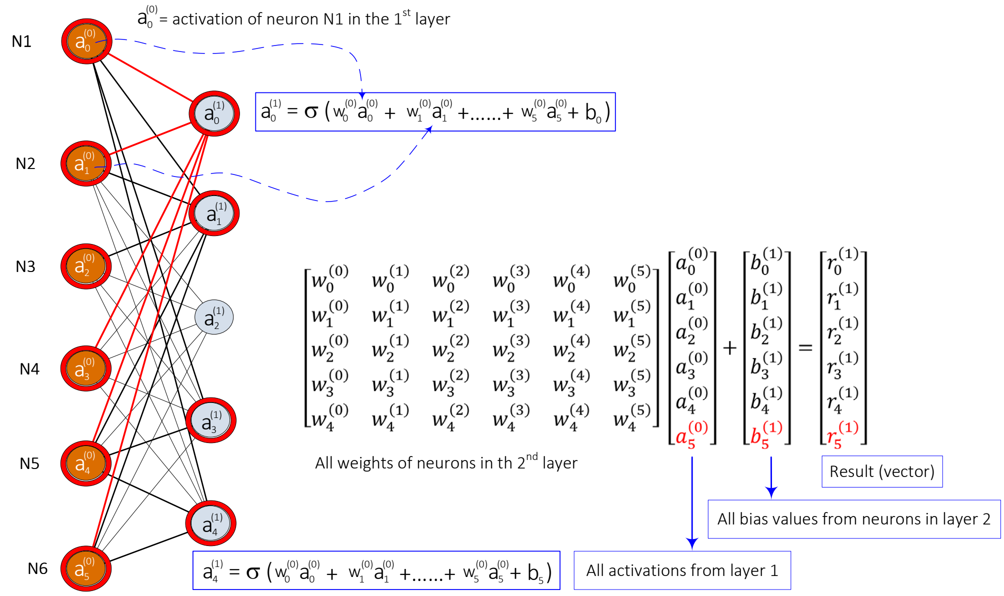
$$\sigma\left\{\begin{bmatrix} w_0^{(0)} & w_0^{(1)} & w_0^{(2)} & w_0^{(3)} & w_0^{(4)} & w_0^{(5)} \\ w_1^{(0)} & w_1^{(1)} & w_1^{(2)} & w_1^{(3)} & w_1^{(4)} & w_1^{(5)} \\ w_2^{(0)} & w_2^{(1)} & w_2^{(2)} & w_2^{(3)} & w_2^{(4)} & w_2^{(5)} \\ w_3^{(0)} & w_3^{(1)} & w_3^{(2)} & w_3^{(3)} & w_3^{(4)} & w_3^{(5)} \\ w_4^{(0)} & w_4^{(1)} & w_4^{(2)} & w_4^{(3)} & w_4^{(4)} & w_4^{(5)} \end{bmatrix} \begin{bmatrix} a_0^{(0)} \\ a_1^{(0)} \\ a_2^{(0)} \\ a_3^{(0)} \\ a_4^{(0)} \\ a_5^{(0)} \end{bmatrix} + \begin{bmatrix} b_0^{(1)} \\ b_1^{(1)} \\ b_2^{(1)} \\ b_3^{(1)} \\ b_4^{(1)} \\ b_5^{(1)} \end{bmatrix} = \begin{bmatrix} r_0^{(1)} \\ r_1^{(1)} \\ r_2^{(1)} \\ r_3^{(1)} \\ r_4^{(1)} \\ r_5^{(1)} \end{bmatrix}\right\} \qquad \text{\{F-9\}}$$

Note that the Sigmoid function should be applied to each of the resulting components of the resulting vector:

$$\begin{bmatrix} \sigma(r_0^{(1)}) \\ \sigma(r_1^{(1)}) \\ \sigma(r_2^{(1)}) \\ \sigma(r_3^{(1)}) \\ \sigma(r_4^{(1)}) \\ \sigma(r_5^{(1)}) \end{bmatrix} \quad \{F\text{-}10\}$$

A simplification of {F-9} can be expressed as {F-11}

$$a^{(1)} = \sigma\{wa^{(0)} + b\} \quad \{F\text{-}11\}$$



Appendix figure F-6 - Activation of neurons subsequent layer 1.

