

MATERIAL SUPPLY SIMULATION FOR OFFSHORE PIPELAYING CONSTRUCTION

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ABSTRACT

The planning and execution of offshore construction projects such as pipelaying traditionally rely to a great extent on the expertise of the offshore personnel. The state of practice that is facilitated by this expertise often leads to good solutions, but it has the following limitations: (1) the expertise resides with a few experienced people who are not always available, (2) communication between the contractor and the customer is based on opinions and past experiences, and not necessarily on objective information, (3) consideration and comparison of alternative solutions and their impact on cost and time is not straightforward, (4) estimation, planning and control under new conditions and different ones from the past are not always effective leading to either conservative or inadequate solutions. In this paper, simulation is used as a decision support, planning, control, and process improvement tool. The simulation model developed is applied to the loading of the barge at the coating yard, the transportation of the material to the pipelaying site, and the pipelaying activity performed by the pipelaying vessel. The model captures the expertise of the offshore personnel and addresses effectively the limitations listed above. An object-oriented environment is used to develop the simulation model that is proven to be very effective for the particular project for which it was developed and easily adjustable to any new pipelaying project.

1 INTRODUCTION

The application of computers to simulate construction operations or processes that exhibit repetitive nature has been increasing in the recent years. Several reasons have attributed to this increase: the successes of simulation in the manufacturing world, the intense efforts of the academic researchers with focus on investigating the potential of simulation in construction, the improvement of the simulation tools (Profozich 1997), the limitations of the critical path and PERT methods especially in addressing construction problems at the process level (Dabbas and

Halpin 1982; Senior and Halpin 1998), the increasing awareness of construction professionals to interpret and understand results of simulation expressed in statistical measures, and finally the initiatives of the industry to “reengineer” its business processes at all levels. With regard to the reengineering initiatives, process flow mapping and simulation have played a serious role. Halpin (1993) calls the construction industry “a process-based industry” and he feels that “... the basis for a theory of construction operations and the study of construction lies in the area of process modeling and simulation”.

The concept of hierarchical modeling in simulation was first presented by Halpin and Woodhead (1976); it was used by AbouRizk and Dozzi (1993) and enhanced by Sawhney and AbouRizk (1995). The last two researchers demonstrated the potential of reusability and assembly of modular operations and processes that can be facilitated by object-oriented technology and by the creation of “libraries”.

Computer simulation has also been applied to modeling offshore construction operations and specifically pipelaying operations. The number of cases reported is limited compare with on-land construction applications. McCarron (1971) used computer simulation to evaluate bids on offshore pipeline projects. The simulation model developed in that study focuses on the pipelaying vessel and specifically on the evaluation of weather effects on laying time and cost materialized by the pipelaying vessel. The simulation model accounts for delays in construction due to bad weather, but does not allow for any major equipment breakdowns or mechanical failures.

Pearce and Kishpaugh (1973) applied simulation to estimate the cost and length of time required to complete offshore pipeline construction. They accounted for interruptions due to weather, laybarge towing, abandonment and recovery operations of the pipe, equipment and pipe repair, and pipe re-supply. The model was focused on the pipelaying vessel operations.

In this paper discrete-event simulation is used to model offshore pipelaying operations. The model generated in this effort spans over the several components

of the pipelaying operations. The generic nature of the model due to its architecture, which is facilitated by an object-oriented computing environment and an integrated database, allows detailed customization of the model to all components of any pipelaying operation. In this paper in particular, the model is properly customized to represent more thoroughly the details of the movement of the fleet of the material barges and tugboats between the coating yard and the pipelaying vessel. Sufficient planning and controlling of the movement of the fleet is important for efficiently maintaining the material flow to the pipelaying vessel uninterrupted. The simulation model is demonstrated as both a planning tool prior to the commencement of the job and a control tool during the job execution. The paper is organized as follows. Section 2 states the problem definition and objectives. Section 3 outlines the simulation model developed. Section 4 presents the input data and the results of the simulation experiments, and compares the alternative solutions to the problem. Finally, the last section presents the conclusions.

2 PROBLEM DEFINITION AND OBJECTIVES

2.1 Overall Description

The safest and most efficient way to bring oil and gas ashore is through pipelines laid on the ocean floor. Laying pipelines is conducted with pipelaying vessels that include conventional barges and semisubmersibles. There are primarily three methods for laying pipelines: the conventional method called S-laying, the J-laying method and the reel methods.

