Repeated Overshoot and Collapse Behavior:

An Example from the Petroleum Industry

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Repeated overshoot and collapse behavior is commonly observed both in manufacturing and service industries, as well as in other social and ecological systems. This paper uses an example from the petroleum industry to illustrate a causal structure that can give rise to such behavior. Increasing business unit performance repeatedly erodes and overshoots the capacity of the business to continue to produce increasing performance. When business unit performance falls due to eroded capacity, the capacity gradually recovers, eventually enabling resumption of business growth. Changing the capacity acquisition policy shifts business performance behavior from repeated overshoot and collapse to desired exponential growth. Model extensions, including balancing capacity acquisition against the risk of having too much capacity in a market downturn, are discussed.

Keywords: petroleum, gas, drilling, overshoot, collapse, oscillation, capacity

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Background: Undesirable Business Performance

Repeated overshoot and collapse behavior is a systemic problem commonly observed both in manufacturing and service industries, as well as in ecological and social systems. This paper uses an example from the petroleum industry to illustrate a potential systemic cause of such problematic behavior, and one way to identify better solutions to such problems.

Business units (BUs) within petroleum industry companies contract with separate internal drilling organizations (IDOs) for drilling services, which, in turn, typically contract drill rigs from outside the firm. Over time, BUs set "stretch" business goals for themselves for the purpose of achieving accelerating growth over time. Of course, these stretch goals require more and more drilling services. The IDOs work harder and harder to keep up with these stretch goals, stressing their workers, their equipment, and their management. Pressure to meet these stretch goals with inadequate capacity often results in:

1) reduced maintenance of drilling equipment,
2) requirements for excessive overtime for long periods, and
3) lack of adequate preparation for drilling operations, sometimes resulting in breakdowns or long holdups in drilling operations while waiting for materials that would have been readily available at the drilling site had preparation time and quality not been so rushed and inadequate.

The eventual result may be that BUs are unable to meet their stretch business goals, simply because IDOs cannot meet their drilling commitments.

As more and more BUs fail to meet their stretch business goals due to these drilling problems, investigative teams are sent out to figure out what is wrong, eventually resulting in the IDOs being funded to support additional drilling capacity, which temporarily fixes the problem. Over a period of many years, this process repeats itself over and over. System dynamicists refer to this as "repeated overshoot and collapse" behavior.

This paper briefly describes a model, "Petroleum repeated overshoot collapse.mdl." The model is simple, yet structurally realistic, and creates the repeated overshoot and collapse behavior as described above. Building and exercising such models can help us, first, to improve our thinking about the causes of specific overshoot and collapse problems, and second, to find better solutions than we would find in the absence of such models.

The reader is encouraged to build the model from the equations in the Appendix, and then run it while reading this paper.[2]

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[2] If the reader does not already own system dynamics software, s/he may build and run the model from the equations in the Appendix by downloading and installing Vensim PLE software from www.vensim.com. . Alternatively, the reader may contact the author at paulnewton@StewardshipModeling.com to obtain the

Structure of the Drilling System: Dynamic Hypothesis

Loop R1: The Capacity Utilization Loop

Figure 1 illustrates the basic idea behind how the IDOs help the BU's achieve stretch business performance goals. Based on past performance, the BU forecasts its future performance.[3] The forecast is then bumped up by a "stretch" factor to create a "stretch BU performance goal." Of course, drilling productivity (distance drilled per quarter) must increase if the BU is to be able to meet its stretch goal. Therefore, "drilling productivity" rises to meet the needs of the BU.

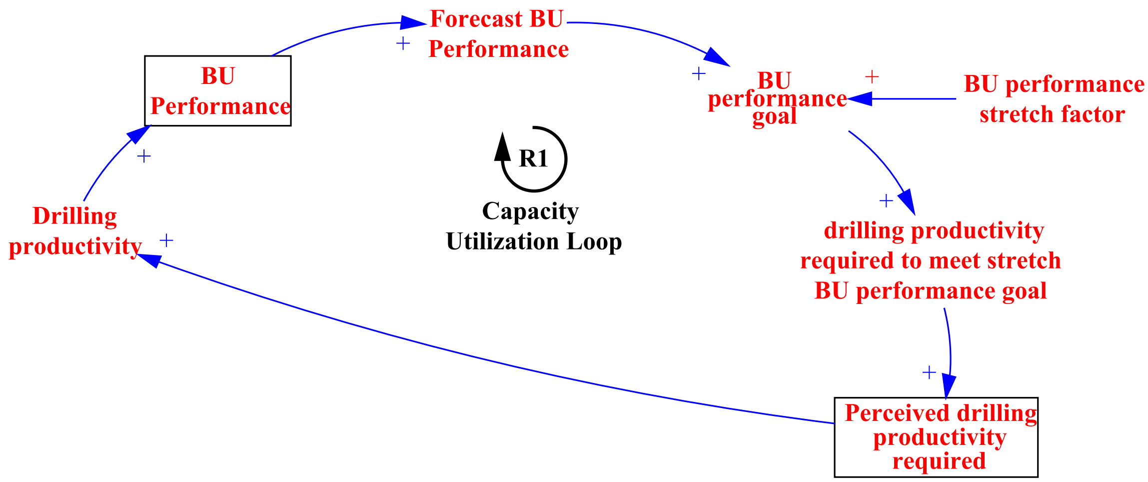

Figure 1: Loop R1: The Capacity Utilization Loop

The "R" in "R1" stands for "reinforcing". This means that a change in any variable in the loop is reinforced, that is, the change moves further in the initial direction of the change. If the initial change is an increase (decrease), the action of the loop is to increase (decrease) the change.

Suppose that BU management had never implemented stretch goals, that is, "BU performance stretch factor" in Figure 1 had always been equal to zero. Suppose further that there was a management change, and the new management decided to implement stretch goals, meaning "BU Performance Stretch Factor" is now greater than one. At the time the new management implements the stretch factor, "BU performance goal" would then immediately be larger than it had been before the new management had implemented the change. Further, the reinforcing feedback loop R1 would act to ensure that every variable in the loop would always be larger, and growing faster, than it would have had management not implemented the stretch goal. Therefore, this loop, by itself, will create the exponential growth in BU Performance expected by management as a result of their "stretch" goals. However, another loop in the system can work against such growth.

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model without having to build it from the equations in the Appendix. Note that Vensim PLE supports running, but not building, models with multiple "Views."

[3] See Sterman (2000) for a discussion of the trend function, and forecasting approaches used in this model. The model also uses the trend function in Vensim for a portion of Sterman's trend function. See the Vensim PLE online software documentation for descriptions of Vensim's trend function.

Loop B1: The Performance Pressure Loop

If the IDO does not purchase sufficient capacity to keep up with the stretch goals of the BU, then the IDO must attempt to meet the stretch goals by increasing the utilization of existing capacity. IDOs can increase utilization of existing capacity by working more overtime, managing the logistics of their drilling equipment to improve the percentage of time that it is actually drilling, temporarily reducing maintenance time, cutting back on drilling planning time, etc. Such actions can increase worker and manager fatigue, increase costs, increase accidents, and increase the likelihood that improper materials will be on site due to rushed planning. In short, attempts at excessive capacity utilization increase drilling problems. In the face of increasing drilling problems that reduce productivity, the BUs continue to press for more drilling. These two opposing pressures, when sustained or increasing, give rise to increasing "Drilling Performance Pressure." To capture this story in shorthand, "Drilling Performance Pressure" is modeled as a delayed reaction to "Desired drilling capacity utilization." "Desired drilling capacity utilization" is the ratio of "Perceived drilling productivity required" over "Physical drilling capacity."

