An Example of Feature Modeling Application: Smart Design for Well-Drilling Systems

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Abstract The reported effort is intended to develop a semi-automated, knowledge-based, and integrated petroleum well-drilling engineering design system, considering various aspects such as drill-string [40] and casing design models. The goal was to significantly increase the dynamic drilling engineering responsiveness to real field changes through the automation of conceptual design and 3D modeling processes. Built-in rules and knowledge are used to develop the conceptual design; the system then automatically generates the assembly configuration and retrieves part specifications from a data sheet to generate the CAD parameter files. These parameter files are used to further generate the full CAD model. The conceptual design and CAD models are integrated in such a way that any changes in the design can be reflected automatically throughout the system. Hopefully, this chapter serves not only as an example application for feature-based design, but also as a research reference for the energy industry to leverage modern informatics advancement for its efficiency and cost effectiveness.

1 Introduction

Traditional feature technology has been reviewed thoroughly in previous two chapters, i.e. "Introduction to Engineering Informatics" and "A Review of Data Representation of Product and Process Models". The effective use of feature technology varies considerably from industry to industry. This is due to both the nature of an industry's engineering process and the extent of new technology

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penetration into industrial practice. Kasravi [21] has pointed out that human expertise and knowledge are scarce, and that the need for knowledge embodiment within the geometric model is obvious. However, most 3D CAD software offer only simple geometric modeling functions and fail to provide users with sufficient design knowledge. Design knowledge embedded in a computer system is of great help in most engineering tasks. Therefore, the design of automatic and knowledge-based systems has been an active research topic for quite some time [25]. Zha et al. [48] have developed a knowledge-based expert design system for assembly-oriented design. Koo et al. [22] have constructed an expert paper-feeding mechanism design system, where the physical part of the paper-feeding mechanisms are represented as objects, and the design knowledge and constraints are represented by rules and object methods. The researchers did not extend the program to CAD application, however. Myung et al. [37] have proposed a design expert system to redesign assemblies of machine tools in a CAD environment. Roh and Lee [43] have created a hull structural modeling system for ship design, which was developed using C++ and was built on top of 3D CAD software.

Transferring knowledge-based engineering (KBE) intelligence to a CAD system presents a challenge because there is no readily available mechanism to enable such information flow, as identified by Ma et al. [27]. As introduced by Kasravi [21] preliminarily, parametric engineering uses the design requirements as the input data, and the parameters of the key features of the constituent components as the output. More recently, numerous industrial applications have been developed with feature technology; for example, Chu et al. [11] have constructed a parametric design system for 3D tire mold production. Lee et al. [24] have developed a parametric tool design system for cold forging using Autolisp. Researchers have commonly used parametric part templates to generate new 3D designs; changes are realized by setting values to the driving parameters [46]. Ma et al. [26] have considered the topological and configuration changes of parts.

Feature technology has been a cornerstone of engineering informatics since the 1990s. The abundant literature on feature technology shows its versatility in capturing, modeling, and deploying the best engineering practices in a number of industries. This chapter showcases an example of a typical feature technology application in a less common CAD application area: well-drilling system design for the oil and gas industry.

The research effort at the University of Alberta is intended to develop a semi-automated, knowledge-based, and integrated petroleum well-drilling engineering design system, considering various aspects such as drill-string [40] and casing design models. This proposed comprehensive and intelligent drilling design package is named “DrillSoft.” The goal is to significantly increase the dynamic drilling engineering responsiveness to real field changes through the automation of conceptual design and 3D modeling processes. Built-in rules and knowledge are used to develop the conceptual design; the system then automatically generates the assembly configuration and retrieves part specifications from a data sheet to generate the CAD parameter files. These parameter files are used to further generate the full CAD model. The conceptual design and CAD models are integrated in such a way that any changes in the design can be reflected automatically throughout the system. Such intelligent CAD design practice is new in the drilling industry.

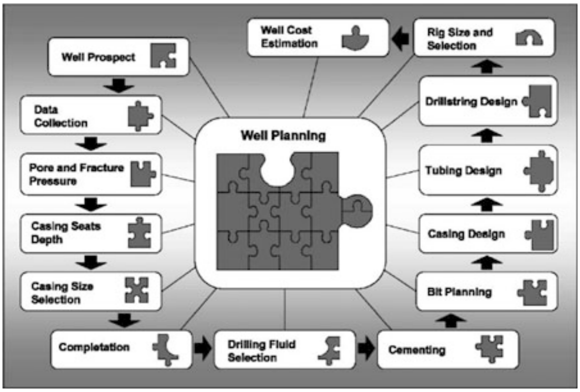
It is the authors' intention that this chapter serves not only as an example for feature-based engineering design, but also as a research reference for the energy industry to leverage modern informatics advancement for its efficiency and cost-effectiveness.

Naturally, intelligent computer tools supporting petroleum well-drilling design have attracted a lot of attention. As pointed out by Mattiello et al. [32], an accurate well and casing design can significantly reduce drilling costs and risks. A computer-aided support system for casing design and shoe depth selection has been reported [33] and was intended to improve the reliability of solutions, reduce total project time, and help reduce costs. However, their well casing design is still manual. Casing design is rigorous, time-consuming, and obsolescent; it is also error-prone due to the difference in the analytical computation of stresses and their graphical representation against depth [1]. The authors strongly believe that modern CAD technology can play a significant role in enhancing the consistency and efficiency of well-drilling design.

As evidenced by this body of research, the petroleum industry has been using knowledge bases and expert systems for decades; Hayes-Roth identified as early as 1987 that expert systems would play a dramatic role in the success of the outstanding performers in the petroleum industry [18]. Mabile et al. [28] developed an expert system that helps in formation recognition. Martinez et al. [31] constructed a directional drilling expert system for the use of advisory tools, which recommended changes in the bottom hole assembly (BHA). Kulakofsky et al. [23] proposed an expert slurry-design system (ESDS) in order to guide users in the selection process of cement slurry. Chiu et al. [9] implemented an expert system that can be used efficiently as a tool to advise engineers of the proper base fluids and additives to be selected for a given set of well conditions. Fear et al. [16] created an expert system for drill bit selection; their system uses a knowledge base of bit selection rules to produce a generic description of the most suitable bit for a particular set of drilling and geologic conditions. Their approach has several limitations; for example, the bit selection cannot demonstrate best use of past experience and relies too heavily on data that is conveniently available rather than the best fit for the purpose. Several case-based systems have also been reported [35, 36, 45]. Mendes et al. [35] developed a petroleum well design system capable of reusing previous designs which included considerations for potential failure in new designs. Shokouhi et al. [45] integrated real-time data with past experience to reduce operational problems. Al-Yami et al. [2] developed a software tool to guide drilling engineers in formulating effective cement slurries for entire well sections.

This work studies well-drilling planning and design applications with an automatic and generative approach. The first step in well-drilling is to plan the well. Current well-planning practice is usually done section by section with limited help from computer-based tools. Well-drilling planning has to follow a systematic approach. It involves several stages, as shown in Fig. 1. The planning tasks at different stages depend on one or more other stages; for example, casing selection

Fig. 1 Well-drilling planning stages [36]



requires input of casing setting depth and casing size. Therefore, the planning stages are commonly developed concurrently and interactively by a team of experts. A great deal of specialized knowledge is required to achieve a safe and economical design. Although many drilling software tools are available on the market to assist the planning team, most of them are standalone and support only one or two stages of the planning process.

One critical application of expert systems in the drilling industry is the design of casing strings, as identified by Heinze [19], who constructed an expert system to design the casing and hydraulic system of a drilling well. Jellison et al. [20] proposed a rule-based expert system for casing design, but casing setting depth was not included in their model. Wajtanowicz and Maidla [47] proposed an optimization program for minimum-cost casing design. This method was, however, unable to handle complex load conditions. Roque et al. [44] have developed an optimized methodology and an algorithm to minimize the cost of combined casing design for complex loading conditions. Unfortunately, the researchers separated the load calculation from the optimization model, and as a result sacrificed the efficiency of the overall design process. In addition, their system required many hours to complete a single string design. A solution to this problem was attempted by Halal et al. [17], who proposed a minimum-cost casing design technique that employed a recursive branch-and-bound search method together with a streamlined load generator for complex loading conditions. Their technique designed the casing string quickly, but their system did not include casing setting depth. Rabia [39] pointed out that not every company has unlimited access to all grades and types of available casings; he argued that cost calculations come into play after the grades and weights are selected. Akpan [1] created a computer program for selecting casing design using a graphical method, but his program does not automatically select the casing; instead, each casing has to be chosen by the user and fed to the system manually for evaluation.

As can be seen in the literature, to date most of the existing drilling software tools are standalone. Those reviewed computer systems suffer from a common shortcoming, i.e. the software packages require a tedious setup process to run for each analysis or generation cycle, and the solution development process is geared toward experienced users, hence the limited popularity of such applications. From the author's point of view, the knowledge modules implemented in such packages are not adaptive enough to new input from real situations in the field. The need for a comprehensive casing design program still exists. A properly developed well-drilling program can improve design cycle time and reliability while reducing the total cost.

With the advancement of information technologies, an integrated and comprehensive well-drilling engineering system is now feasible, because data sharing and constraint management can be carried out in a coherent manner with sophisticated new methodologies [26, 27]. As will be described below, an integrated computer software package, "DrillSoft," has been designed at the University of Alberta to meet this objective. The package currently consists of three modules: casing design, drill-string design, and operational parameter optimization.

By using a feature-based approach, the system under research is also integrated with CAD software to parametrically model the 3D well structure and drill-string. To the best of the author's knowledge, there is no such software solution that integrates well planning with 3D CAD modeling. The overall objective of this project is the integration of well-drilling planning with automatic model generation.

2 Research Approach

Knowledge-based engineering is commonly applied in capturing and structuring reusable engineering cases to create and enhance solutions for a product during its entire life cycle [11]. Knowledge bases can exist in many forms, such as spreadsheets, handbooks, engineering formulas, drawings, and documents. The current research at the University of Alberta is aimed toward developing a generic and parametric drilling system driven by knowledge-based rules and constraints, which can be reused repeatedly. At the current stage of the research, this system can now produce the conceptual design and further generate the parametric 3D models of the well casings and the drill-string. Unlike the efforts using CAD templates, which require part libraries and are difficult to manage, this research uses a generative approach to program generic drill-string models. There are many advantages of using a generative approach instead of template files, including: geometry and features can be easily created and edited, parameters can be created and manipulated in a more controlled manner, geometry analysis and part standardization can be easily achieved, files can be managed more efficiently, and finally, data access and family parts creation are more convenient.

To develop the target knowledge-driven system for well-drilling system design, feature technology has been employed, and the software has been prototyped. It considers the geological input, such as pore pressure or overburden, to generate a step-by-step interactive drilling plan. The implemented well-planning stages include the casing setting depth, casing and hole size determination, casing selection, and finally drill-string design and modeling. The system is integrated with a feature-based CAD system for generating 3D parametric models. An operational parameter module is developed in the system to predict the drilling coefficients and to minimize the drilling cost per foot by using offset well data, determining the optimum WOB, and optimizing the drill-string rotation speed for a single bit run. Based on this approach, an integrated well-planning system can be fully developed and will be very useful for the decision making of drilling companies.