In this study data of the S-laying method is used. In the S-laying method, the pipelaying vessels have a production line along the length of the vessel at which pipe sections are assembled sequentially at a series of welding stations manually or automatically. The continuous pipeline passes over the vessel stern and onto the stinger, which supports the pipe and prevents overstressing as it curves from an horizontal position downward the sea floor (see Fig. 1). The pipe undergoes a second bend above the contact point at sea bottom and comes to rest on the sea floor. The profile of the pipe looks like an “S” and this has generated the name S-laying. Meanwhile heavy anchors and strong cables restrain the pipelaying vessel. Periodically, the anchors are moved ahead individually to maintain a proper mooring pattern and allow continuous pipelaying progress, so as not to lose tension on the pipe and to allow the vessel to pull ahead.

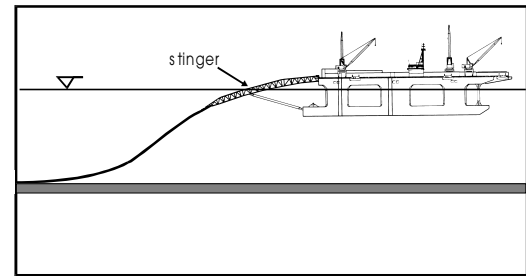


Figure 1: Schematic of Conventional (S-laying) Pipelaying

2.2 Problem Details

In this section, the overall pipelaying operations are described. Primarily the following operations are distinguished:

(a) The Coating Yard.- In this area steel pipe segments are coated with concrete to provide the weight necessary to counteract the buoyancy. The coated pipe segments are then loaded onto proper material barges. These barges are moved in and out of the docking stations with tugboats. The coating yard can handle one material barge at the time, and is open from certain time to certain time. Overtime hours can be used for the loading of the material barges depending upon the need. The barge loading time can vary depending upon the yard and the equipment.

(b) Travel from the Coating Yard to the Sea Buoy.- This travel can follow different routes depending upon the draft of the tugboats relative to the water depth of the route as well as the location of the area where the pipelaying operation will take place. Delays at locks or curfews at bridges may occur along the route.

(c) Travel from the Sea Buoy to the Pipelaying Vessel.- Mean travel time of the material barge and a sea-going tugboat to the pipelaying vessel is dependent upon the location of the pipelaying vessel; this vessel moves during the pipelaying operation along the predetermined path of the pipeline.

(d) Barge unloading and pipelaying by the Pipelaying Vessel.- The material barge is tied to the pipelaying vessel during the unloading of the barge and while pipe is laid on the bottom of the sea. A tugboat stays with the material barge during the unloading operation. The pipe segments are unloaded, as they are needed by the pipelaying operation. An initial inventory of joints is maintained on the pipelaying vessel. It should be noted that traditionally the operations personnel on the pipelaying vessel, under normal conditions, would try to avoid making use of the inventory. Inventory was used only under exceptional conditions when there was a delay of the arrival of the material barge for example due to weather conditions. In this study the initial inventory is treated as material available for use during normal operations and not

only under exceptional conditions. Therefore, when no pipe is available from the material barge, the pipelaying vessel will draw from its initial inventory. The initial inventory is then restocked from the next material barge.

(e) Travel from the Pipelaying Vessel to the Sea Buoy.- Mean return travel time of the material barge and the sea-going tugboat to the sea buoy is dependent upon the location of the pipelaying vessel at the time the material barge is emptied. This time can be calculated based on the number and length of pipes on the material barge, the coordinates along the pipeline, and the speed of the tugboat.

(f) Travel from the Sea Buoy to the Coating Yard.- The empty material barge is swapped for a full one at the sea buoy and is transported by tugboats back to the coating yard. Delays at locks or curfews at bridges may occur along the route.

(h) Weather.- Weather conditions may impact the travel times and the pipelaying vessel operation, but not the coating yard operations.

2.3 Problem Objectives

The objectives of the problem primarily are to determine:

- the minimum number of material barges and tugboats necessary to support the pipelaying vessel operation without shutting it down
- the cost and total duration of the operations
- the required loading rate and operating hours of the coating yard
- the initial date as well as the total duration required for the equipment to be engaged to the project
- the preferred route from the coating yard to the pipelaying vessel.

3 SIMULATION MODEL

The pipelaying operations were analyzed with discrete simulation. The simulation models were developed using Extend version 3.2.2 for the PC (see Extend user manual 1995). It is an Object-Oriented environment in which models are built by assembling and connecting objects. These objects are supplied in libraries or can be created using a built-in, compiled scripting language.

A very useful feature used in this study is the *Hierarchical modeling*. This modeling technique makes complex systems easy to build and understand. The basis of hierarchical modeling is the hierarchical object, which contains other objects that are connected like they would be in a model. These objects represent a portion of the model, or a subsystem. Hierarchical objects can be saved in libraries, and they can have custom icons and animation.

The simulation model was built as a generic model applicable to a whole class of pipelaying projects. Due to the modular and hierarchical object-oriented environment, customization of the structure of the model can be done easily.