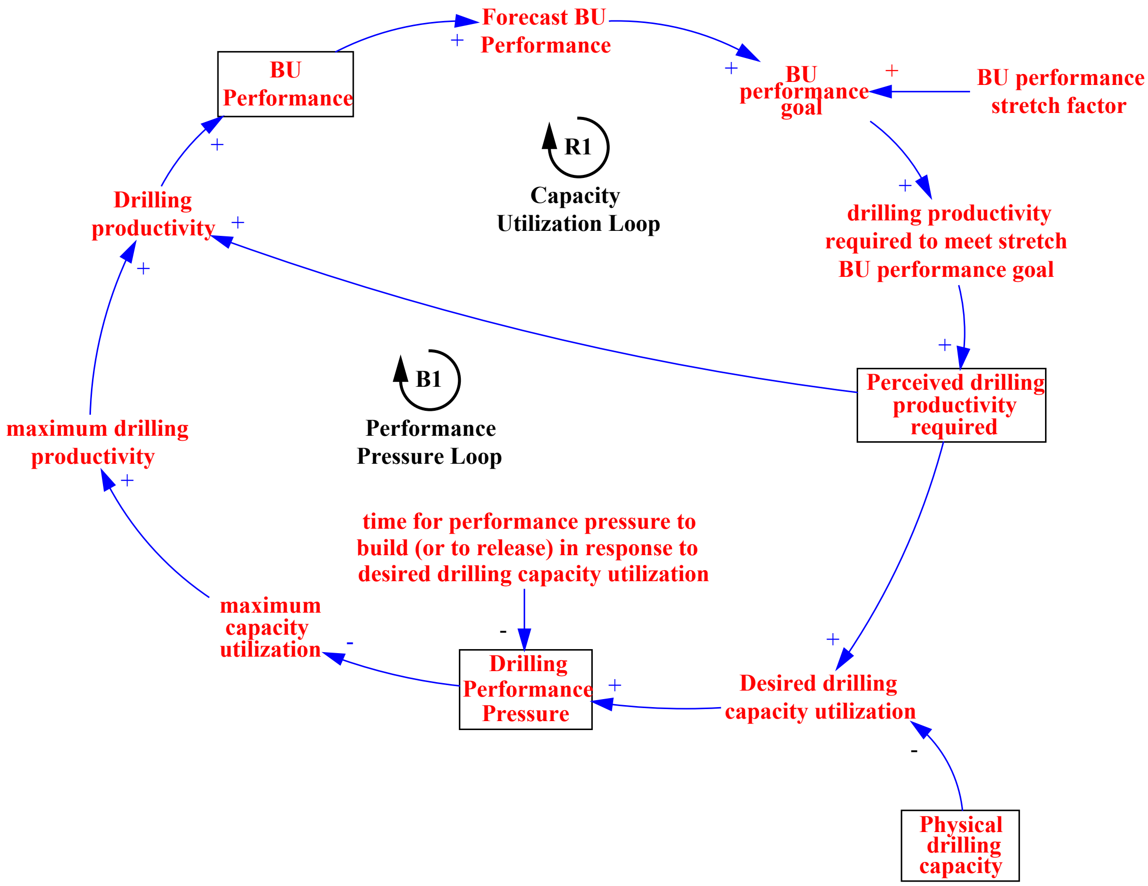

Figure 2: Adding Loop B1: Performance Pressure Loop

"Maximum capacity utilization" at any point in time is defined as the maximum drilling performance achievable, divided by the normal drilling performance of the physical drilling capacity used to achieve this maximum. "Maximum capacity utilization" decreases (increases) in response to increases (decreases) in "Drilling Performance Pressure.

"Maximum capacity utilization" is multiplied by "physical drilling capacity" to obtain the "maximum drilling productivity." Drilling productivity is then the lesser of "maximum drilling productivity" or "perceived drilling productivity required."

Summarizing Loop B1. Inadequate capacity will cause a buildup of capacity utilization beyond normal levels. If this over-utilization is sustained, especially under continually increasing BU drilling demand, drilling performance pressure rises above normal, causing a reduction in maximum drilling productivity. If maximum drilling productivity falls below the drilling productivity required to meet the BU's stretch goals, then the BU will not achieve its goals.

The "B" in "B1" stands for "balancing." This means that a change in any variable in the loop is balanced by the loop, that is, the loop acts to counter the initial direction of change. If the initial change is an increase (decrease), the action of the loop is to decrease (increase) the change.

Using the same example as before, if new management implements stretch goals that had not been in place before, loop B1 will act to counter the stretch goal that the managers desire. That is, loop B1 will act to reduce performance below the stretch goal.

Loop R2: The Performance Pressure Relief Loop

In the presence of sustained pressure on existing capacity, IDOs forecast[3] and order new physical drilling capacity (equipment, labor, managers, engineers, outside services, etc.). This acts to relieve drilling performance pressure by reducing "Desired drilling capacity utilization."

A salient feature of this loop is the delay from ordering to delivery of new capacity (note the constant, "capacity delivery time"). This delay means that in the face of increasing demands on drilling capacity, IDOs will always experience a delay in acquisition of new capacity to fill the need. Therefore it is important to think about the nature of the forecasting rule ("forecast drilling productivity required") that should be employed to deal with this delay.[3]

This loop is another reinforcing loop. Again, if BU management implements new stretch goals, immediately causing an increase (decrease) in "BU performance goal," then Loop R2 acts to reinforce the change, that is, to increase (decrease) "BU performance goal" even further.