3 Well-Drilling System Design Principles and Processes

Well-drilling planning is a systematic and team-based process. Achieving a safe and economical design requires a great deal of specialized knowledge. Although drilling software is widely available on the market to assist planning teams, data integration and information exchange still cause serious inefficiencies in response to application conditions and low-quality output models.

3.1 Well Casing Design

A casing is a collection of steel tubes that becomes a permanent part of an oil or gas well. A well consists of several sections of holes of different diameters, and a string of casing is run after each section of hole has been drilled. Casing serves many important functions during the life of a well. The major functions of the casing are as follows [8, 32]:

- Maintaining the structural integrity of the bore hole;
- Serving as a high-strength flow conduit to surface for both drilling and production fluids;
- Providing support for wellhead equipment and blowout preventers;
- Preventing contamination of nearby fresh water zones;
- Facilitating the running of wireline equipment up and down for testing;
- Allowing isolated communication with selectively perforated formation(s) of interest.

At nearly 20 % of overall well cost, casing design engineering for well-drilling represents a significant amount of well expenditure [44]. A small reduction in cost will therefore result in huge savings. But just as importantly, the casing design solution should satisfy all the constraint and loading requirements. The casing design module starts with casing setting depth determination, which is the most critical step in casing design. Many parameters must be considered, including pore pressure, fracture pressure, geophysical conditions in the area, bore hole stability problems, corrosive zones, environmental considerations, regulations, and company policies.

Among the input parameters, pore pressure and fracture pressure are the most widely used to determine the setting depth. The rocks inside the earth contain pore spaces, which are filled with fluids in the form of either gas or liquids. These trapped fluids cause the rock wall to experience a pressure known as *formation pore pressure*.

There are two different methods used to determine the formation pore pressure: the geophysical method and the logging method. The geophysical method helps to predict the formation pore pressure before the well is drilled, while the logging method is applicable after the well has been drilled. In this study, *pore pressure* is considered to be an input, while *fracture pressure* is the pressure at which a formation matrix opens to admit hole liquid through an actual crack in the matrix of the rock, as opposed to invasion through the natural porosity of the rock [8].

Two methods are used to determine the fracture pressure: direct and indirect. There is only one direct method: fracture pressure required to fracture the rock or to propagate the resulting fracture can be determined directly by stress analysis so as to predict the fracture gradient. On the other hand, there are three different indirect methods: Hubber and Willis's method [30], Matthews and Kelly's [4], and Eaton's [14]. As a modified version of the Hubber and Willis method, the Eaton method has gained wide acceptance. Eaton suggested that Poisson's ratio for a given field should be fairly constant and can be determined from the data obtained from the nearby well. In this prototyped software tool, Poisson's ratio is considered to be a user input, and the Eaton method is used to determine the fracture gradient of the prospective well.

$$FG = (v/1 - v)\left(\sigma_v - P_f\right)/D + P_f/D \tag{1}$$

here,

FG	Fracture gradient;
D	Depth, ft;
υ	Poisson's ratio;
σ_v	Over-burden, psi/ft; and
P_f	Formation pore pressure, psi/ft.

In the process of determining the well casing settings, two more safety factors related to downhole pressures have to be considered: trip margin and kick margin. They are considered during mud density determination according to the following two rules: the mud density should be slightly higher than the formation pressure (trip margin); and the mud density should be lower than the fracture pressure (kick margin).

Trip margin allows the mud density to be slightly higher than the formation pore pressure and eliminates the negative surge effect. A negative surge pressure is produced during tripping of the pipe. When making a trip the pipe is pulled upward, and due to this pulling action a negative pressure is created inside the hole; this results in a reduction of hydrostatic pressure. This phenomenon is known as the negative surge effect. Conversely, in order to eliminate the positive surge effect, another safety factor, the kick margin, is considered. When the drill-string is put back into the hole, a positive surge pressure is produced. If the pressure is more than the fracture pressure of the well, the stability of the well will be compromised.

After calculating the casing setting depth, the second step of the casing design cycle is casing size determination. Usually a well consists of several sections; it is an important task to determine the bore hole and casing size in each section. The following rules should be considered during casing size determination [8]:

- The bore hole must be large enough for the casing to pass freely with little chance of getting stuck;
- There should be enough clearance around the casing to allow for a good cement job; and
- The hole should be minimized because the bigger the bore hole, the more costly it is to drill.

The third step of the casing design cycle is casing selection. Devereux [12] identified two important aspects of casing selection: the casing strength to resist the forces that are imposed on it during drilling and its reliability throughout the life of the well without requiring a workover. Three basic loads are considered: collapse load, burst load, and axial load. *Collapse load* can be defined as differential pressure load between the external and internal pressures when the external pressure exceeds the internal pressure and causes the casing to collapse. During the design process, worst-case scenarios are considered. When the collapse load is calculated, for example, the minimum internal pressure and the maximum external pressure are both considered. A safety margin is also included. *Burst load* is defined by the difference between the internal and external pressure when the internal pressure exceeds the external pressure and causes the casing to rupture or burst. *Axial load* is the cumulative tension or compression load caused by gravitational and frictional forces on the pipe. As mentioned earlier, a well has several sections and casing design is required for each of them.

During casing selection, the engineer first calculates collapse and burst loads and sets their values as constraints. Depending on the type of casing section, the engineer selects the appropriate rules from the rule base for load calculation. For example, the collapse load calculation for surface and intermediate casings are not the same, so different procedures have to be followed. Next, the engineer checks whether the available casings are capable of meeting the total depth. If not, the engineer asks for more casings. The engineer then determines the allowable length for each available casing based on collapse and burst ratings. Once the casing selection has been made, the next step is to check whether the selected casing is capable of sustaining the axial load. After the conceptual design of the casing is completed, a formal report has to be developed.

3.2 Drill-String Design

Oil well drill-string design is another major task in drilling engineering that requires geological information input and, informed by knowledge and experience, is carried out upfront. A drill-string is a collection of drill pipes, drill collars, heavyweight drill pipe, crossover sub, and bit sub that transmits drilling fluid and rotational power to the drill bit. Drilling pipes connected by drilling collars and crossover subs form hollow shafts through which drilling fluid can be pumped down, and the fluid and cutting (such as the produced drilling mud with rock chips) can be brought back to the surface through the annulus.

According to Chuna [10], drill-string design is the most important part of operations in drilling engineering. It is the responsibility of the drilling engineer to design a system suitable for varying field conditions. The success of a drilling job is very much dependent on the design of the drill-string. In order to reduce the risk of drill-string failure, the design should be justified beforehand by simulation or finite element analysis. Austin [5] has argued that a 3D model can provide closer links between geoscientists and reservoir engineers, while promoting the integration as well as the interaction of the two. Although it has long been clear that 3D well-design models, especially the drill-string model, will be quite useful in simulation and finite element analysis (FEA) [34] to predict the behavior of the well, it is cumbersome to develop repetitive 3D models for each section of the well in order to perform such analyses. At present, analytical models, or rough FEA for the whole drill-string, are used to compute torque and drag.

3.3 Drilling Optimization via Operational Parameters

The design of a well program must satisfy all the technical considerations. Considering only the normal design aspect of drilling tools may not result in the most economical design; operational parameters must also be considered. Drilling optimization can be carried out by selecting the best combination of drilling parameters. Drilling parameters are divided into two groups: alterable and unalterable. Alterable drilling parameters, or *variables*, are related to mud, hydraulics, bit type, WOB, and rotary speed. Unalterable parameters, or *conditional parameters*, are weather, location, depth, rig condition, and so on. A comprehensive drilling optimization program has been one of the most important research areas in drilling engineering since the 1960s.

Several researchers have developed algorithms, models, and programs to optimize drilling performance by maximizing the rate of penetration (ROP) and minimizing the cost per foot. Bourgoyne et al. [7] constructed a comprehensive drilling model to calculate formation pore pressure, optimum weight of bit (WOB), rotary speed, and jet bit hydraulics, and also provided a multiple regression approach to determine the drilling coefficients in order to calibrate the drilling model with different field conditions. Maidla et al. [29] used a computer program to select drill bit, WOB, and rotary speed. Bjornsson et al. [6] proposed a rule-based bit selection expert system by employing the mechanical specific energy (MSE) concept. Their system aimed to increase the ROP and bit life and significantly reduce drilling time. Dupriest and Koederitz [13] effectively used the MSE concept in evaluating the drilling efficiency of bits in real time. Rashidi et al. [42] used both MSE and inverted ROP models to develop a method for evaluating real-time bit wear; the method can be useful in assisting the field engineer in deciding when to pull the bit. Eren et al. [15] constructed a real-time optimization model for drilling parameters.

4 Proposed Software System Structure

This section investigates an integrated and comprehensive system for well design: the computer program DrillSoft. The program is intended and prototyped to address the difficulty of manual management of a complete drilling plan. Figure 2 shows DrillSoft's various modules. The program consists of two functional modules: casing design and drill-string design. Another parameter determination module, the drilling coefficient calculator, is designed to work out those commonly used engineering coefficients related to real application conditions. This module serves as a central engineering data sharing block among various functional modules.

For implementing engineering rules and calculations, the Microsoft Visual Basic application in Excel was used. Siemens NX6 was used for CAD modeling with its "Open C" application programming interfaces (APIs). The concept is to make full use of the capability of CAD API functions that can be called within an object-oriented system environment to generate standard component and assembly models. The CAD API functions can also integrate CAD functions with Excel application programs. Figure 3 shows the main user interface.

4.1 Casing Design Module

As shown in Fig. 3, DrillSoft first takes input from the user. The following inputs are required: type of well, unit system, pore pressures at various depths, kick margin, and trip margin. Pore pressure and fracture pressure are the main determinants for casing setting depth and size calculation, as shown in Fig. 4.

The design software tool contains a rule base to calculate collapse, burst, and axial load. Every company has its own set of standards to calculate these loads during casing design, using flexible software that can be adapted according to need. This flexibility can be achieved by adding new rules to the Excel model used in this work. A casing selection process flowchart is shown in Fig. 5.