The basic components of the simulation model are presented in figure 2. The arrows present the flow of information between the components. The components of the model are described below, except for the Control Blocks and Model Blocks due to space limitations. For those components and for a more detailed explanation of the simulation model we refer to Angelides, et al. (1998).

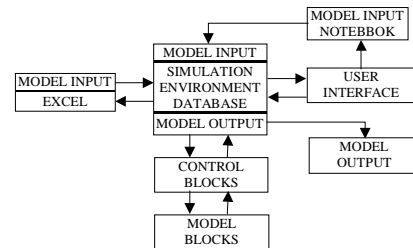


Figure 2: Overall System Architecture

3.1 User Interface

Once a set of scenarios has been defined in the database and loaded into the simulation model, the user runs the model using the interface. The hierarchical nature of the simulation environment allowed the details of the model to be hidden behind a generic animated picture of the pipelaying operation. In figure 3, this model interface is shown midway through a run. The animation of the basic elements of the problem allows the user to watch the model run, identifying any setup problems that may exist. Animation shows the operation of the coating yard, the location and movements of the barges and tugboats, the location of the sea buoy, the pipelaying operation, and the pipeline that has been laid.

Animation allows the user to become familiar and comfortable with how the simulation is working, providing a visual means of validation. But watching the animation is not sufficient for validation of the model or verification of the computer program. To truly see the details of what is happening in the model, a text trace reports the decisions and actions of the model, with each message date and time stamped. These trace messages flash across the bottom of the screen as seen in figure 3. The model can be paused at each message to allow detailed examination of the workings of the model.

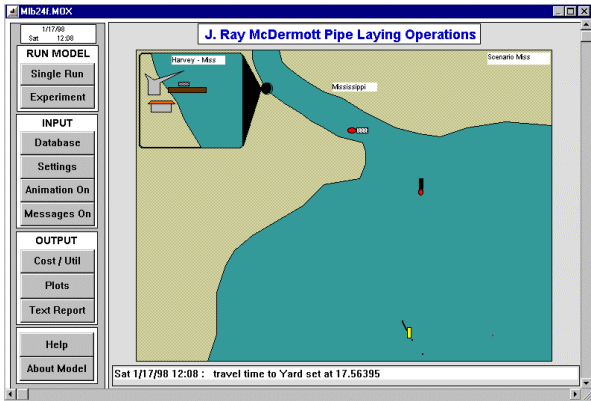


Figure 3: User Interface

The model user interface has everything the user needs to operate the model without opening the innards of the model or even having to access the software's menu. Buttons allow the user to run the model, view the output data and plots, or view and modify the input data in the integrated database.

3.2 Model Input

All the data that drives the model is stored in an integrated simulation database. The database exists both: in Excel, as tables in a Workbook, and in the Extend simulation environment, as shared arrays. The Excel instance of the database has the advantage of providing an environment familiar to the model users. Once the data has been defined in Excel, it is written to a text file and read into the simulation environment. The simulation environment instance of the database facilitates rapid simulation execution as all data is in memory when the model executes; in the same time it makes the data readily available to the users to manipulate as they explore and experiment with the model.

The database consists of 27 tables of data. Each table contains data specific to one aspect of the model, from the running of the coating yard to the offshore pipelaying operation. Tables contain the capacities of the material barge for each type of pipe used in the model, the number of joints of pipe of that size to be laid, the length of each joint, and the time required to load the material barge. Each time in the database can be defined as a fixed (constant) value or as a probability distribution. Tables also contain descriptions of the possible routes that can be traveled, the coordinates of the pipe to be laid and the sea buoy to be used for barge transfer, costs of the equipment, productivity rates of the laying operation (by day or by distance laid), or contain output data.

While all model data resides in the database, there are certain data that needs special accessibility. This data was added to the model's notebook, which can be accessed by clicking on the "Settings" button of the User Interface. An example is the arrival and departure dates for the various

pieces of support equipment. This data over-rides the data read in from the database, and is used in place of the database tables for initial study and final tuning of the equipment requirements.

3.3 Model Output

The "Text Report" button under "OUTPUT" on the left side of the User Interface screen can be used to open the trace, previously mentioned, using Microsoft's Wordpad or Notepad.

Clicking on the "Cost / Util" button of the User Interface screen opens the screen shown in figure 4. In this figure, number of days and equipment cost for the last replication of the simulation are presented on the first three lines. Also, presented are the number of each equipment type with their utilization, the number of operating days and idle time for the pipelaying vessel (LBxx), and the yard overtime used. All these quantities are presented by their mean, standard deviation and the difference of the 95% *t* confidence intervals from the mean for all the replications run in the simulation. The simulation environment database contains output data for every run and it allows additional statistical analysis if this is desired.