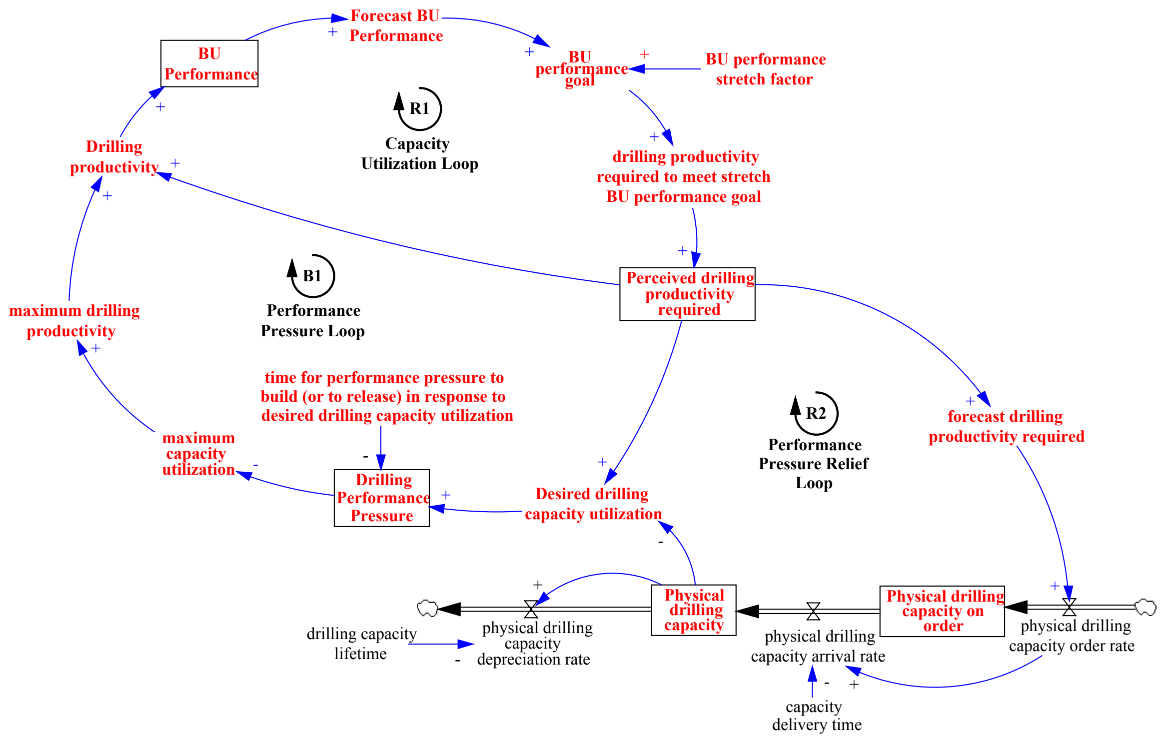

Figure 3: Adding Loop R2: The Performance Pressure Relief Loop

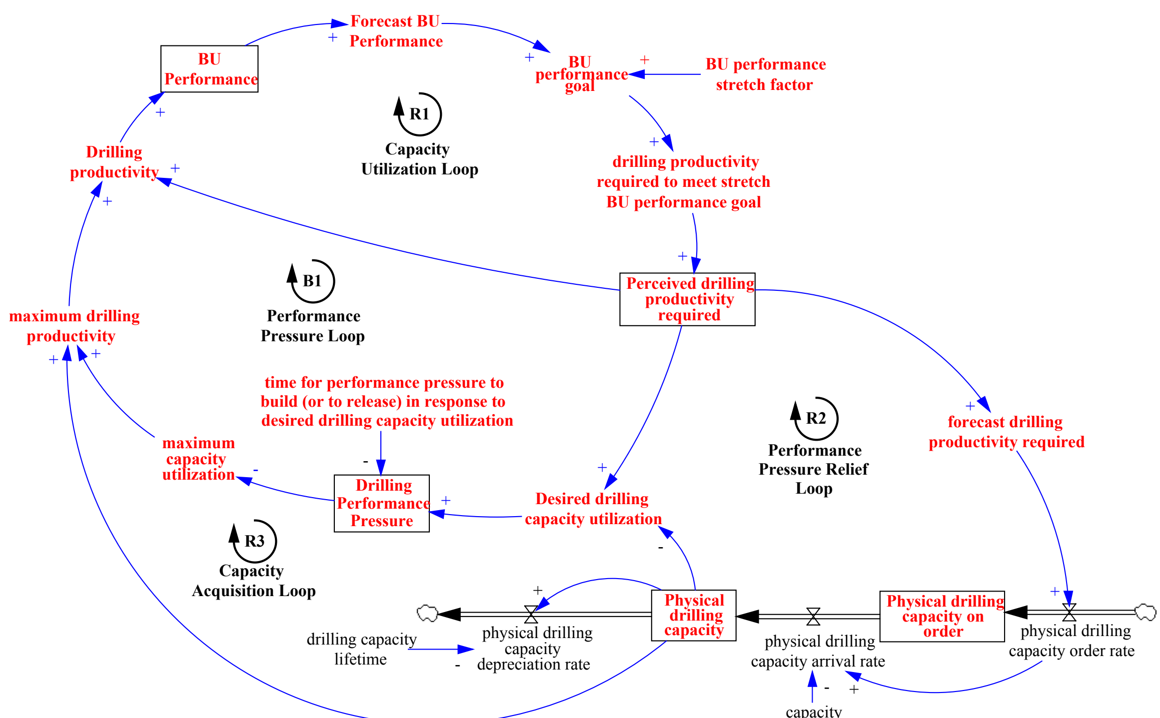

Figure 4: Adding Loop R3: Capacity Acquisition Loop

Loop R3: The Capacity Acquisition Loop

The last major feedback loop in the model is established with only one additional link (see Figure 4). This link was implicitly mentioned in the third paragraph of the description for Loop B1. As "Physical drilling capacity" increases, not only is "drilling performance pressure" relieved (Loop R2 just introduced), but also "maximum drilling productivity" is increased. Again, this loop is reinforcing.

More detail on structure

The appendix to this document contains the three "Views" in this model, as well as model equations, including units and documentation. Note that the red variables in the three "Views" in the appendix are the same as the red variables in Figures 1 through 4 above. This commonality should help you to trace out feedback loops R1, B1, R2, and R3 on the three Views, which is an informative exercise. Of course, all of the equations are also in the model that you can create and run.[2]

Behavior of the Drilling System

Behavior overview:

The model can produce a range of behaviors, but here we are initially concerned with the repeated overshoot & collapse behavior that the model can produce (see Figure 5). In overshoot & collapse, a state in a system initially increases due to the availability of some resource required to support increase of the state. Over time, increases in the state deplete the resource required to support further increases in the state. Delays in the system can cause the state to overshoot the capacity of the resource to support the state, eventually causing the state to collapse.

In this case, the resource is the "maximum drilling productivity" (the thick pink line in Figure 5), and the system state is "BU Performance" (the thick brown line). Essentially "BU Performance" repeatedly overshoots the capacity of the drilling system to support desired BU Performance. You will find all the variables in Figure 5 in the diagram in Figure 4. Before continuing, it's a worthwhile exercise to "mentally simulate" Figure 4, and then to compare the results of your mental simulation with the behavior in Figure 5.

More detailed description of behavior:

"Perceived drilling productivity required" (the blue line in Figure 5) increases abruptly with the imposition of stretch goals in quarter 10. "Drilling productivity" (the green line) follows the blue line with no immediate problem, since drilling demand by the BU's is well below "maximum drilling productivity" (the pink line). However, although the IDOs begin ordering physical capacity (the red line), their orders not keep up with the blue and green lines. As the gap between the green line and the red line widens over time, "Drilling performance pressure" (the black line) builds, causing the pink line to eventually begin to fall. When the pink line and the blue line cross, the green line must switch horses from the blue line to the pink line (about quarter 35).

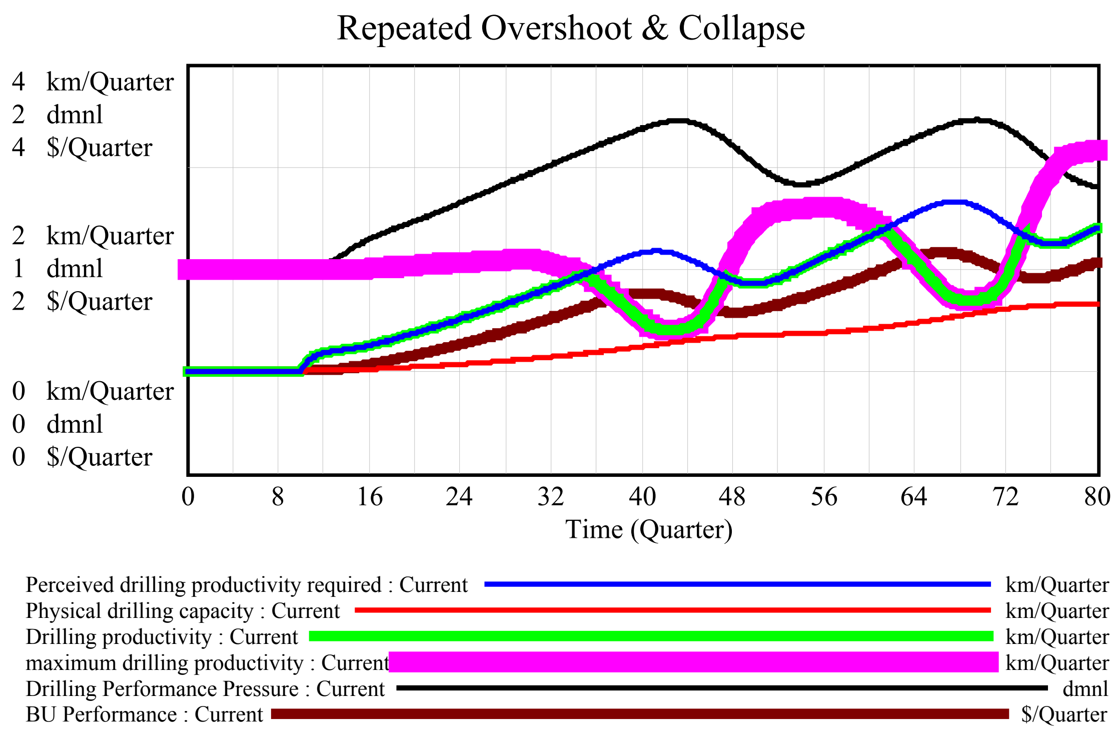

Figure 5: Repeating overshoot & collapse behavior.[4]

After quarter 35, "BU Performance" (the brown line) continues to rise because of the delay from "Drilling productivity" to achievement of BU performance. Therefore the blue line ("Perceived drilling productivity required") continues to rise as well, continuing to increase the gap between itself and the red line ("Physical drilling capacity"), thus causing "Drilling performance pressure"(the black line) to continue to rise, further depressing "maximum drilling productivity" (the pink line), and hence likewise depressing "Drilling productivity" (the green line).

Eventually around quarter 40, "BU Performance" (the brown line) peaks and then begins to decline around quarter 42, causing a decline in "perceived drilling productivity required" (the blue line). Note that "Physical drilling capacity" (the red line) has been increasing all along. Thus, around quarter 40, the decrease in the rate of increase of the blue line, and the increasing of the red line, decrease the gap between the red and blue lines, thus finally causing "drilling performance pressure" (the black line) to peak around quarter 43.

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[4] Do the following in the model to replicate the behavior over time graph (BOTG) in Figure 5:

1. Click on "Set", then click thru the integration methods on the far left (click on "Euler" first) until you reach "RK4". Leave "RK4" showing.
2. Turn "Synthesim" on (click on the running person with the horizontal lines through her).
3. Change the "Stretch fraction" slider to 0.2. (Click on the arrow itself to obtain a dialog box)
4. Change the slider, "fraction of adjustment for capacity that management is willing to pursue" to 0.1. (<PgDn> to the 3rd View-Drilling Capacity Acquisition to find it.)
5. Open the "Overshoot & Collapse" custom graph in the Control Panel (top right).