Appendix F.2.1 Training neural networks

Neural networks can be set up to train themselves to perform better. When reading an image with known content, the score in each neuron in the result layer is used in a so called “cost function”. Appendix figure F-7 outlines a full cycle of reading an image and the principle of training the network. The cost function is a measure of how the network is performing. A high value indicates that a considerable adjustment is in order, see example in the blue frame of the cost function in Appendix figure F-7.

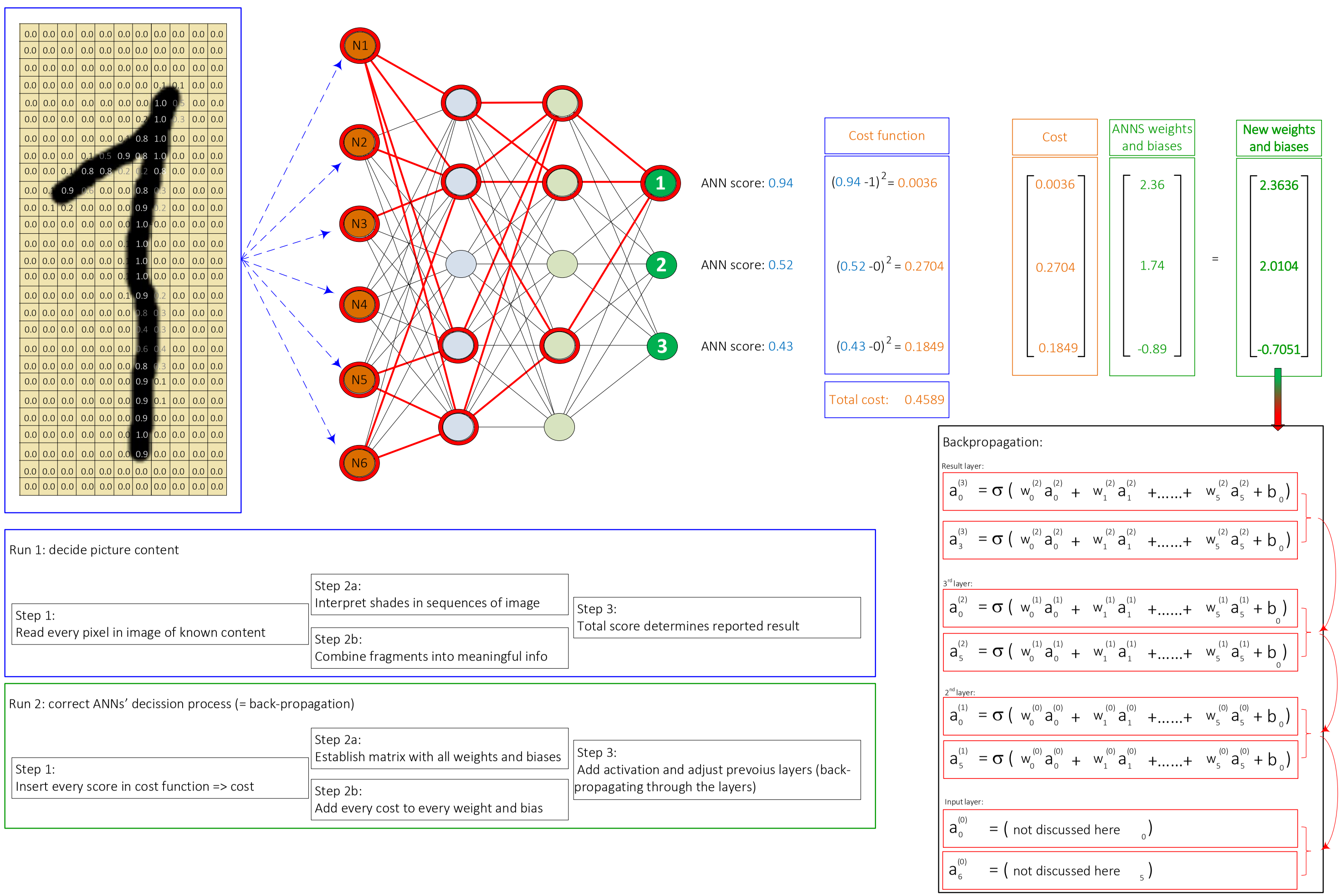
The learning process manipulates the variables in the network individually starting with the last layer and working backwards to the first, i.e. the input layer. All weights and biases are arranged in a single column matrix and corrected according to the cost as shown in Appendix