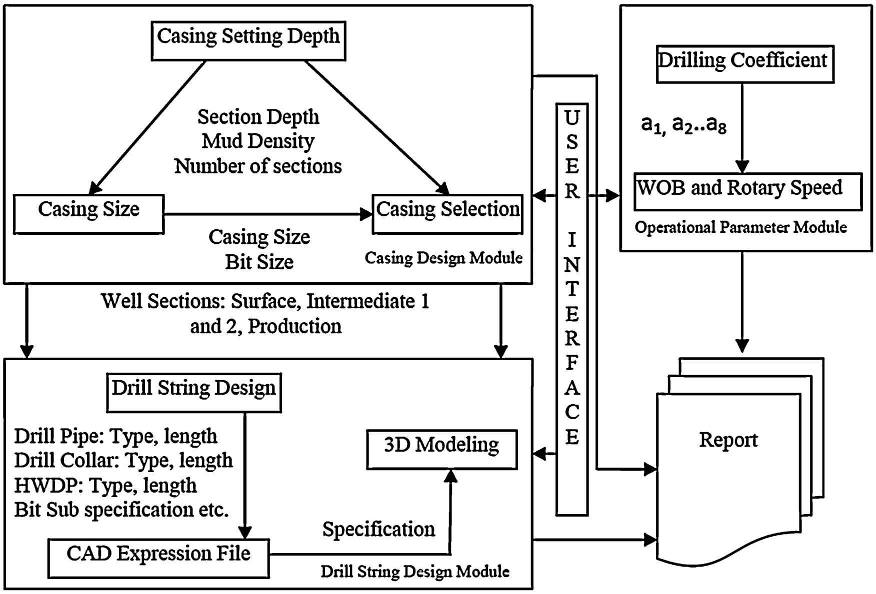
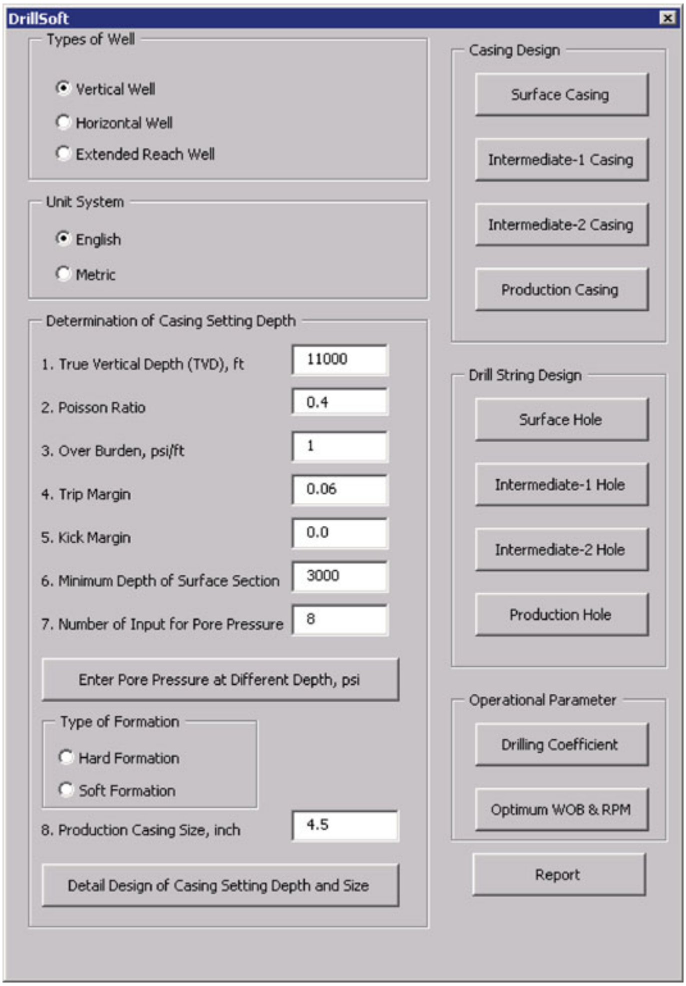


Fig. 2 DrillSoft modules

Depending on the type of casing section, the software selects the appropriate rules from the rule base for load calculation. The system identifies which rules are to be applied by considering the type of section. After determining the collapse and burst rating, DrillSoft checks whether the available casings are capable of meeting the total depth. If the available casings do not meet whole depth, then the software module asks to provide more casings. Once it finds that the total depth is achievable with these casings, the program then determines the allowable length for each available casing based on collapse and burst rating. The allowable length is used as break points for the algorithm.

The potential candidates are those types of casings that can be used safely in the concerned depth interval. It is assumed that the available casing input is provided sequentially, moving from those with the lowest cost to highest costs. DrillSoft selects the lowest-cost casing type (and thus the most economical) from the potential candidates and adds a length equal to the minimum casing section. The minimum casing section is a key factor in this algorithm, as it limits the number of different types of casing used in a combined casing string. Byrom [8] suggests that this minimum casing section length should not be less than 500 ft. The system selects the first casing type and adds a length equal to the minimum casing section length. The next step is to check whether the casing string achieves the total depth. If the total depth has not yet been achieved, the program chooses again the lowest-cost casing type from the available candidates. If the candidate selected in that stage is similar to the previous casing type, the system works out the remaining



● Vertical Well
○ Horizontal Well
○ Extended Reach Well

● English
○ Metric

1. True Vertical Depth (TVD), ft 11000
2. Poisson Ratio 0.4
3. Over Burden, psi/ft 1
4. Trip Margin 0.06
5. Kick Margin 0.0
6. Minimum Depth of Surface Section 3000
7. Number of Input for Pore Pressure 8

○ Hard Formation
○ Soft Formation

8. Production Casing Size, inch 4.5

Fig. 3 DrillSoft's main user interface

depth range by using the next break point minus casing covered, and chooses the smaller value between the minimum casing section and the remaining range.

Next, DrillSoft takes the resulting depth value and adds it to the casing length. Then it checks again whether the casing string can support the total depth. If it does not achieve the total depth, the casing selection process continues until the whole depth has been achieved.

After the casing selection, the axial load is checked. A rule base is used to calculate the axial load of each section of casing. If any portion of the casing string fails to satisfy the axial load condition, the casing selection starts again from the beginning. If the axial load with the designed casing is satisfactory, the conceptual design of the casing is complete. This conceptual design will be stored in a data sheet

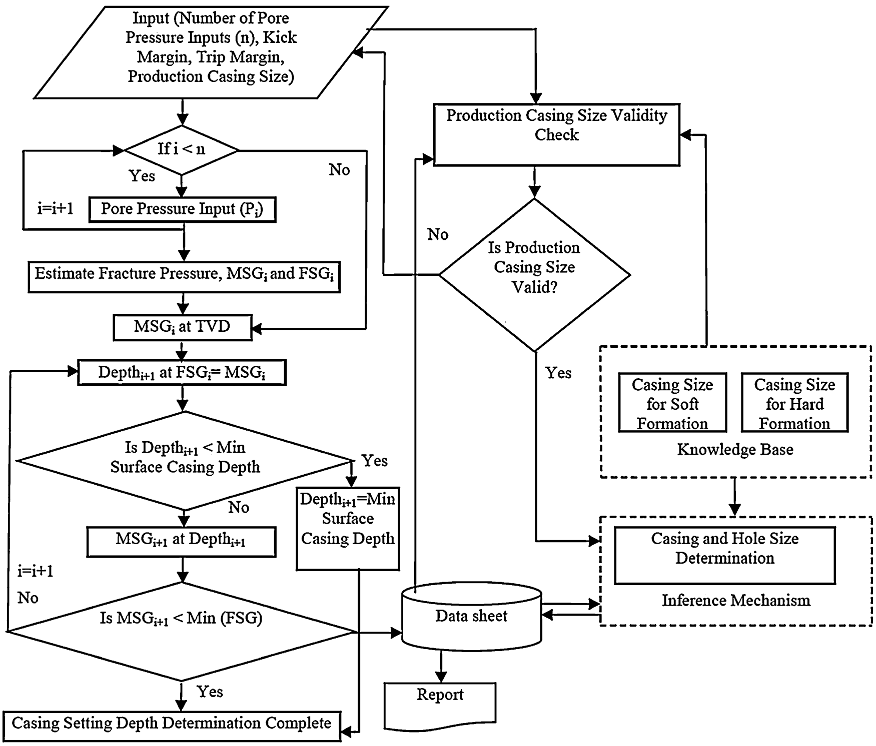


Fig. 4 Flowchart for determining casing setting depth and size

and can be further used by other modules. At the end of casing design, a formal report is generated. This process can be repeated for other sections of the hole.

4.2 Drill-String Design Module

The success of a drilling job is very much dependent on the design of the drill-string. It is a well-known fact that drill-string failure represents one of the major causes of “fishing” operations that likely lead to millions of dollars in loss for the industry. It is therefore crucial to validate the design beforehand by doing FEA or simulation. In addition, a 3D drill-string model will be very helpful in carrying out such analyses.

The DrillSoft program is connected to a CAD system. A knowledge-driven CAD modeling approach has been followed. To eliminate repetitive modeling tasks, a parametric and smart oil well drill-string) module has been prototyped, which enables generation of 3D models with built-in engineering rules, constraints, and controls on various application cases with changing situations

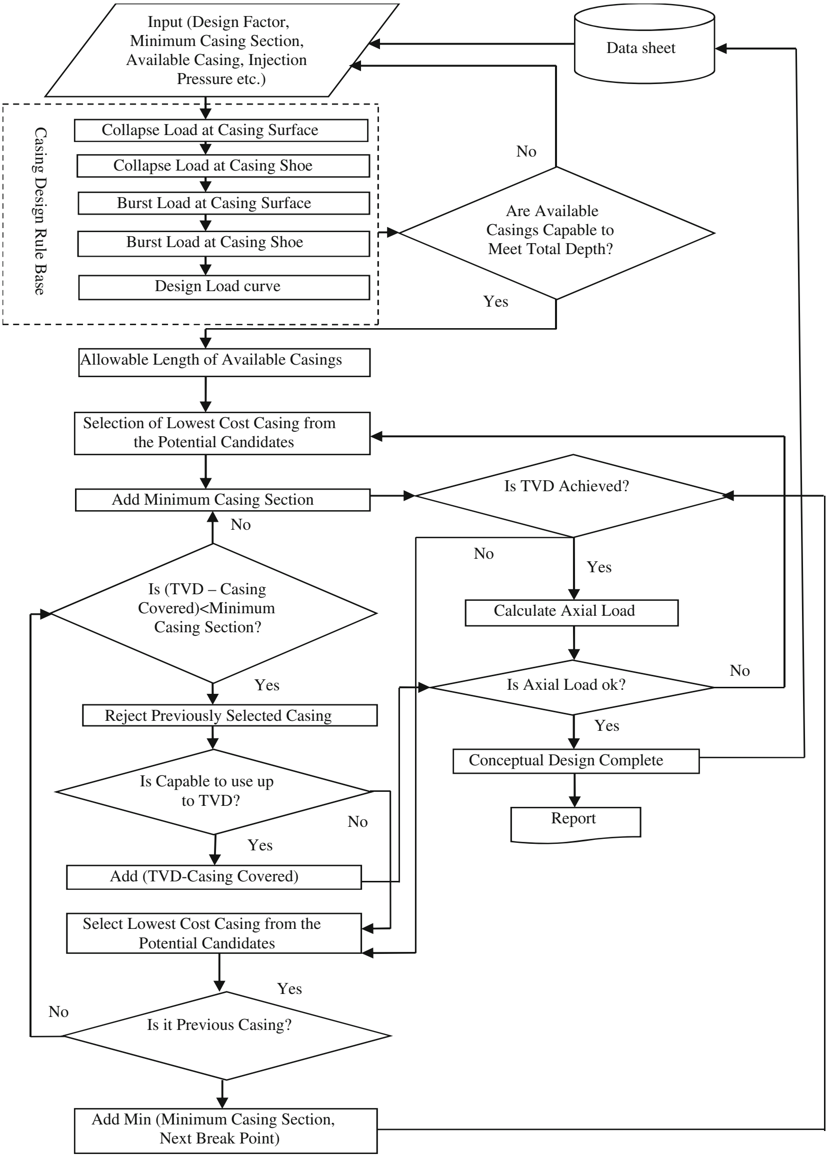


Fig. 5 Flowchart of casing selection

throughout a well-drilling life cycle. A common part data sheet has been integrated into the system so that standard parts can be reused from a well-defined library. Figure 6 shows the steps of the drill-string design process, from conceptual design to 3D model realization.