The relatively rapid increase in the red line from quarter 40 to 44, brings the "Capacity Acquisition Loop" R3 (Figure 4) to the fore, causing "maximum drilling productivity" to bottom out and begin to rise a bit before "Drilling performance pressure" (the black line) peaks.

With the gap between the blue and red lines now rapidly decreasing, performance pressure (the black line) also rapidly decreases. With "physical drilling capacity" (the red line) continuing to increase, "maximum drilling productivity" (the pink line) rises rapidly. Further, with the fall in "BU Performance" (the brown line), "perceived drilling productivity required" (the blue line) rapidly declines. Finally, between quarters 47 and 48, the blue line and pink lines cross again, and desired drilling productivity is again less than maximum drilling productivity. So, the green line switches horses again and now follows the blue line.

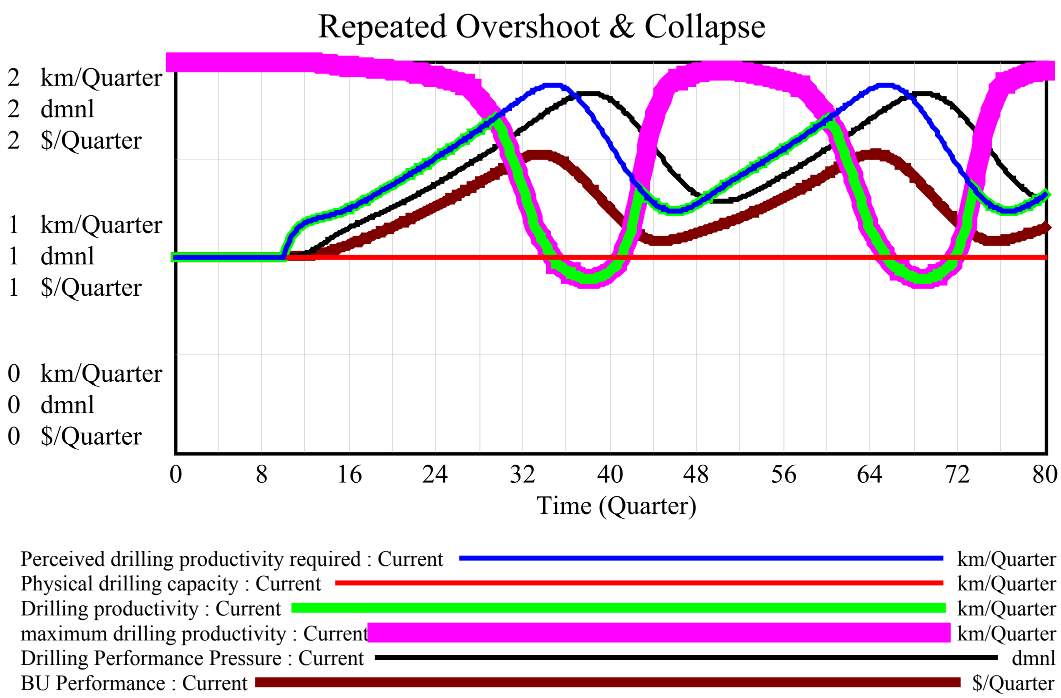
Eventually the story repeats itself and they cross again in the neighborhood of quarters 62 and 74.

Figure 5 shows the behavior of the model when the IDO is purchasing 10% of the difference between their forecast of drilling productivity required, and the physical drilling capacity they already have (See step 4 in footnote 4, where the "fraction of adjustment for capacity that management is willing to pursue" is set to 0.1.).

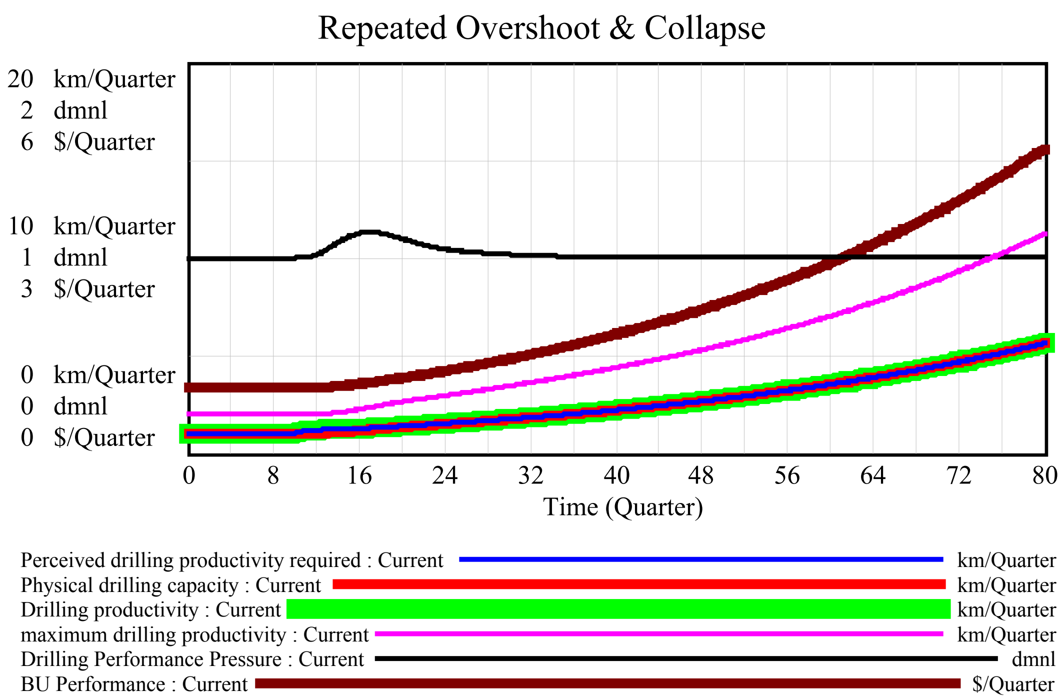
Challenge: What would the behavior in Figure 5 have been had the fraction been set to "0"?

Challenge: What would the behavior in Figure 5 have been had the fraction been set to "1"?

Sketch what you think the behavior would have been; then compare with the results in Figure 6a and Figure 6b.



a. "Fraction of adjustment for capacity that management is willing to pursue" set to 0



b. "Fraction of adjustment for capacity that management is willing to pursue" set to 1

Figure 6: Behavior when "fraction of adjustment for capacity that management is willing to pursue" is set to 0 and 1, instead of to 0.1 as in Figure 5. "Stretch fraction" = 0.2.

Policies to Improve Business Performance

Intermediate Capacity Ordering Policies:

Obviously, from Figure 6b, ordering the full gap between current physical capacity and forecast required physical capacity, eliminates the repeated overshoot and collapse behavior. How would the system respond to intermediate ordering policies in which various fractions of desired capacity are ordered? This can be tested by varying the "fraction of adjustment for capacity that management is willing to purchase" on the "Capacity acquisition" view. Note in Figure 7a-f how the system's behavior gradually changes from repeated overshoot and collapse to exponential growth as management chooses to order larger fractions of the capacity gap. Isn't it remarkable how changing one parameter can shift the behavior so dramatically!

Ordering the Full Gap Between Actual and Forecast Capacity:

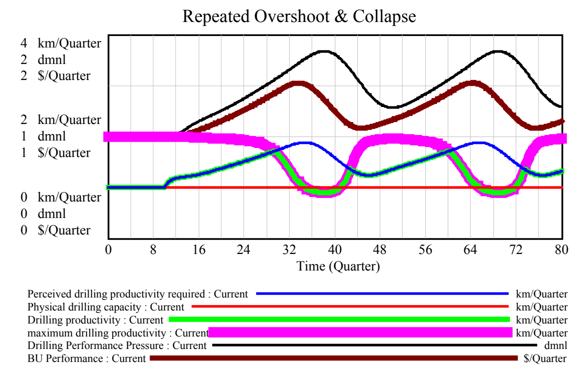
In the model, the only limitations to BU growth are drilling capacity and capacity utilization. Therefore, in the absence of drilling capacity restrictions, that is, when IBOs order new capacity when needed, BU Performance should grow exponentially. We have just seen that the model produces this result in Figure 6b.