figure F-7. Training a network like this has shown that it can perform with more than 98% accuracy[34].
Every activation is a function that results in a score. Reducing this score is done by taking the derivative of the function, see dark green frame with new weights and biases in Appendix figure F-7. The earlier layers are also adjusted in a similar manner. The principal is shown schematically in the red frame in Appendix figure F-7, but the details in this technique will not be discussed here. Going back to the derivative of the functions, it should be mentioned that method is referred to as “gradient decent” due to the search / training to identify the functions which yields the smaller cost.

Appendix F.3 Endnote on Artificial Intelligence

The brief introduction and few examples of AI techniques were added for the benefit of the readers with less insight in the area. Hopefully, this addition made it easier to see where and how AI can contribute to the well construction and integrity routines. AI is already a part of our private lives through consumer behavior, banking, google searches and other. The work related to well construction and integrity may be improved in many ways by assistance of AI technology. For the generation with decades of experience, most will see smarter applications that are easier to work with and less administration. Some of the students coming out of the universities today will join the ranks of software development and be part of the teams developing these solutions based on cooperation with the experienced engineers. Smart solutions can lower both Capex and Opex.

[34] Michael A. Nielsen, "Neural Networks and Deep Learning", Determination Press, 2015. http://neuralnetworksanddeeplearning.com/ (link date: 18Aug2019).



Appendix figure F-7 - Full cycle reading and training a CNN.

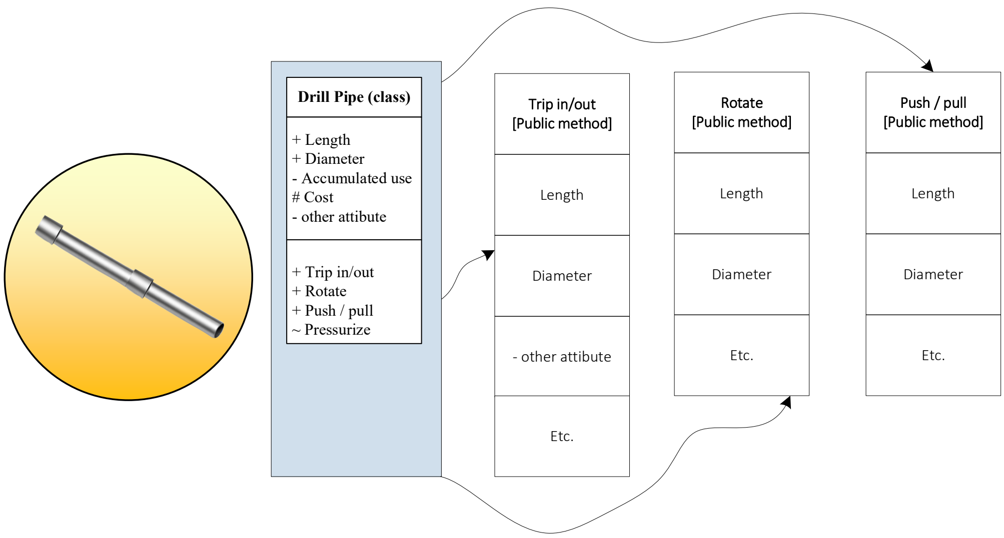
Appendix G Introduction to OOP

Developing a software often starts with mapping the functionality and architecture. This section is limited to give the reader an understanding of how the LCWIM can be mapped using the OOP technique. Appendix table G-1 shows some common nomenclature used to visualize software architecture.