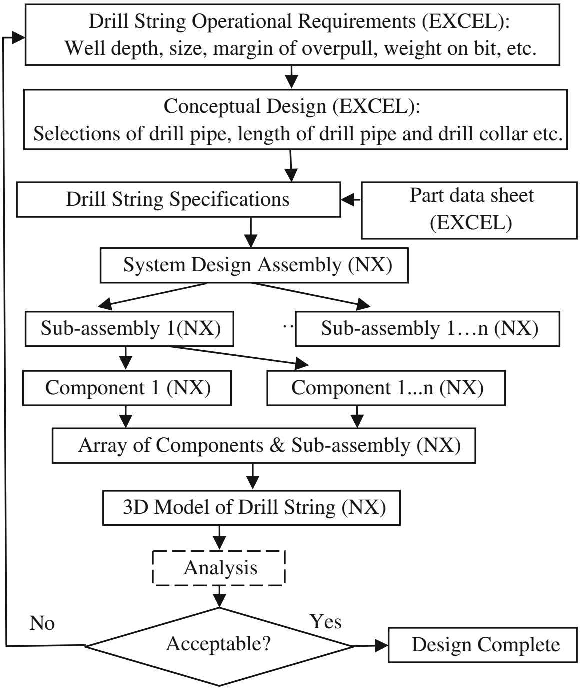


Fig. 6 Drill-string design module

Drill-string design begins after the operational requirements have been defined based on the casing design output and customer input. The operational requirements include type of the well, depth, mud-specific gravity, maximum WOB, margin of over pull, safety factors for collapse, type of drill pipe available in the inventory, drill collar, and heavyweight drill pipe size.

The drill-string design module of the DrillSoft system generates the conceptual design based on a set of built-in engineering rules embedded in the module that follow the recommended practice for drill-stem design standards [3]. One such rule is that the “drill pipe should always be under effective tensile stress; neutral point of buckling should be in the drill collar.” In the conceptual design stage, calculating the length of the drill collar requires WOB data. The system then selects the cheapest (in most of the cases also the weakest) drill pipe type from the available inventory and checks it against the load criteria. If the type is not safe to run the whole length of the drill-string, the allowed maximum length of that drill pipe type is worked out. The drill pipe selection cycle continues until the whole length of the drill-string is achieved. Hence, the algorithm selects the cheapest drill-string assembly based on the lowest grade and the unit weight of the pipes in the inventory.

Once the conceptual design of the drill-string is complete, the next step is to determine the drill-string component specifications and configurations. The configuration design determines the number and types of components and their orientation and position in the drill-string assembly. As the drill-string is a vertical column, all components of the string possess the same origin for the x and y coordinates, i.e., (0, 0). Only the vertical coordinate changes when a new part is added to the assembly. Rules have been created to determine the origin or position of a new component. The following rule determines the z-coordinate of the drill pipe:

$$Origin\ (z - coordinate)\ of\ Drill\ pipe = HWDP\_o + Drill\_collar\_o + Bit\_sub\_o + Drill\_bit\_o$$

here,

HWDP_o,	Number of HWDP*Length of HWDP + Origin *(z-coordinate)*
Drill_collar_o,	*Number of Drill_collar * Length of Drill_collar + Origin (z-coordinate),*
Bit_sub_o,	*Origin (z-coordinate),*
Drill_bit_o,	*Origin (z-coordinate).*

The positions of other components are similarly determined. A part data sheet prototype has been developed, containing the geometric and non-geometric specifications of each component. For example, a drill pipe has length, outer diameter (OD) , inner diameter (ID) and tool-joint diameter, upset diameter, and so on. Figure 7 shows a drill pipe sub-assembly with its components.

Figure 8 shows part of the drill pipe data sheet prototype. In this data sheet, each drill pipe is defined by six unique factors: size, class, nominal weight, grade, type of upset, and connection. The values of these six factors must be provided, but the specification generation method will retrieve the rest of the specifications from the data sheet that requires generation of the 3D model.

The system automatically retrieves the necessary data according to the library specifications of each component, and generates the 3D CAD model as well as a

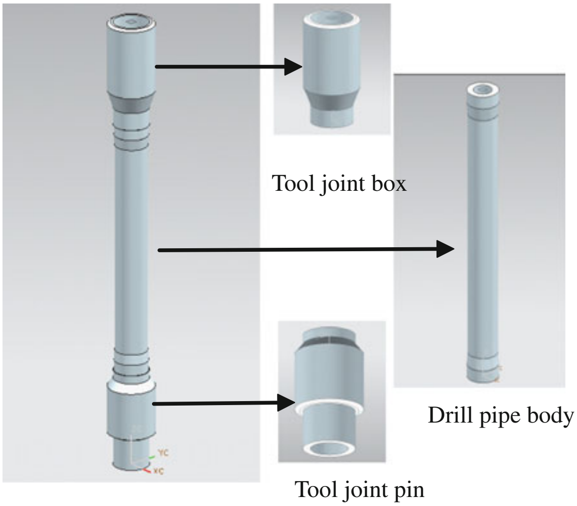
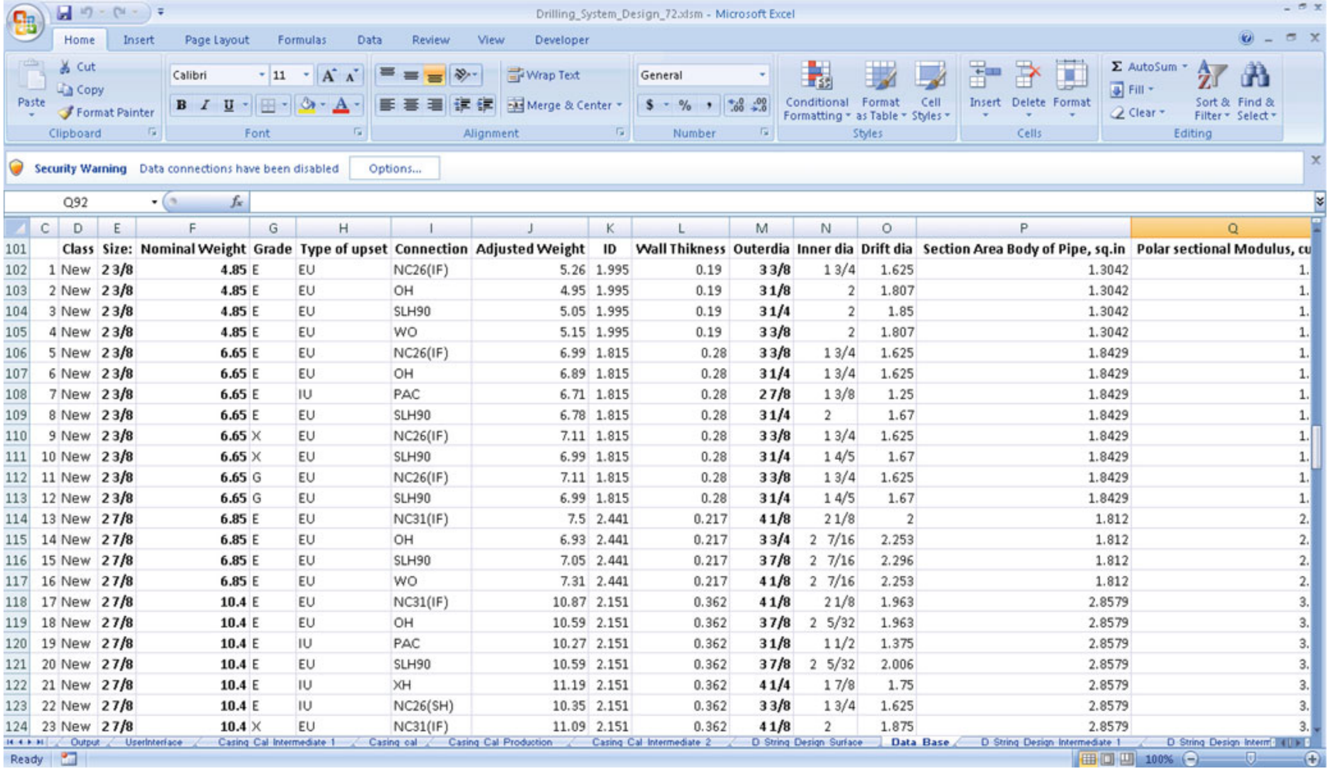


Fig. 7 Drill pipe sub-assembly and components



Security Warning Data connections have been disabled Options...

Q92

	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
101		Class	Size:	Nominal Weight	Grade	Type of upset	Connection	Adjusted Weight	ID	Wall Thikness	Outerdia	Inner dia	Drift dia	Section Area Body of Pipe, sq.in	Polar sectional Modulus, cu
102	1	New	**2 3/8**	**4.85**	E	EU	NC26(IF)	5.26	1.995	0.19	**3 3/8**	1 3/4	1.625	1.3042	1.
103	2	New	**2 3/8**	**4.85**	E	EU	OH	4.95	1.995	0.19	**3 1/8**	2	1.807	1.3042	1.
104	3	New	**2 3/8**	**4.85**	E	EU	SLH90	5.05	1.995	0.19	**3 1/4**	2	1.85	1.3042	1.
105	4	New	**2 3/8**	**4.85**	E	EU	WO	5.15	1.995	0.19	**3 3/8**	2	1.807	1.3042	1.
106	5	New	**2 3/8**	**6.65**	E	EU	NC26(IF)	6.99	1.815	0.28	**3 3/8**	1 3/4	1.625	1.8429	1.
107	6	New	**2 3/8**	**6.65**	E	EU	OH	6.89	1.815	0.28	**3 1/4**	1 3/4	1.625	1.8429	1.
108	7	New	**2 3/8**	**6.65**	E	IU	PAC	6.71	1.815	0.28	**2 7/8**	1 3/8	1.25	1.8429	1.
109	8	New	**2 3/8**	**6.65**	E	EU	SLH90	6.78	1.815	0.28	**3 1/4**	2	1.67	1.8429	1.
110	9	New	**2 3/8**	**6.65**	X	EU	NC26(IF)	7.11	1.815	0.28	**3 3/8**	1 3/4	1.625	1.8429	1.
111	10	New	**2 3/8**	**6.65**	X	EU	SLH90	6.99	1.815	0.28	**3 1/4**	1 4/5	1.67	1.8429	1.
112	11	New	**2 3/8**	**6.65**	G	EU	NC26(IF)	7.11	1.815	0.28	**3 3/8**	1 3/4	1.625	1.8429	1.
113	12	New	**2 3/8**	**6.65**	G	EU	SLH90	6.99	1.815	0.28	**3 1/4**	1 4/5	1.67	1.8429	1.
114	13	New	**2 7/8**	**6.85**	E	EU	NC31(IF)	7.5	2.441	0.217	**4 1/8**	2 1/8	2	1.812	2.
115	14	New	**2 7/8**	**6.85**	E	EU	OH	6.93	2.441	0.217	**3 3/4**	2 7/16	2.253	1.812	2.
116	15	New	**2 7/8**	**6.85**	E	EU	SLH90	7.05	2.441	0.217	**3 7/8**	2 7/16	2.296	1.812	2.
117	16	New	**2 7/8**	**6.85**	E	EU	WO	7.31	2.441	0.217	**4 1/8**	2 7/16	2.253	1.812	2.
118	17	New	**2 7/8**	**10.4**	E	EU	NC31(IF)	10.87	2.151	0.362	**4 1/8**	2 1/8	1.963	2.8579	3.
119	18	New	**2 7/8**	**10.4**	E	EU	OH	10.59	2.151	0.362	**3 7/8**	2 5/32	1.963	2.8579	3.
120	19	New	**2 7/8**	**10.4**	E	IU	PAC	10.27	2.151	0.362	**3 1/8**	1 1/2	1.375	2.8579	3.
121	20	New	**2 7/8**	**10.4**	E	EU	SLH90	10.59	2.151	0.362	**3 7/8**	2 5/32	2.006	2.8579	3.
122	21	New	**2 7/8**	**10.4**	E	IU	XH	11.19	2.151	0.362	**4 1/4**	1 7/8	1.75	2.8579	3.
123	22	New	**2 7/8**	**10.4**	E	IU	NC26(SH)	10.35	2.151	0.362	**3 3/8**	1 3/4	1.625	2.8579	3.
124	23	New	**2 7/8**	**10.4**	X	EU	NC31(IF)	11.09	2.151	0.362	**4 1/8**	2	1.875	2.8579	3.