Another interesting thing to note in Figure 7f is how "Drilling Performance Pressure" (the black line in the middle) seems to approach and remain at a little more than 1.5, indicating that the IDO will be forever under constant drilling performance pressure. Yet, looking at Figure 6b we see that "Drilling Performance Pressure" ended up at approximately 1. This is confirmed in Table 1 for the run in Figure 6b. The runs in Figure 8 a. and b. show two runs with "fraction of adjustment for capacity that management is willing to purchase" set to 0.5 and 0.75. In these two runs, "Drilling Performance Pressure" finishes at about 1.2, and 1.1, respectively.

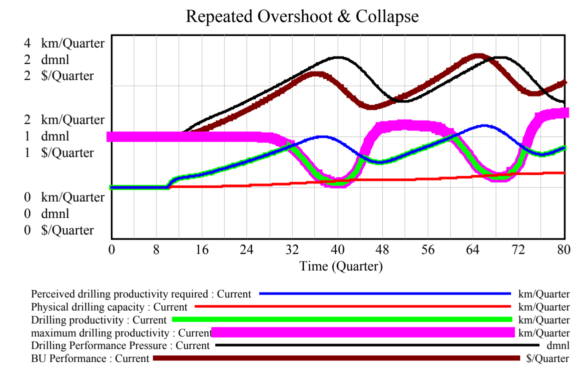
It turns out that, when "fraction of adjustment for capacity that management is willing to purchase" is set to 1, the "forecast horizon for drilling productivity required" (in the "Drilling Capacity Acquisition" view) must be adjusted to fit the delays in the model in order to get the capacity ordering policy adjusted to yield "Drilling Performance Pressure" = 1 over the long term. Intuitively, it would seem that the "forecast horizon for required drilling productivity" should be equivalent to the "capacity delivery time." Figure 9 tests this intuition. Note the permanent increase in "Drilling Performance Pressure" to 1.044, indicating a fault in this intuition.

To adjust the forecast horizon to fit the delays in the system, the model contains a parameter, "capacity forecast horizon multiplier," which factors "capacity delivery time" to yield the "forecast horizon for required drilling productivity" required to produce "1" as the long-term value for "Drilling Performance Pressure." With experimentation, it was found that, when "fraction of adjustment for capacity that management is willing to purchase" is set to "1," a "capacity forecast horizon multiplier" of "1.305" yields "1" for long term "Drilling Performance Pressure."

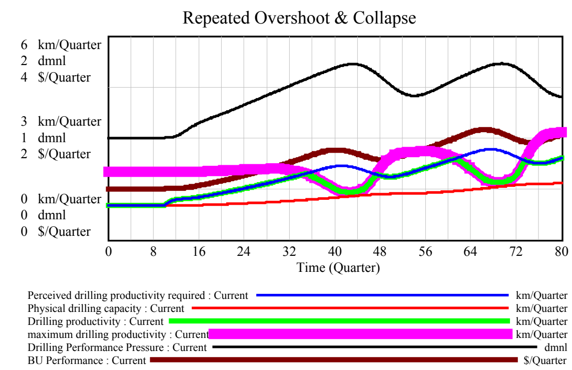
Thus, we reach the non-intuitive conclusion that the forecasting rule, which is part of the capacity ordering rule, should vary as a function of the length o f all the delays in the system, not just the “capacity delivery time” delay.



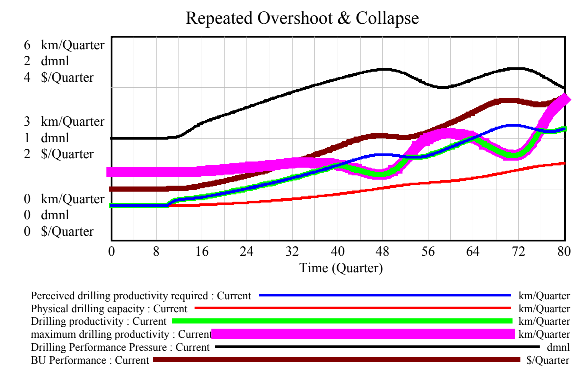
a. Fraction of adjustment for capacity that management is willing to purchase = 0 (same as Figure 6a)



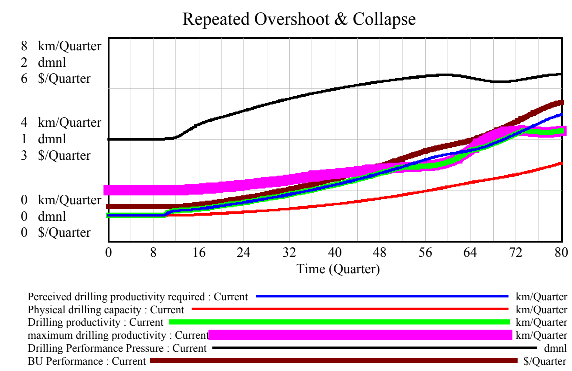
b. Fraction of adjustment for capacity that management is willing to purchase = 0.05



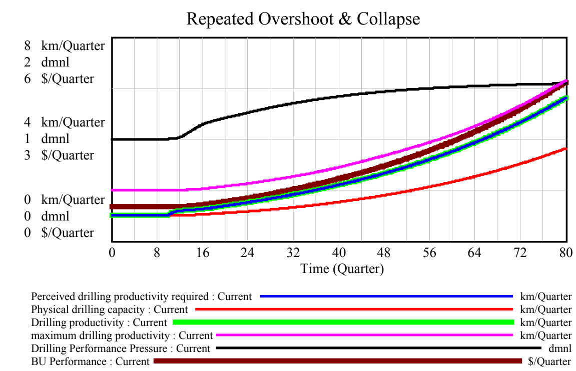
c. Fraction of adjustment for capacity that management is willing to purchase = 0.1 (same as Figure 5



d. Fraction of adjustment for capacity that management is willing to purchase = 0.15



e. Fraction of adjustment for capacity that management is willing to purchase = 0.2

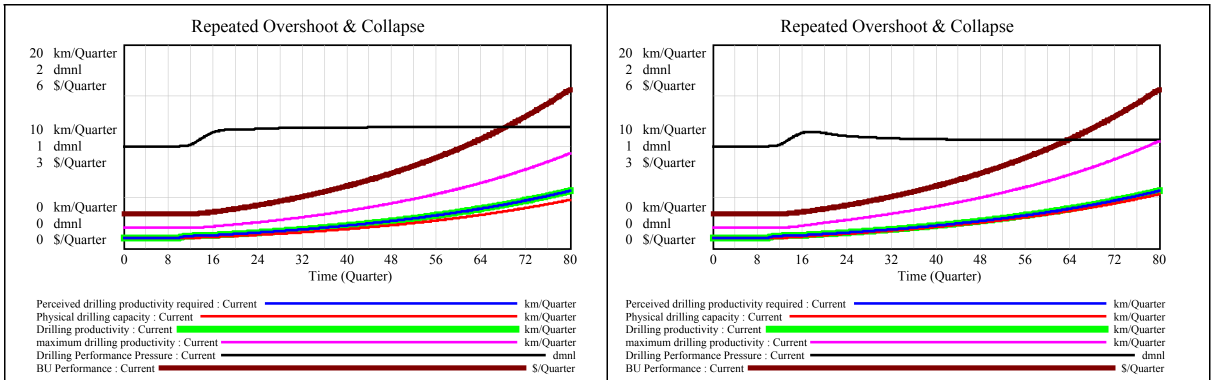


f. Fraction of adjustment for capacity that management is willing to purchase = 0.25

Figure 7: Differences in behavior as "fraction of adjustment for capacity that management is willing to purchase" is adjusted from 0 to 0.25. “Stretch fraction” = 0.2. Note the gradual shift in behavior mode from repeated overshoot and collapse in the top left, to exponential growth in the bottom right. Note that y-axis scales change as you move down the page.