Appendix table G-1 - Basic OOP visualization diagram.

Visibility (sharing)	Class	***Relationship***	
- Private (only locally know info, not shared)	- Attribute 1	Inheritance	Group attributes (age, weight, etc.)
+ Public (global info)	- Attribute 2		
# Protected info	- Attribute 3	Association	Simple relationship
~ Package (info shared in "group")	# Attribute 4		
	- Attribute 5	Aggregation	Can be part of Class, but don't have to be (independent)
Attribute:			
Data containing values describing instances of "Class"	- Method 1	Composition	Sub class / child that is gone if parent is gone
	+ Method 2		
Method:	+ Method 3		
Behavior of "Class"	~ Method 4		

An introduction to the typical OOP can be seen in Appendix figure G-1, connecting objects like drill-pipe and the methods, "trip in/out", "rotate", "push/pull".

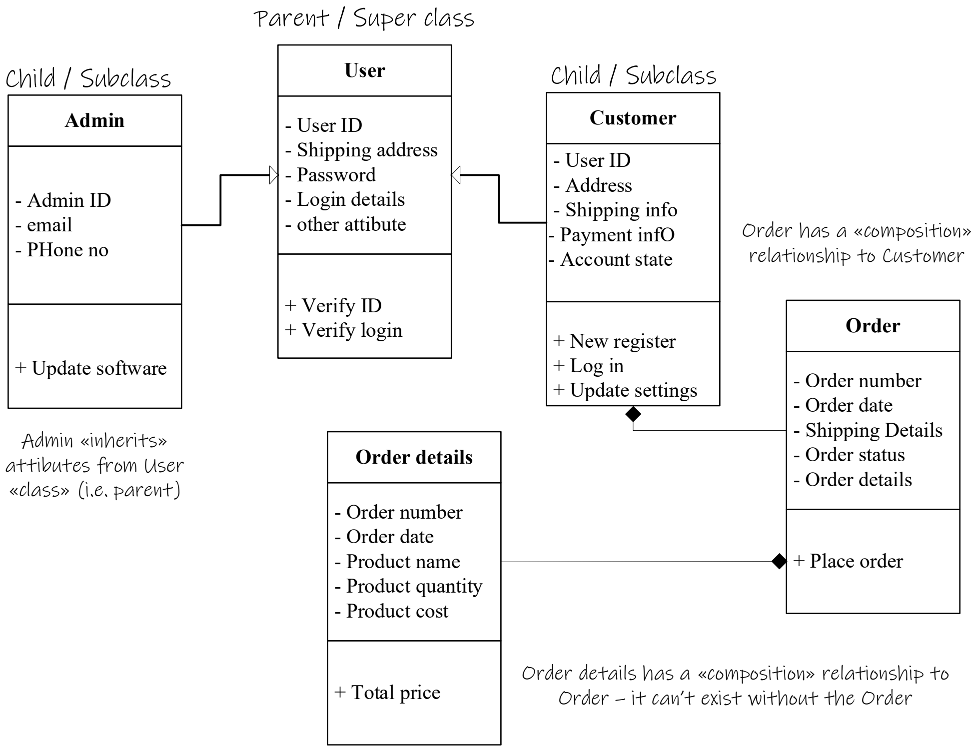


Appendix figure G-1 - Example of traditional Object-Oriented Programming (OOP) structure.