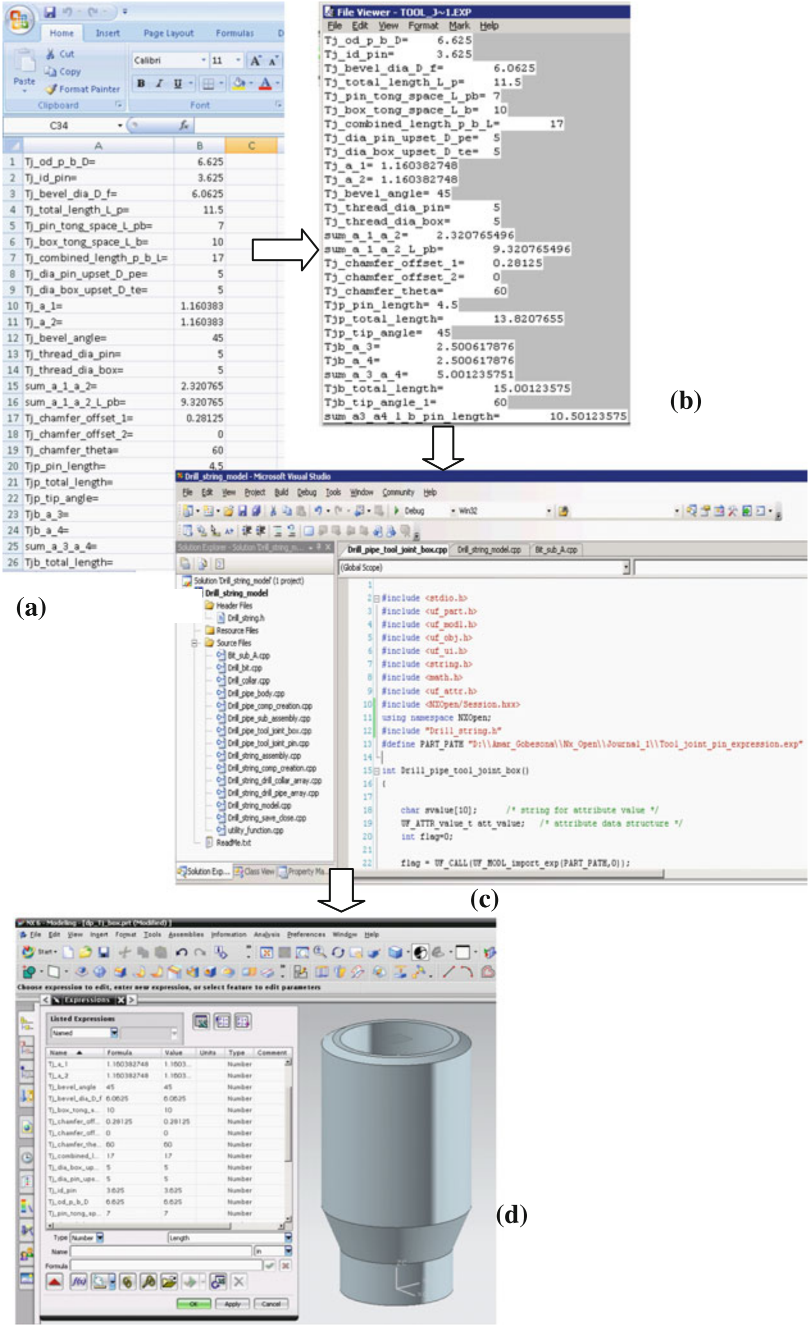
Fig. 8 Partial view of drill pipe data sheet

parametric data file known as a CAD expression file. Figure 9 shows the steps involved in the parametric approach for designing the drill pipe tool-joint box. First, the design parameters are identified and initiated by an engineer in Excel format, as shown in Fig. 9a. Engineering constraints are modeled as embedded formulas across different cells and are checked interactively or semiautomatically by using Excel functions, such as a "goal seeking" algorithm. Next, after verifying the accuracy and constraints involved, the parameter names and the result values are exported into a text format in the form of expressions, as shown in Fig. 9b; this is an acceptable format that allows CAD software NX to import into it directly as data input corresponding to built-in expressions. Third, the CAD solid model is constructed by programming NX Open API functions, which are available as a development extension for the CAD software. The source codes are shown in Fig. 9c. Fourth, once the initial template models are generated, the expressions associated with the predefined parameters in the CAD models are then imported into the CAD environment for the given well drill-string and the casing. A CAD part model is shown in Fig. 9d.

For better appreciation of the procedure, the next part of this section explains how NX Open API functions are used with C programming language to generate 3D models. A "top–down" assembly approach has been followed. First, the structure of the whole assembly of the drill-string is created; the generic configuration of the drill-string assembly contains all possible drill-string components. For example, a drill-string assembly consists of drill pipe, drill collar, heavyweight drill pipe, bit sub, cross-over sub, drill bit, and so on. Depending on the operational requirements, some components may not be required. For example, sometimes heavyweight drill pipe is not used in the drill-string; in that case, the module that creates the assembly structure will suppress the heavyweight drill pipe in the assembly.

The next level of model generation is sub-assembly generation. The program first finds out which member of the assembly contains sub-assembly from a configuration definition, and then fires the rule to initiate sub-assembly creation. Refer again to Fig. 7, in which a drill pipe sub-assembly was shown to contain three parts: drill-pipe body, tool-joint pin, and tool-joint box. Such a structure generation algorithm continues iteratively until the configuration of the whole assembly is completed. It is worth mentioning that, in the "top–down" approach, though the conceptual assembly tree structure is created first, in each of the structure members, no physical component geometry entities are created until the program reaches the next stage, in which the component geometry entities are created.

Components have been created using feature modeling methodology. A component is a collection of several features, such as a drill pipe composed of cylinder, cone, hole, chamfer, and so on. Each component therefore requires its own parametric feature-based program. Hence, individual parametric programs have been written for each component to generate a generic 3D model. To reflect the topological variations, the algorithm selects which generation functions to run. For



	A	B	C
1	Tj_od_p_b_D=	6.625	
2	Tj_id_pin=	3.625	
3	Tj_bevel_dia_D_f=	6.0625	
4	Tj_total_length_L_p=	11.5	
5	Tj_pin_tong_space_L_pb=	7	
6	Tj_box_tong_space_L_b=	10	
7	Tj_combined_length_p_b_L=	17	
8	Tj_dia_pin_upset_D_pe=	5	
9	Tj_dia_box_upset_D_te=	5	
10	Tj_a_1=	1.160383	
11	Tj_a_2=	1.160383	
12	Tj_bevel_angle=	45	
13	Tj_thread_dia_pin=	5	
14	Tj_thread_dia_box=	5	
15	sum_a_1_a_2=	2.320765	
16	sum_a_1_a_2_L_pb=	9.320765	
17	Tj_chamfer_offset_1=	0.28125	
18	Tj_chamfer_offset_2=	0	
19	Tj_chamfer_theta=	60	
20	Tjp_pin_length=	4.5	
21	Tjp_total_length=		
22	Tjp_tip_angle=		
23	Tjb_a_3=		
24	Tjb_a_4=		
25	sum_a_3_a_4=		
26	Tjb_total_length=		

```
Tj_od_p_b_D=     6.625
Tj_id_pin=       3.625
Tj_bevel_dia_D_f=        6.0625
Tj_total_length_L_p=     11.5
Tj_pin_tong_space_L_pb= 7
Tj_box_tong_space_L_b=  10
Tj_combined_length_p_b_L=          17
Tj_dia_pin_upset_D_pe=  5
Tj_dia_box_upset_D_te=  5
Tj_a_1= 1.160382748
Tj_a_2= 1.160382748
Tj_bevel_angle= 45
Tj_thread_dia_pin=       5
Tj_thread_dia_box=       5
sum_a_1_a_2=     2.320765496
sum_a_1_a_2_L_pb=        9.320765496
Tj_chamfer_offset_1=     0.28125
Tj_chamfer_offset_2=     0
Tj_chamfer_theta=        60
Tjp_pin_length= 4.5
Tjp_total_length=        13.8207655
Tjp_tip_angle=  45
Tjb_a_3=         2.500617876
Tjb_a_4=         2.500617876
sum_a_3_a_4=     5.001235751
Tjb_total_length=        15.00123575
Tjb_tip_angle_1=         60
sum_a3_a4_l_b_pin_length=          10.50123575
```

```

#include <stdio.h>
#include <uf_part.h>
#include <uf_modl.h>
#include <uf_obj.h>
#include <uf_ui.h>
#include <string.h>
#include <math.h>
#include <uf_attr.h>
#include <NXOpen/Session.hxx>
using namespace NXOpen;
#include "Drill_string.h"
#define PART_PATH "D:\\Amar_Gobesona\\Nx_Open\\Journal_1\\Tool_joint_pin_expression.exp"

int Drill_pipe_tool_joint_box()
{

    char svalue[10];      /* string for attribute value */
    UF_ATTR_value_t att_value;   /* attribute data structure */
    int flag=0;

    flag = UF_CALL(UF_MODL_import_exp(PART_PATH,0));
```

Name	Formula	Value	Units	Type	Comment
Tj_a_1	1.160382748	1.1603...		Number	
Tj_a_2	1.160382748	1.1603...		Number	
Tj_bevel_angle	45	45		Number	
Tj_bevel_dia_D_f	6.0625	6.0625		Number	
Tj_box_tong_s...	10	10		Number	
Tj_chamfer_off...	0.28125	0.28125		Number	
Tj_chamfer_off...	0	0		Number	
Tj_chamfer_the...	60	60		Number	
Tj_combined_l...	17	17		Number	
Tj_dia_box_up...	5	5		Number	
Tj_dia_pin_ups...	5	5		Number	
Tj_id_pin	3.625	3.625		Number	
Tj_od_p_b_D	6.625	6.625		Number	
Tj_pin_tong_sp...	7	7		Number	

Fig. 9 Steps involved in 3D modeling. **a** Data file. **b** Imported expressions. **c** NX open programming. **d** CAD model realization and expression file

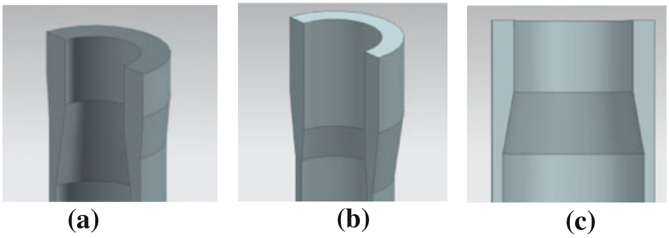


Fig. 10 Drill pipe features. **a** Internal-external upset. **b** External upset. **c** Internal upset

```
for(i=0; i<dptotal; i++) {
  {   if (i == 0) continue;
      origin[2]=pos[2]+i*dst_btn_dp;
      strcpy(iname,cname);
      sprintf(iname+strlen(cname),"_%d",i);
      flag=UF_ASSEM_add_part_to_assembly(*parent, pname, refset, cname,
           origin, matrix, layer, &newinst, &status);
      if(flag!=0) return(flag);
  }
  return(0);     }
```

Fig. 11 Pseudo code to generate drill-string component and sub-assembly array

example, as shown in Fig. 10, a drill pipe body may have three different topologies: internal-external upset, external upset, and internal upset.