Time (Quarter)	Drilling Performance Pressure
0	1
10	1
20	1.097
30	1.017
40	1.003
50	1.000
60	1.000
70	1.000
80	1.000

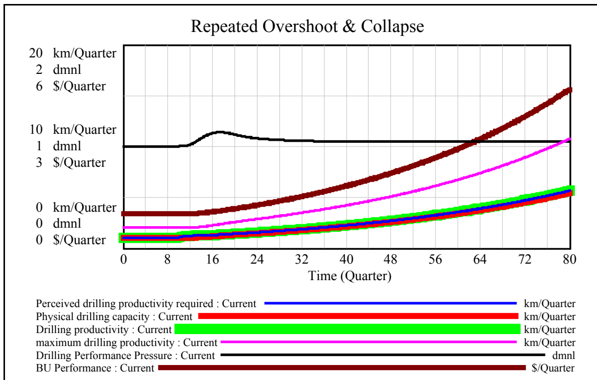
Table 1: "Drilling Performance Pressure" for Run in Figure 6b when "fraction of adjustment for capacity that management is willing to pursue" is set to 1, "Stretch fraction" = 0.2, and "capacity forecast horizon multiplier" = 1.305.



a. **Fraction of adjustment for capacity that management is willing to purchase =0.5**

b. **Fraction of adjustment for capacity that management is willing to purchase = 0.75**

Figure 8 Differences in behavior for "fraction of adjustment for capacity that management is willing to purchase" = 0.5 and 0.75. "Stretch fraction" = 0.2 in both runs. Note difference in behavior for "Drilling Performance Pressure." Compare behavior of "Drilling Performance Pressure" here with its behavior in Figures 6 & 7.



Time (Quarter)	Drilling Performance Pressure
0	1
10	1
20	1.116
30	1.057
40	1.046
50	1.044
60	1.044
70	1.044
80	1.044

Figure 9: "forecast horizon for required drilling productivity" set equal to "capacity delivery time"

Extending the Model

In all probability, real-world managers have good reasons for not immediately ordering sufficient capacity to make up for the entire gap between actual and desired capacity. Probably their reasoning includes risk of being caught with expensive capacity in a market downturn, risks which could also have extreme IDO performance implications. The model could be expanded to include managers' reasoning for their partial ordering policies. An expanded model could be useful in helping managers think about how their varying estimates of the risk of a market downturn should influence their capacity ordering policies. Perhaps there are ordering policies that produce relatively consistent BU Performance across widely varying market downturn risk estimates.

Certainly managers would want to order some capacity to mitigate repeated overshoot and collapse behavior. But what should the ordering rule be? Managers could also use the model to first study the generic BU profitability implications of the degree to which they account for the capacity acquisition supply line in their ordering rule[5]. The model could then be expanded to be more representative of the real structure of the firm's specific supply lines, and thus could be used for more detailed capacity ordering rule analysis.

Cautions on Use of the Model

The model assumes "BU Performance" varies only with "Drilling productivity," that is, all other variables that influence "BU Performance" are assumed constant. This is because our interest here is specifically the feedback between BU performance and drilling productivity. Although this is acceptable modeling practice in light of the model's purpose, we should be aware of this assumption in interpreting model results.

The model does not employ "operational thinking" (Richmond, 1993, p. 127) in its depiction of how "Drilling productivity" influences "BU Performance." A better model would include the real operational structure. This is less acceptable modeling practice, but deemed reasonable here to maintain simplicity in achieving the model's purpose. Again, being aware of this limitation is important when interpreting model results.

Finally, it's important to remember that the model structure may represent only one of many potential dynamic hypotheses for the causes of the repeated overshoot and collapse behavior. That the individual relationships between the model's variables, and that the values of the model's individual parameters, are based on the author's experience, and yet that the model produces behavior expected by the author, gives the author some degree of confidence in the model. Nevertheless, more confidence in the model would be inspired by incorporation of the mental models of more people experienced in the petroleum industry[Error! Bookmark not defined.], as well as by parameterization of the model using any available real-world data, and comparison of its behavior to real-world historical behavior.

[5] The ordering rule in "Drilling performance 14.mdl" takes the full supply line into account, which is atypical of most ordering rules. See Chapter 17 in Sterman (2000).

References

Richmond, Barry (1993) "Systems thinking: critical thinking skills for the 1990s and beyond" System Dynamics Review Vol. 9 No. 2 (Summer 1993): 113-133. Available for download from http://sysdyn.mit.edu/ as part of Road Maps Chapter 6.

Sterman, John (2000) Business Dynamics, McGraw-Hill. See: http://web.mit.edu/jsterman/www/BusDyn2.html and http://www.mhhe.com/business/opsci/sterman/

Appendix A: Vensim software "Views" of the model

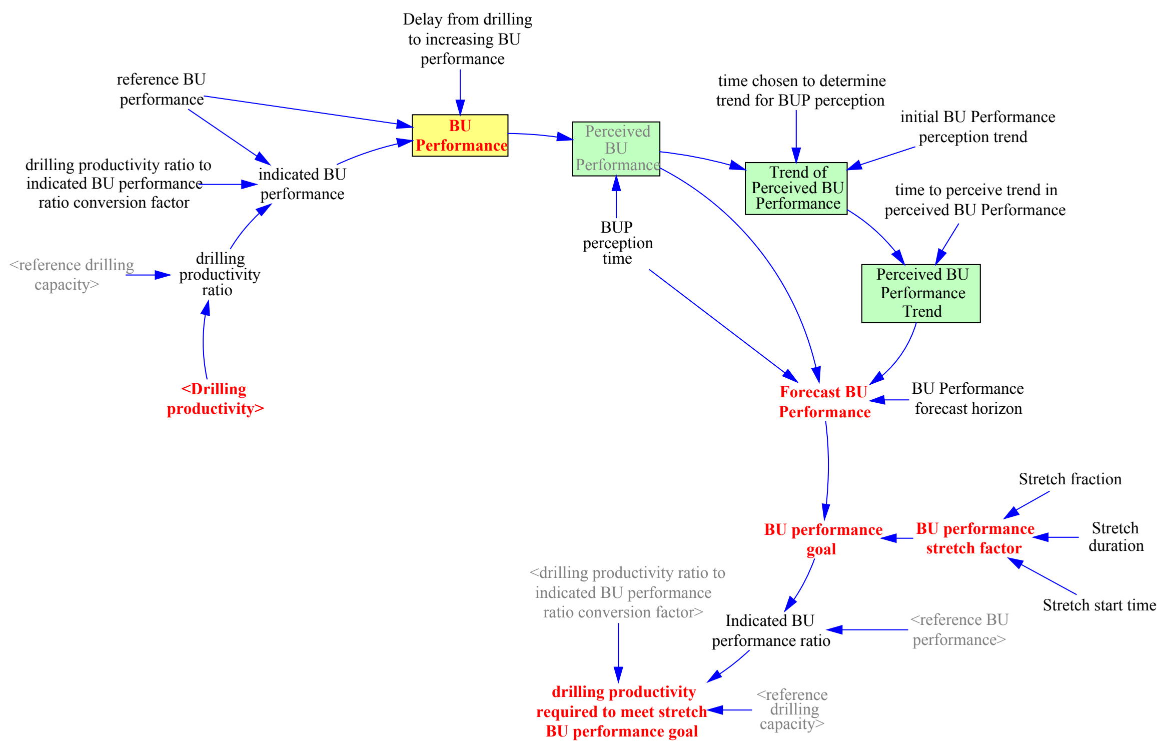


Figure 10: Business Unit Performance View (red variables shown in Figures 1, 2 & 3)

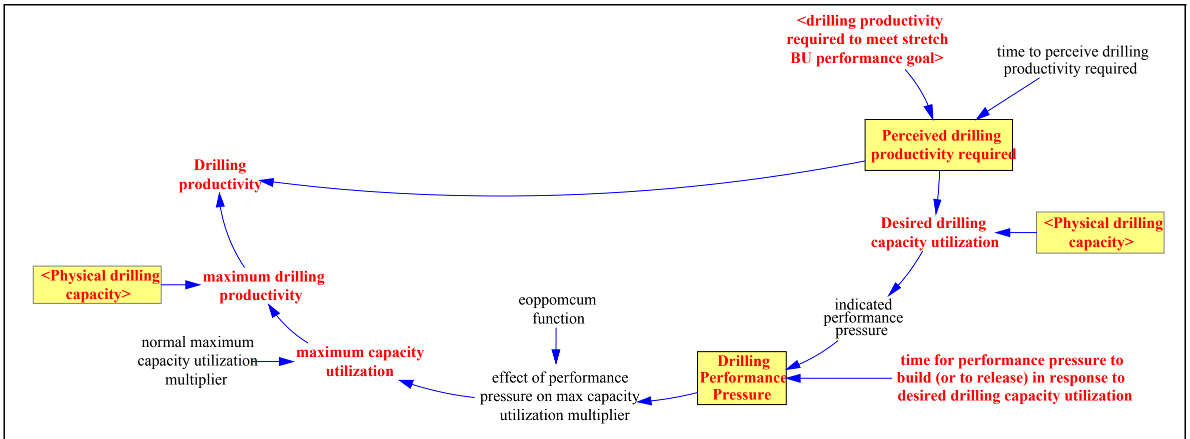


Figure 11: Drilling Capacity Utilization View (red variables shown in Figures 1, 2 & 3)