A few terms often used in OOP:

Abstraction => General class with specific sub-classes
Encapsulation => a program in a program (read / write access)
Inheritance => Group attributes (age, weight, etc.)
Polymorphism=> Reuse info – parent / child relationship
Association => Simple relationship (Otter east sea urchin)
Aggregation => Can be part of Class, but don't have to be (independent)
Composition => Sub class / child that is gone if parent is gone (house => bathroom),
Multiplicity => Numerical constraint on relationships (between classes / subclasses)

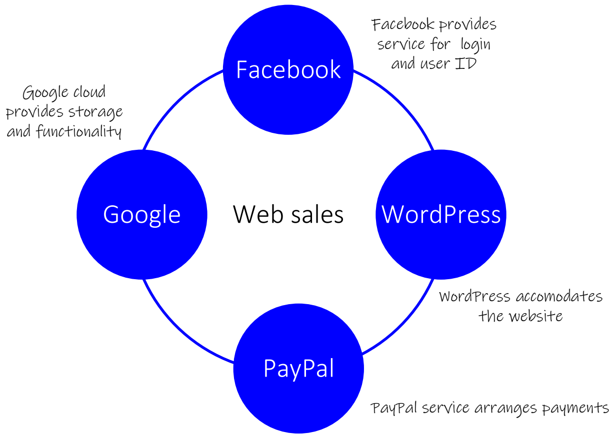
Appendix figure G-2 shows an OOP diagram of web shopping. Structuring the flow of information can enable a “clean” code where the information is reused where needed.



Appendix figure G-2 - OOP diagram for web shopping.

Appendix G.1 Introduction to SOA

The prototype under development is designed using Service Oriented Architecture (SOA) and Object-Oriented Programming techniques. Service oriented architecture can be described as a simplification of a complex process. Applications built using an SOA style deliver “services” that can be used and reused in a software. “Services” are building blocks that can be reused by other applications and part take in small or large and complex “business flows”. A “service” provides a discrete function that operates on data with consistent, predictable results and with the required quality. Following the example in Appendix figure G-2, the web sale can be simplified as shown in Appendix figure G-3. Each service is quite complex, something which is restricted to the service itself. Externally, the service has a modest interface and returns a simple response to a query. This is per definition “encapsulation”. I.e., the complexity of the service process is abstracted by encapsulation.



Appendix figure G-3 - SOA layout of web sales in previous example.

SOA can be used to describe and make micro and macro functionality. But the full capacity of SOA can be better seen in large complex corporate systems, design of urban environments and full-scale economies.

(intentionally left blank)

Appendix H Status of programmed applications

Below follows an overview of the applications developed as part of the research, see Appendix table H-1.

Appendix table H-1 - Readiness of applications, where engineering and administrative applications are in grey.

#	Prototype	State
1	Well paths	Partly ready (Algorithms sorted) Mapping system with conversion: programmed* Curvature calculations modelled**
2	T&D	Running prototype: programmed
3	Hydraulic	Running prototype: programmed
4	Tubular design	Partly ready: Casing design1: all load cases modelled Casing design2: collapse loads programmed Casing design3: burst loads - programmed Packer calculations: modelled Annular Fluid Expansion: modelled Buckling: programmed
5	Temperature model	Running prototype: programmed Need to add injectors (opposite direction)
6	Casing wear	Running prototype: programmed (advanced)
7	Gravel pack calcs	Running prototype: programmed
8	2D Frac	Running prototype: programmed
9	Cement bond limit	Running prototype: modelled (max pressure before de-bond)
10	Drilling optimizing	Running prototype: programmed
11	Well integrity	Running prototype: modelled (automated risk assessment)
12	Admin - reporting	Prototype modelled
13	Admin - contract	Form of contract: Prototype modelled
14	WOS	Loop 1: Programmed

* Programmed means that a running prototype exist.
** Modelled means that functionality is tested but programming is not complete.

WOS loop 1 is programmed (see Figure 3-11), but loop 2 (see Figure 3-22) is prepared only with few checks of functions. The first prototype of the WOS is therefore about 20% complete. Further development need support and funding of resources.