An *array* method has been implemented to repeat the component and subassembly instantiation. As shown in Fig. 10, a large quantity of similar types of drill pipe may exist in the drill-string; this *array* method helps to reproduce the drill pipe and other components throughout the assembly.

The pseudocode shown in Fig. 11 is created to execute the *array* method for drill pipe. Here, the *dptotal* is the number of drill pipes in the array, and "*dst_btn_dp*" is the distance between two neighboring drill pipes. These two variables depend on both conceptual design and user input. Similar programs have been written for other components that require repetition.

After the arrays of components and sub-assemblies are carried out, the 3D model of the whole drill-string assembly is realized. This can be used to perform FEA and simulation. If the result of the analysis is unsatisfactory, the program redesigns the drill-string by following the same steps mentioned earlier; the whole design loop is then integrated. Due to the time constraints of this research, the drill-string module and analysis module have not been integrated, although more work is to be done in the future.

4.3 Operational Parameter Module

DrillSoft selects the best combination of WOB and RPM by calculating the cost per foot for a given situation to predict bit performance. The program can be useful for selecting the bit that yields the lowest cost per foot by repeating a set of WOBs and drill-string rotation for several combinations of bits. The operational parameter module contains two parts. First, drilling coefficients are determined by using offset data; second, these coefficients are used to determine the optimum WOB and RPM. This module is constructed based on Bourgoyne and Young's multiple regression approach. According to Bourgoyne et al. [7], eight types of primary drilling variables are required for the regression analysis: depth (D), penetration rate (R), weight per inch of bit diameter (w/d), rotary speed (N), fractional tooth wear (h_f), Reynolds number parameter (N_{RE}), mud density (ECD), and pore pressure gradient (g_p). These eight operational parameters are used to determine the drilling coefficients. The drilling coefficients are then used to predict the behavior of the field and are combined with other input to determine the optimum WOB and RPM.

4.4 Report Generation

The developed program is capable of generating formal reports of design outcome. These reports are very useful for future references and also helpful for further analysis. For example, the operational parameter module generates a cost-per-foot table. This table can be used as a tool for selecting the best bit for a particular interval. Every module has a separate report-generation option; whenever a design is complete the system can generate the corresponding report.

5 Demonstration of the System and Procedure with a Case Study

The casing design module calculates casing setting depth by using formation pore pressure and formation fracture pressure, and determines the size of hole and casing of each section of the well. It then selects the optimum combination of casing string from the available inventory. The drill-string design module will be discussed in more detail later in this chapter. The operational parameter module works out drilling coefficients, the optimum WOB, and the drilling rotary speed (RPM). Drilling coefficients are determined according to the regression analysis procedure of Bourgoyne and Young et al. [7]; at least 30 offset drilling data sets are required. Optimum WOB and RPM are determined for the minimum cost. This program also generates six different tables of economic performance as a function of WOB and RPM as an operational guide, and produces formal reports for design details.

5.1 Casing Setting Depth and Size Determination

The following inputs [38] are provided:

True vertical depth	TVD = 11,000 ft;
Poisson's ratio	$\upsilon = 0.4$;
Over burden	$\sigma_v = 1$psi/ft;
Trip margin (SG)	0.06;
Kick margin (SG)	0;
Minimum depth of surface section	3,000 ft;
Number of pore pressure input	8;
Type of formation	Hard;
Production casing size	4.5 in.

The procedure first estimates the fracture pressure and determines the pore pressure-trip margin (MSG) and fracture pressure-trip margin (FSG) based on the input provided. Table 1 shows the estimated values.

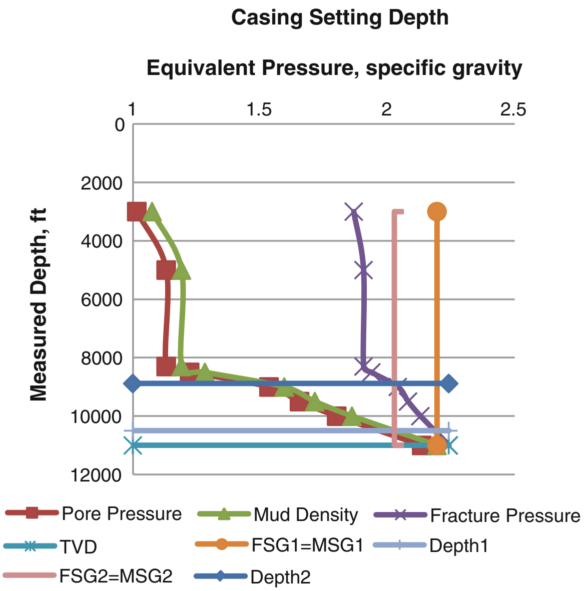
After processing the input, the software tool calculates the mud density at the true vertical depth (TVD). According to the theory, this is the density of mud required to drill the well to the final depth. From here, the design stage is referred to as production section design for the well. The next step is to determine the depth at which the fracture gradient is equal to the mud-specific gravity; in other words, the depth should reach the point at which the vertical line drawn from the mud density curve touches the fracture gradient curve (Fig. 12). Once the depth of the next section is known, the program determines the mud density required to drill up to this depth. In this way, the process continues until the mud density becomes smaller than the minimum fracture gradient or the depth becomes smaller than the minimum casing setting depth. After the determination of casing setting depth, the information is stored in a data sheet and can be shared with other modules.

Mud density at the TVD is $\mathrm{MSG}_1 = 2.195$. The depth at which $\mathrm{MSG}_1 = \mathrm{FSG}_1$ can be found by linear interpolation. In this program it is assumed that the connecting line between the two neighboring points is linear. The program now determines the depth at which $\mathrm{FSG}_1 = 2.195$. The two neighboring points of FSG_1

Table 1 Fracture pressure, FSG and MSG estimation

Input number	Depth (ft)	Pore pressure (psi)	Pore pressure (SG)	Mud density (MSG)	Fracture pressure	FSG
1	3,000	1,320	1.01	1.076	1.878	1.878
2	5,000	2,450	1.131	1.191	1.916	1.916
3	8,300	4,067	1.131	1.191	1.916	1.916
4	8,500	4,504	1.223	1.283	1.947	1.947
5	9,000	5,984	1.535	1.595	2.051	2.051
6	9,500	6,810	1.655	1.715	2.091	2.091
7	10,000	7,800	1.801	1.860	2.139	2.139
8	11,000	10,171	2.135	2.195	2.251	2.251

Fig. 12 Casing setting depth



are $FSG_2 = 2.250$ and $FSG_3 = 2.139$ and the corresponding depths are $\text{Depth}_2 = 11{,}000$ ft and $\text{Depth}_3 = 10{,}000$ ft, respectively.

$$\text{Depth}_1 = \frac{(\text{FSG}_1 - \text{FSG}_2)(\text{Depth}_3 - \text{Depth}_2)}{\text{FSG}_3 - \text{FSG}_2} + \text{Depth}_2 \tag{2}$$

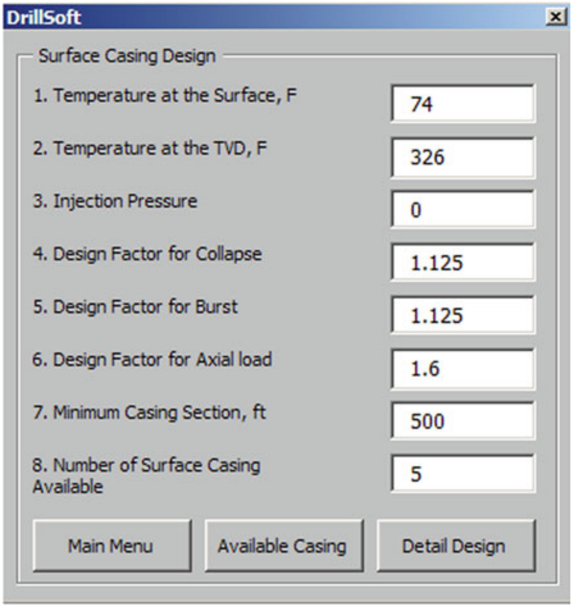
$$\text{Depth}_1 = 10,496\,\text{ft}$$

The next casing setting depth should thus be at 10,496 ft. The mud density above 10,496 ft must now be determined. Again, the program uses linear interpolation; the following equation should be used:

$$\text{MSG}_1 = \frac{(\text{MSG}_3 - \text{MSG}_2)(\text{Depth}_1 - \text{Depth}_2)}{\text{Depth}_3 - \text{Depth}_2} + \text{MSG}_2 \tag{3}$$

Here, $\text{Depth}_1 = 10{,}496$ ft, $\text{Depth}_2 = 11{,}000$ ft, $\text{Depth}_3 = 10{,}000$ ft, $\text{MSG}_2 = 2.195$, and $\text{MSG}_3 = 1.861$. Thus, $\text{MSG}_1 = 2.026$. These processes continue until the mud density becomes smaller than the minimum value of the fracture-specific gravity or the depth becomes smaller than the minimum surface casing depth.

Figure 12 provides the graphical method of casing setting depth determination. Figure 13 shows the partial view of the well schematic based on the output provided by the system. The casing and hole sizes are provided in Table 2.



DrillSoft

Surface Casing Design

1. Temperature at the Surface, F: 74
2. Temperature at the TVD, F: 326
3. Injection Pressure: 0
4. Design Factor for Collapse: 1.125
5. Design Factor for Burst: 1.125
6. Design Factor for Axial load: 1.6
7. Minimum Casing Section, ft: 500
8. Number of Surface Casing Available: 5

Fig. 13 Surface casing design user interface

5.2 *Case Study for Casing Selection*

Surface casing is designed as per the procedure specified by Byrom [8]. The necessary inputs are Depth = 3,000 ft, Mud density = 1.11, and Casing size = 13 3/8. Figure 13 shows the surface casing design user interface filled with input. It should be noted that the options for depth and mud density are not provided in the user interface. This is owing to the integration of different parts of the software, which helps the program to automatically retrieve necessary information from the system database. In this particular case, the program automatically retrieves the depth and mud density values from the casing setting depth data sheet. The user needs to provide the specifications of the available casing. The system takes in such casing specifications as input data in a text file format, from which it retrieves the required information. A sample file with the available surface casing specifications is tabulated in Table 3.