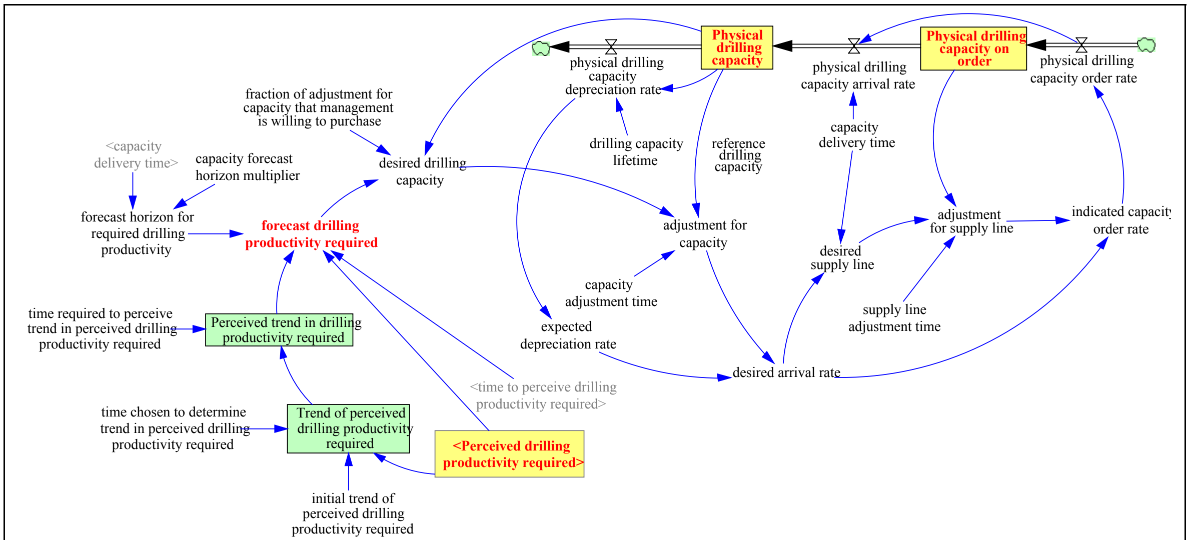


Figure 12: Drilling Capacity Acquisition View (red variables shown in Figures 1, 2 & 3)

Appendix B: Model Equations

(01) adjustment for capacity=(desired drilling capacity - Physical drilling capacity) / capacity adjustment time
Units: km/(Quarter*Quarter)
Owners of capacity seek to close the gap between their desired and physical drilling capacity. They seek to do this over some capacity adjustment time that they select.

(02) adjustment for supply line=(desired supply line - Physical drilling capacity on order) / supply line adjustment time

Units: km/(Quarter*Quarter)
The supply line is adjusted towards desired supply line over the supply line adjustment time.

(03) BU Performance=SMOOTH3I(indicated BU performance, Delay from drilling to increasing BU performance , reference BU performance)
Units: $/Quarter
Financial performance of the business unit (BU).

(04) BU Performance forecast horizon= 1
Units: Quarter
Time between the present and the time of the forecast

(05) BU performance goal=Forecast BU Performance* BU performance stretch factor
Units: $/Quarter
The BU performance goal determined by multiplying forecast BU performance by the stretch factor.

(06) BU performance stretch factor= 1 + Stretch fraction * PULSE(Stretch start time, Stretch duration)
Units: dmnl
The factor by which forecast BU performance is multiplied to obtain the BU performance goal.

(07) BUP perception time= 1
Units: Quarter
The time required to perceive business unit performance; includes measurement and reporting, as well as perception delays.

(08) capacity adjustment time= 8
Units: Quarter
The average time over which owners of drilling capacity seek to close the gap between their desired and actual drilling capacity.

(09) capacity delivery time= 6
Units: Quarter
The amount of time required for ordered capacity to be delivered and come on line.

(10) capacity forecast horizon multiplier= 1.305
Units: dmnl
A multiplier used to test the effects of various forecast horizons on long term drilling performance pressure. If management is willing to purchase all the capacity that is required, and if this multiplier is set such that all the delays in the system are accounted for, then the long term drilling performance pressure should return to 1.

(11) Delay from drilling to increasing BU performance= 8
Units: Quarter
The time required for drilling performance changes to impact BU performance.

(12) desired arrival rate= MAX (0, expected depreciation rate + adjustment for capacity)
Units: km/(Quarter*Quarter)
The rate at which new capacity is desired to arrive, given the expected capacity depreciation rate and the adjustment to bring the stock of capacity in line with desired capacity.

(13) desired drilling capacity=Physical drilling capacity + (forecast drilling productivity required - Physical drilling capacity) * fraction of adjustment for capacity that management is willing to purchase
Units: km/Quarter
The drilling capacity that the managers desire to have. Determined by adding to the existing drilling capacity the fraction, of the difference between the forecast capacity and the existing capacity, that managers are willing to purchase.

(14) Desired drilling capacity utilization= Perceived drilling productivity required / Physical drilling capacity
Units: dmnl
The degree to which the physical drilling capacity must be utilized in order to meet the perceived drilling productivity required to meet stretch the stretch BU goal.

(15) desired supply line=desired arrival rate * capacity delivery time
Units: km/Quarter
The required supply line of physical drilling capacity on order and under construction, given the desired arrival rate and the expected delay in delivery of capacity.

(16) drilling capacity lifetime= 20
Units: Quarter
The average lifetime of drilling capacity.

(17) Drilling Performance Pressure= SMOOTH3(indicated performance pressure, "time for performance pressure to build (or to release) in response to desired drilling capacity utilization")
Units: dmnl
Drilling performance pressure as it is actually felt by the IDOs. Note that sustained high values of desired drilling capacity utilization create more drilling performance pressure than do spikes in desired drilling capacity utilization.

(18) Drilling productivity= MIN (Perceived drilling productivity required , maximum drilling productivity)
Units: km/Quarter
Actual drilling productivity in kilometers drilled per quarter. It is the lesser of the drilling productivity required to meet BU performance stretch goals or the maximum drilling productivity possible.

(19) drilling productivity ratio=Drilling productivity / reference drilling capacity
Units: dmnl
The ratio of drilling productivity to reference drilling capacity. A normalized measure of drilling productivity.

(20) drilling productivity ratio to indicated BU performance ratio conversion factor
= 1
Units: dmnl/dmnl
Conversion factor for translating drilling productivity ratio into an indicated BU performance ratio. Because we are more concerned with behavior than with specific numbers, this is set at 1.

(21) drilling productivity required to meet stretch BU performance goal=reference drilling capacity * Indicated BU performance ratio / drilling productivity ratio to indicated BU performance ratio conversion factor
Units: km/Quarter
The drilling productivity required to meet the current stretch BU performance goal.

(22) effect of performance pressure on max capacity utilization multiplier = eoppomcum function (Drilling Performance Pressure)
Units: dmnl
Given a specific drilling performance pressure input, this is the output from the eospomcuf function. This output factors the normal maximum capacity utilization multiplier to produce maximum capacity utilization.

(23) eoppomcum function ([(1 , 0) - (2 , 1)] , (1 , 1) , (1.30581 , 0.973684) , (1.45566 , 0.942982) , (1.48624 , 0.925439) , (1.51682 , 0.894737) , (1.55046 , 0.864035) , (1.5841 , 0.820175) , (1.64526 , 0.697368) , (1.70031 , 0.574561) , (1.7737 , 0.482456) , (1.85015 , 0.434211) , (1.91437 , 0.407895) , (2 , 0.4))
Units: dmnl
The maximum capacity utilization multiplier factor as a nonlinear function of drilling performance pressure. At low levels of performance pressure (close to 1), the effect is minimal. At high levels, maximum capacity utilization can actually be reduced to less than normal physical drilling capacity.\!\!