Table 2 Casing setting depth and size

	Surface casing	Intermediate 1 casing	Intermediate 2 casing	Production casing
Depth (ft.)	3,000	8,882	10,496	11,000
Mud-specific gravity	1.521	1.521	2.026	2.195
Casing size (in.)	13.375	9.625	7	4.5
Bit size (in.)	17.5	12.25	8.5	6.15

Table 3 Specification and priority sequence of available casing

Casing number	OD(inch)	ID(inch)	Weight (Kg/ft)	Grade	Connection
1	16	12.615	54.5	K-55	ST&C
2	16	12.515	61	K-55	ST&C
3	16	12.415	68	K-55	ST&C
4	16	12.415	68	N-80	ST&C
5	16	12.347	72	N-80	ST&C

Table 4 Casing selection break points and potential candidates

No.	Break points (ft.)	Potential candidates
1	0	1,2,3,4,5
2	2,092	2,3,4,5
3	2,852	3,4,5
4	3,000	3,4,5

After receiving the input, the system calculates the collapse and burst rating at the surface and at the casing shoe. In this particular case, the design collapse pressure at the surface and shoe are 0 and 2,220 psi, respectively, and the design burst pressure at the surface and shoe are 2,180 and 750 psi. The program then determines the break points and the potential candidates that satisfy both the collapse and burst ratings (as shown in Table 4).

In the course of developing this project, the researchers have created a knowledge base containing various configurations of casing sizes for hard and unconsolidated formation. Casing size usually depends on the formation types, the number of casing subsections, and the production casing size. After receiving input from the user, the inference mechanism sorts out the specific sizes for each section of the well. Various combinations of casing sizes are possible. If the specific production casing size is not available, then the system will recommend sizes from the knowledge base.

According to the algorithm, the first break point (0 ft) contains all five available casings as potential candidates. As available casings were listed according to the priority of the user, the system assumes that the first casing is more economical and then the next one, and so on. The system selects the first candidate, casing number 1, with grade K-55 and weight 54.5, and adds the minimum casing section (500 ft). The program then determines if the total depth has been achieved; if it has not, the program again selects casing number 1 from the potential candidates. As it is similar to the previous casing, this time the program will add a minimum value of [Minimum casing section or (Next break point-Casing covered)], i.e., Min [500 (2,092−500 = 1,592)]. The program determines that the minimum casing section (500 ft) is the smaller of these two values. Another 500 ft will then be added to the previous casing. Its length is now 1,000 ft. As the closest break point is at 2,092 ft, this process continues until the casing length has reached 2,000 ft. At this point, the system determines that casing number 1 is still a potential candidate and is similar to the previous casing. The minimum value here is (500, 2,092−2,000 = 92) = 92 ft. Based on these conditions, the system selects casing number 1 and adds a length of 92 ft to the existing length. The total length of casing covered is now 2,092 ft. As the desired depth is 3,000 ft, the system checks the available potential candidates, selects casing number 2, and adds 500 ft to the previous length. The new length is 2,592 ft, still less than the total desired depth. The system again selects casing number 2 and works out the minimum value between (500, 2,852−2,592 = 260 ft) = 260 ft. After adding this value, the length becomes 2,852 ft. Another 148 ft of casing is required to complete the casing string for the surface section. However, this remaining section is less than the minimum casing section length and previously used casing (Number 1 and 2) are not allowed to be used up to the full depth. Another casing type should be selected, but if the system selects a new casing type it will not satisfy the minimum casing section length. To solve this problem, a re-evaluation of the design is required. The system re-evaluates the design and concludes that, instead of using casing number 2 from 2,093 to 2,852 ft, casing 3 should be used to the total depth. In this case, all the design criteria will be satisfied. The preliminary design based on collapse and burst is now complete.

The next step is to check whether the casing string design will satisfy the axial load criteria. From the case study presented, it is found that the casing string meets sufficient safety standards with casings 1 and 3, in their relevant sections. This concludes the surface casing conceptual design. Figures 14, 15, and 16 represent the combined casing selection based on collapse, burst, and axial load. Table 5 shows the sample casing selection output as compared with a published result [38].

Fig. 14 Casing selection based on collapse load

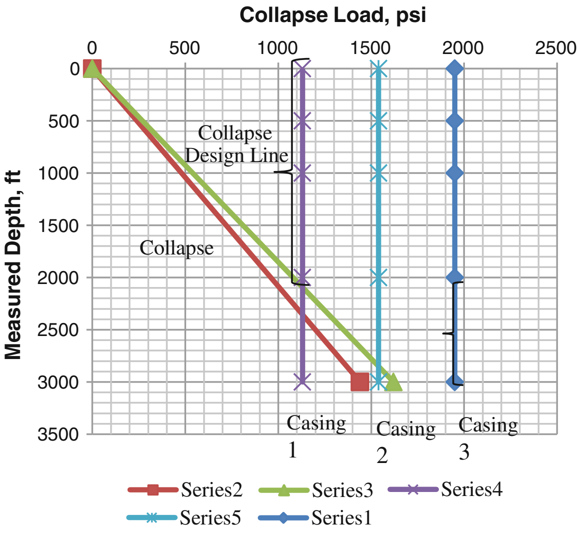


Fig. 15 Casing selection based on burst load

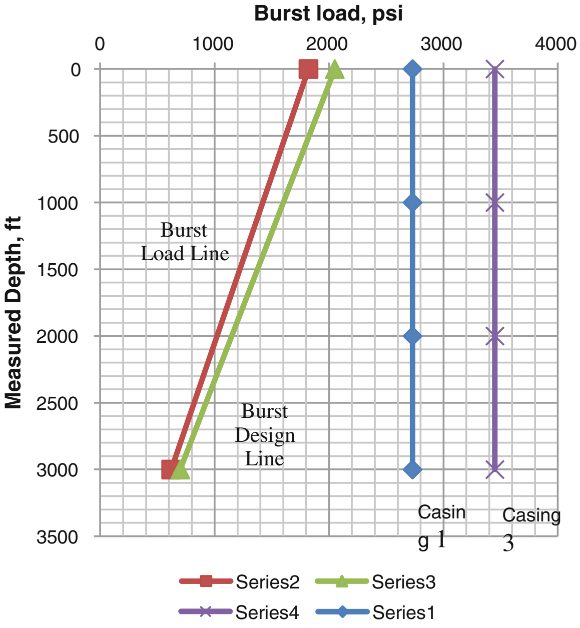
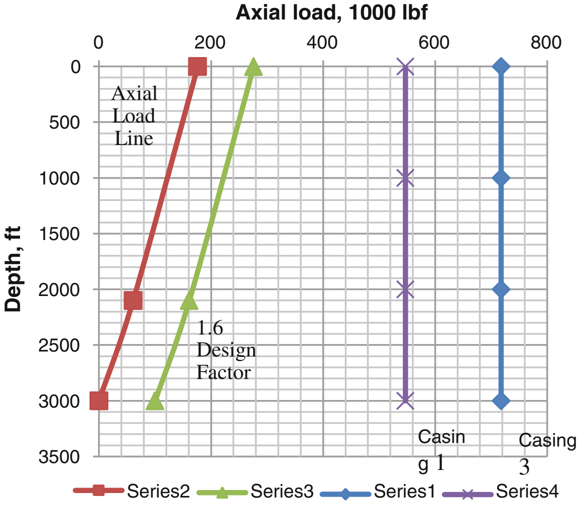


Fig. 16 Casing selection based on axial load

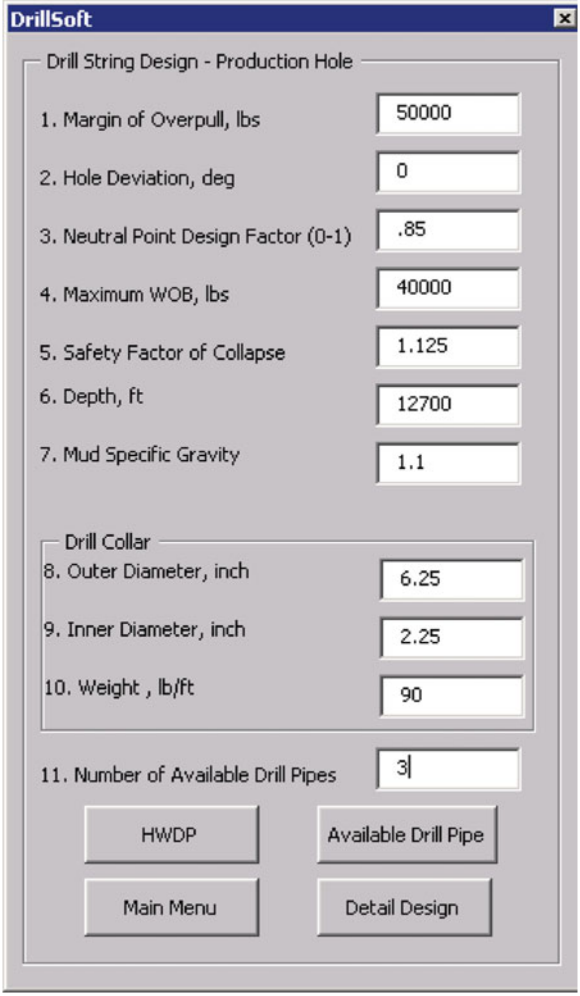


5.3 *Drill-String Design Demonstration*

Embedded knowledge assists the system in developing the conceptual design of the drill string based on previous modules' output and users' input. This conceptual design is then used to generate the drill-string specifications and configurations, and later this information is converted into expression files. The

Table 5 Comparison of casing setting depth

Section	DrillSoft		Published result [38]	
	Depth (ft)	Mud SG	Depth (ft)	Mud SG
Surface	3,000	1.521	3,000	1.567
Intermediate 1	8,882	1.521	8,850	1.567
Intermediate 2	10,496	2.026	10,500	2.031
Production	11,000	2.194	11,000	2.170



1. Margin of Overpull, lbs: 50000

2. Hole Deviation, deg: 0

3. Neutral Point Design Factor (0-1): .85

4. Maximum WOB, lbs: 40000

5. Safety Factor of Collapse: 1.125

6. Depth, ft: 12700

7. Mud Specific Gravity: 1.1

Drill Collar

8. Outer Diameter, inch: 6.25

9. Inner Diameter, inch: 2.25

10. Weight , lb/ft: 90

11. Number of Available Drill Pipes: 3

Fig. 17 Drill-string design user interface

conceptual design and the CAD model are bridged through the expression files, as shown above in Fig. 9. Any changes in the conceptual design will thus change the expression files, and will be reflected in the 3D model.

Table 6 Conceptual design parameters for a drill-string

Drill-string components	Length (ft)	Number of array
Drill collar: 6 ¼″OD × 2 ¼″ID	630	21
Drill pipe type 1: 4 ½″ × 16.6 lb, grade E75, class2	6,750	225
Drill pipe type 2: 4 1/2″ × 16.6 lb, grade X95, Premium class	5,320	178

To prove the concept of the developed module, a drill-string has been designed as a test case. The case is taken from the API standard handbook. Figure 17 shows the drill-string module user interface filled with input. Table 6 shows two of the drill pipe types available in the inventory. User-friendly interfaces have been created so as to integrate all the modules. The interfaces guide the user to develop the well plan with less effort and in an organized sequence. More UIs are to be introduced in the following sections.