(24) expected depreciation rate= physical drilling capacity depreciation rate
Units: km/(Quarter*Quarter)

The expected depreciation rate is assumed to equal the actual depreciation rate.

(25) FINAL TIME = 80
Units: Quarter
The final time for the simulation.

(26) Forecast BU Performance= Perceived BU Performance * (1 + Perceived BU Performance Trend * BUP perception time) * EXP(Perceived BU Performance Trend * BU Performance forecast horizon)
Units: $/Quarter
The forecast of business unit performance. See Equation 16-2 on page 640 of Sterman, John (2000) Business Dynamics. McGraw-Hill.

(27) forecast drilling productivity required= Perceived drilling productivity required * (1 + Perceived trend in drilling productivity required * time to perceive drilling productivity required) * EXP(Perceived trend in drilling productivity required * forecast horizon for required drilling productivity)
Units: km/Quarter
The forecast of drilling productivity required. See Equation 16-2 on page 640 of Sterman, John (2000) Business Dynamics. McGraw-Hill.

(28) forecast horizon for required drilling productivity= capacity forecast horizon multiplier * capacity delivery time
Units: Quarter
Time between the present and the time of the drilling capacity forecast. This should take into account the delays in acquiring productive capacity as well as the delays in that new capacity's effects on business unit productivity.

(29) fraction of adjustment for capacity that management is willing to purchase = 0
Units: dmnl
Management may choose to purchase all of the difference between actual capacity and forecast capacity, or some portion of it. This is the fraction that management chooses to purchase.

(30) indicated BU performance= drilling productivity ratio * drilling productivity ratio to indicated BU performance ratio conversion factor * reference BU performance
Units: $/Quarter
Business Unit (BU) financial performance that should result from current drilling productivity.

(31) Indicated BU performance ratio=BU performance goal/reference BU performance
Units: dmnl
The ratio of the business unit performance goal to reference business unit performance. A normalized measure of business unit performance.

(32) indicated capacity order rate= desired arrival rate + adjustment for supply line

Units: km/(Quarter*Quarter)
The sum of the desired arrival rate and the adjustment for the supply line, which keeps the supply line of drilling capacity on order aligned with the level required to yield the desired arrival rate.

(33) indicated performance pressure= Desired drilling capacity utilization
Units: dmnl
Performance pressure indicated by desired capacity utilization. Because desired drilling capacity utilization is normalized, the same value is used.

(34) initial BU Performance perception trend= 0
Units: 1/ Quarter
Since business unit performance is initially in equilibrium, the initial BU performance trend (fractional rate of change) is 0.

(35) INITIAL TIME = 0
Units: Quarter
The initial time for the simulation.

(36) initial trend of perceived drilling productivity required= 0
Units: 1/Quarter
The initial fractional rate of change of perceived drilling productivity required. Since the model is initially in equilibrium, the initial trend of perceived drilling productivity required (fractional rate of change) is 0.

(37) maximum capacity utilization= normal maximum capacity utilization multiplier * effect of performance pressure on max capacity utilization multiplier
Units: dmnl
The maximum capacity utilization possible at current levels of drilling performance pressure. Performance pressure reduces the maximum capacity utilization possible by causing reduced maintenance of drilling equipment, excessive overtime for long periods, and lack of adequate preparation for drilling operations.

(38) maximum drilling productivity=Physical drilling capacity * maximum capacity utilization
Units: km/Quarter
The maximum drilling capacity at current levels of drilling performance pressure.

(39) normal maximum capacity utilization multiplier= 2
Units: dmnl
The maximum possible capacity utilization factor under normal drilling performance pressure (= 1).

(40) Perceived BU Performance= SMOOTH(BU Performance, BUP perception time)
Units: $/Quarter

The level of business unit performance cannot be known instantaneously, but is perceived after a delay.

(41) Perceived BU Performance Trend=SMOOTH (Trend of Perceived BU Performance, time to perceive trend in perceived BU Performance)
Units: 1/ Quarter
The perceived fractional rate of change of BU performance.

(42) Perceived drilling productivity required= SMOOTH (drilling productivity required to meet stretch BU performance goal , time to perceive drilling productivity required)
Units: km/Quarter
The IDO's perceptions of the drilling productivity required to meet the BU's performance goal.

(43) Perceived trend in drilling productivity required=SMOOTH (Trend of perceived drilling productivity required , time required to perceive trend in perceived drilling productivity required)
Units: 1/ Quarter
The perceived fractional rate of change of perceived drilling productivity required.

(44) Physical drilling capacity= INTEG (physical drilling capacity arrival rate - physical drilling capacity depreciation rate , reference drilling capacity)
Units: km/Quarter
The IDO's physical drilling capacity, including drilling operations personnel.

(45) physical drilling capacity arrival rate= DELAY3(physical drilling capacity order rate, capacity delivery time)
Units: km/Quarter/Quarter
A third order drilling capacity acquisition delay is assumed for the ordering and construction of drilling capacity.

(46) physical drilling capacity depreciation rate= Physical drilling capacity/drilling capacity lifetime
Units: km/Quarter/Quarter
The drilling capacity lifetime determines the rate at which drilling capacity decays and is discarded.

(47) Physical drilling capacity on order= INTEG (physical drilling capacity order rate - physical drilling capacity arrival rate , (reference drilling capacity / drilling capacity lifetime) * capacity delivery time)
Units: km/Quarter
The physical drilling capacity on order and under construction.

(48) physical drilling capacity order rate= MAX (0, indicated capacity order rate)

Units: km/Quarter/Quarter
The drilling capacity order rate is constrained to be non-negative (cancellation of orders is not permitted).

(49) reference BU performance= 1
Units: $/Quarter
BU performance at the start of the simulation before stretch BU performance goals are implemented. Because we are interested in the modes of behavior rather than exact $ figures, this is set to 1 $/quarter. This could be scaled to match more realistic BU performance.

(50) reference drilling capacity= 1
Units: km/Quarter
Drilling capacity in kilometers drilled per quarter when in equilibrium at the start of the simulation, before stretch goals are implemented, when drilling performance pressure is 1. 1 km/quarter is chosen as its value because we are interested in modes of behavior and not specific values. This could be scaled to match more realistic drilling capacity.

(51) SAVEPER = TIME STEP
Units: Quarter
The frequency with which output is stored.

(52) Stretch duration= 100
Units: Quarter
The length of time over which the stretch factor is applied.

(53) Stretch fraction= 0
Units: dmnl
The fraction which, when added to 1, gives the factor by which forecast BU performance is multiplied to obtain the BU performance goal.

(54) Stretch start time= 10
Units: Quarter
The time when the stretch factor is applied.

(55) supply line adjustment time= 2
Units: Quarter
The time period over which the supply line of drilling capacity on order or under construction is adjusted to the desired supply line.

(56) time chosen to determine trend for BUP perception= 2
Units: Quarter
The amount of time chosen by the business over which to determine its fractional rate of change of performance (trend of BU performance).

(57) time chosen to determine trend in perceived drilling productivity required = 3
Units: Quarter
The amount of time chosen by the capacity owner over which to determine the trend (frational rate of change) of drilling productivity required.

(58) "time for performance pressure to build (or to release) in response to desired drilling capacity utilization"= 4
Units: Quarter
The time required for performance pressure to respond to changes in desired drilling capacity utilization.

(59) time required to perceive trend in perceived drilling productivity required = 1
Units: Quarter
The time required for the capacity owner to perceive the trend in drilling productivity required.

(60) TIME STEP = 0.125
Units: Quarter
The time step for the simulation.

(61) time to perceive drilling productivity required= 1
Units: Quarter
The time required for the IDOs to perceive the drilling productivity required by the BUs to meet their performance goals.

(62) time to perceive trend in perceived BU Performance= 1
Units: Quarter
The time required for the business to perceive the trend in its business unit performance.

(63) Trend of Perceived BU Performance= TREND(Perceived BU Performance, time chosen to determine trend for BUP perception , initial BU Performance perception trend)
Units: 1/ Quarter
The fractional rate of change of business unit performance.

(64) Trend of perceived drilling productivity required= TREND(Perceived drilling productivity required, time chosen to determine trend in perceived drilling productivity required , initial trend of perceived drilling productivity required)
Units: 1/ Quarter
The fractional rate of change of perceived drilling productivity required.

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