Based on operational input, the rule-based system designed a drill-string that uses two different types of drill pipes. As mentioned above, the program first considers the most economical drill pipe among the available three. It first chooses grade E75 and determines the safe length of 6,750 ft. After accounting for the length of 21 drill collars, the drill-string has reached a length of 7,380 ft, which is less than the required depth of 12,700 ft. The program then considers the second type of pipe, grade X95, and decides to use this type for the remaining 5,320 ft. When considering the collapse load, the program generates messages for the user; in this case it is worked out to be 10,267 ft. The drill-string should not be run dry below this depth, as doing so may cause damage in the string. Based on this conceptual design, the system generates the necessary configuration and specification files and converts these files into expression files.

In this work, drill-string design is based on the input of casing design as introduced previously and the authors have developed a parametric well structure model, which works out the casing setting depth and casing sizes and generates different 3D casing sections. Figure 18 shows a partial drill-string assembly model.

5.4 *Operational Parameter Optimization*

The program provides two options for operation optimization depending on the input in order to determine the optimum WOB and RPM. Option 1 assumes that the abrasive constant, bearing constant, and drillability are unknown. Option 2 assumes that they are known. In Option 1, abrasive constant, bearing constant, and drillability should be calculated first from the offset bit data; these values will then be used in the rest of the calculations. The list of required input data for this option is shown in Fig. 19. In Option 2, abrasive constant, bearing constant, and drillability are given; the other required inputs are shown in Fig. 20.

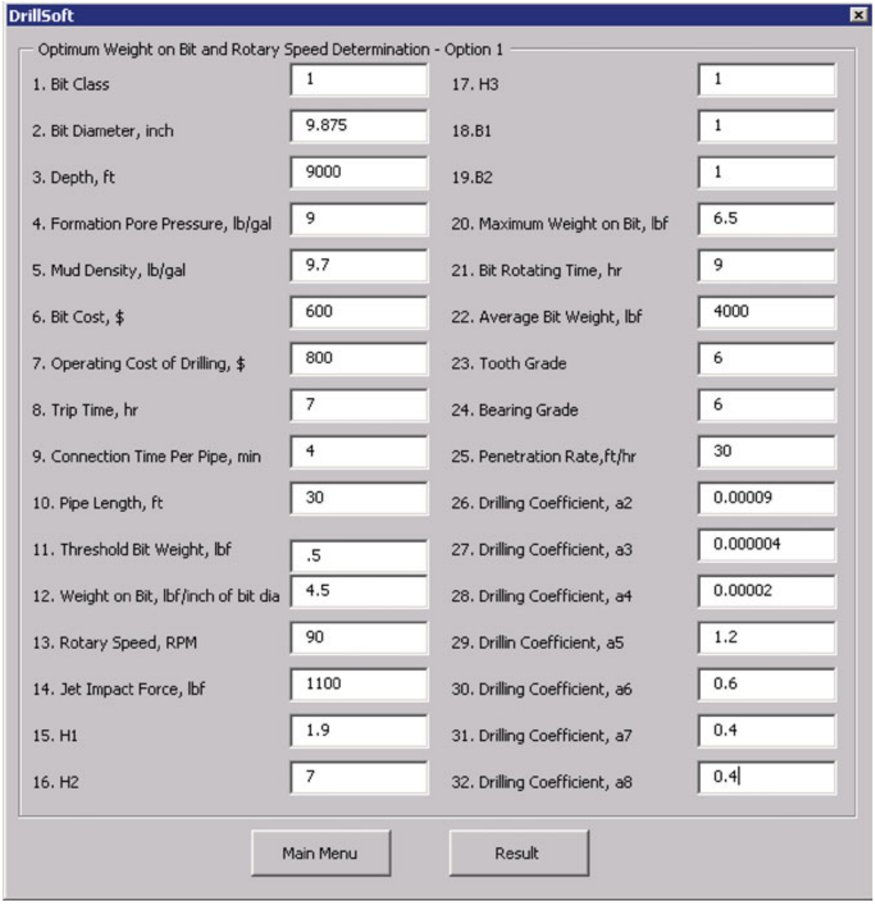
Fig. 18 Partial drill-string assembly [41]

The program also generates six tables, which include cost per foot, bit life, footage drilled, final tooth wear, final bearing wear, and penetration rate. A cost-per-foot table can be used to quickly identify (1) the best combination of bit weight and rotary speed; (2) the best rotary speed for a given bit weight; and (3) the best bit weight for a given rotary speed [7].

6 Comparison of the Generated Results with the Published Sources

Validation of the various modules in the DrillSoft system was based on previously published data. For example, the casing setting depths and mud-specific gravities were compared with the published data from Rabia's work [38]. The casing selections generated were checked against Byrom's [8]. The values of drilling coefficients calculated by DrillSoft were benchmarked against the values from the work of Bourgoyne et al. [7]. From these comparisons, it can be safely concluded that the results produced by the DrillSoft program are satisfactory.

The program has the following advantages: (1) it automatically selects the casing that meets all the loading criteria; (2) different modules are integrated with



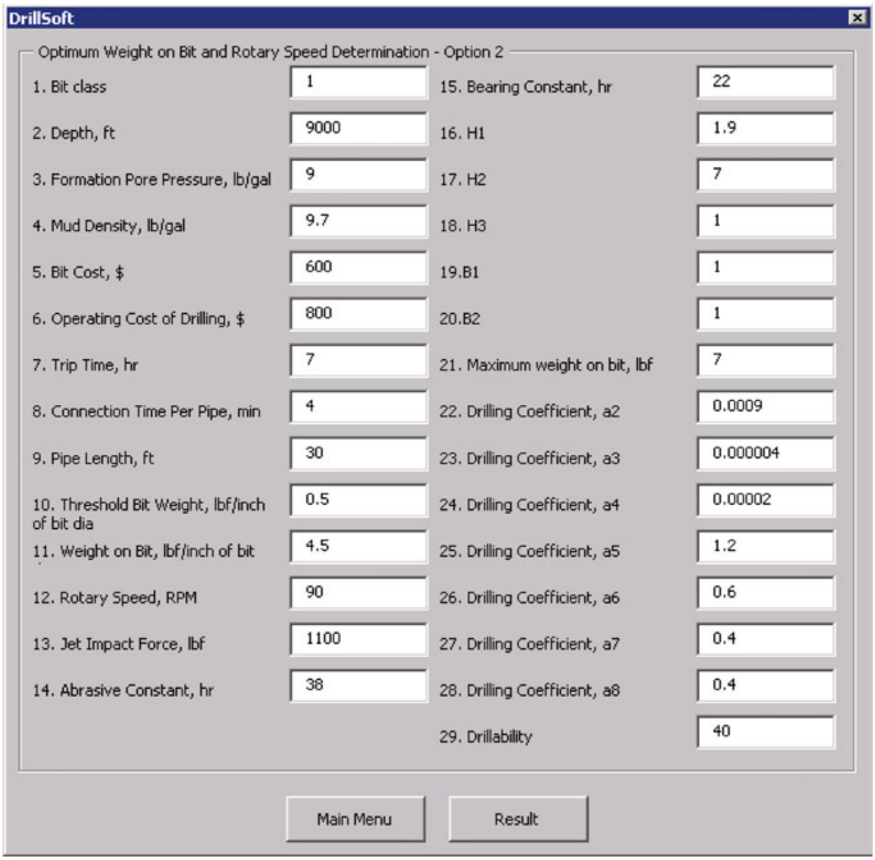
Optimum Weight on Bit and Rotary Speed Determination - Option 1

1. Bit Class	1	17. H3	1
2. Bit Diameter, inch	9.875	18.B1	1
3. Depth, ft	9000	19.B2	1
4. Formation Pore Pressure, lb/gal	9	20. Maximum Weight on Bit, lbf	6.5
5. Mud Density, lb/gal	9.7	21. Bit Rotating Time, hr	9
6. Bit Cost, $	600	22. Average Bit Weight, lbf	4000
7. Operating Cost of Drilling, $	800	23. Tooth Grade	6
8. Trip Time, hr	7	24. Bearing Grade	6
9. Connection Time Per Pipe, min	4	25. Penetration Rate,ft/hr	30
10. Pipe Length, ft	30	26. Drilling Coefficient, a2	0.00009
11. Threshold Bit Weight, lbf	.5	27. Drilling Coefficient, a3	0.000004
12. Weight on Bit, lbf/inch of bit dia	4.5	28. Drilling Coefficient, a4	0.00002
13. Rotary Speed, RPM	90	29. Drillin Coefficient, a5	1.2
14. Jet Impact Force, lbf	1100	30. Drilling Coefficient, a6	0.6
15. H1	1.9	31. Drilling Coefficient, a7	0.4
16. H2	7	32. Drilling Coefficient, a8	0.4

Fig. 19 Operational parameter optimization: option 1

each other and the flow of information from one module to another module is very smooth; (3) design parameters obtained from the program are used to generate a 3D CAD model, i.e., drill-string and casing; and (4) the parametric CAD model (drill-string) is connected with DrillSoft through automatically created expression files.

DrillSoft has some limitations; however: (1) the determination of casing setting depth and mud weight based on formation pore pressure and formation fracture pressure does not always guarantee well bore stability; and (2) biaxial effects of loading were not considered during the selection of casing. More research is still required.



Optimum Weight on Bit and Rotary Speed Determination - Option 2

1. Bit class	1	15. Bearing Constant, hr	22
2. Depth, ft	9000	16. H1	1.9
3. Formation Pore Pressure, lb/gal	9	17. H2	7
4. Mud Density, lb/gal	9.7	18. H3	1
5. Bit Cost, $	600	19.B1	1
6. Operating Cost of Drilling, $	800	20.B2	1
7. Trip Time, hr	7	21. Maximum weight on bit, lbf	7
8. Connection Time Per Pipe, min	4	22. Drilling Coefficient, a2	0.0009
9. Pipe Length, ft	30	23. Drilling Coefficient, a3	0.000004
10. Threshold Bit Weight, lbf/inch of bit dia	0.5	24. Drilling Coefficient, a4	0.00002
11. Weight on Bit, lbf/inch of bit	4.5	25. Drilling Coefficient, a5	1.2
12. Rotary Speed, RPM	90	26. Drilling Coefficient, a6	0.6
13. Jet Impact Force, lbf	1100	27. Drilling Coefficient, a7	0.4
14. Abrasive Constant, hr	38	28. Drilling Coefficient, a8	0.4
		29. Drillability	40

Fig. 20 Operational parameter optimization: option 2

7 Summary

This chapter described a feature-based well-drilling system design approach through a detailed case study. A prototype system that integrates three important well-drilling planning stages (casing design, drill-string design, and operational optimization) has been demonstrated. The software design concepts and the generative algorithms are presented. The results are promising. The prototyped software tool can help the drilling engineer to interactively design and model the well casing and the drill-string. The design modules are parametric and feature-based; hence, they are capable of handling different configurations and topologies of drilling components according to varying application conditions. At this moment, the reported software tool can only handle vertical oil wells. More research should be carried out to develop a generic model that can be equally applicable to horizontal, extended reach, and multilateral wells. The approach proposed here could also be applied to integrate other well-planning modules, such as hydraulic program, bit program, and time and cost estimation, into a comprehensive system. It is expected that, with full implementation in the future, the prototype system will be a very useful support tool for engineering decision making in drilling companies.

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