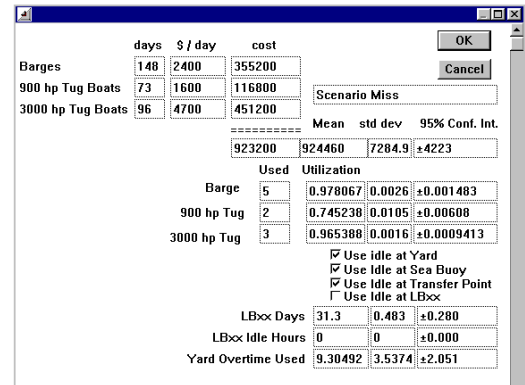


Figure 4: Cost, Utilization and Time Results

By clicking on the "Plots" button of the User Interface screen, another screen is obtained that contains output plots of the model.

3.4 Experimentation

The database was designed to allow the user to set up experiments using the model. These experiments can compare different routing scenarios or the same routing with different equipment configurations. Random numbers in the model database have been carefully configured to assure that an independent stream of random numbers is used for each random input. "Matched pairs" (see Ioannou and Martinez 1986, and Law and Kelton 1991) are used as a variance reduction technique. With this technique, in the analysis of alternatives, each scenario is subjected to the same random events.

4 SIMULATION EXPERIMENTS

4.1 Description of Input Data

In this particular study, the pipelaying vessel named LB30 is laying 6890 pipe sections (joints) of 30” diameter and length 39.3 feet in the Gulf of Mexico. The pipe is transported from the Harvey Coating Yard to LB30 using material barges. The barge load for the first 3712 joints is of 288 joints; the barge load for the remaining joints is 353 joints of pipe. Two sizes of tugboats are used: 900 hp tugboats and 3000 hp sea going tugboats.

The barges/tugboats can travel from and to the Harvey Coating Yard to and from LB30 following three routes. These three routes with the equipment and travel times are presented in Fig. 5. Uniform probability distributions were assumed for travel times. In this figure the double arrows denote the travel of the equipment upstream and downstream as well; the single arrows denote the travel upstream or downstream depending upon the direction of the arrows. In addition to the information presented in Fig. 5, it should be noted that for the case of the ICW route a bridge curfew occurs for Monday through Friday from 6:00 am to 8:30 am and from 4:00 pm to 6:00 pm. In Table 1 the travel speed of the equipment is presented. The cost of the equipment is presented in Table 2.

Table 2: Cost of Equipment

Equipment Type	Cost per day (\$)
250 class material barge	2,400 per barge
900 hp tug boat	1,600 per tug
3000 hp tug boat	4,700 per tug
load out facility	costs paid by others
LB30	135,000

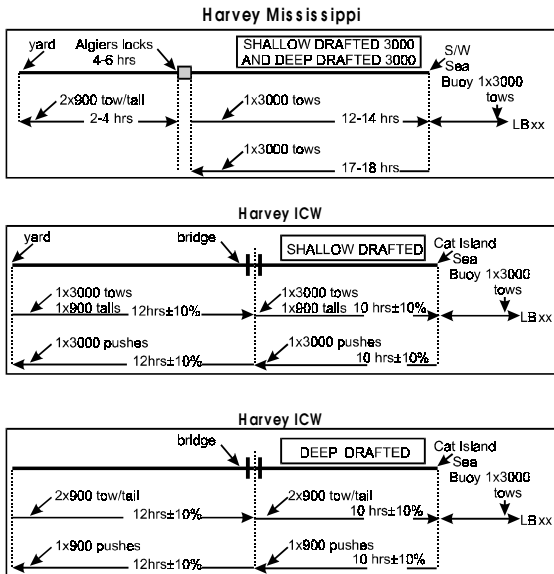
The initial inventory on LB30 is 160 joints. The LB30 estimated pipe laying rates before the commencement of the job are presented in Table 3. During the execution of the job, different actual rates were materialized. The actual rates for the first 33 days are presented in Table 4. It should be noted that experts involved with the operations provided all input information.

Table 3: LB30 Estimated Pipe Laying Rates

Day	Laying Rates (Number of joints per day)	
	Minimum	Maximum
1	30	55
2	60	110
3	70	110
4	100	140
5	110	150
6	150	210
7, 8, 9	190	220
10	200	230
11 - 17	200	250
18....	220	280

Table 4: LB30 Actual Pipe Laying Rates

Day	Laying Rates (No. of joints per day)
1	8
2, 3	46
4	107
5, 6, 7	141
8	165
9	84
10, 11	136
12, 13	175
14	162
15	145
16	173
17	189
18	170
19	151
20, 21	125
22	112
23	22
24, 25, 26	1
27	68
28	218
29	227
30, 31	190
32	206
33	201



Note: ICW Stands for Inter Coastal Waterway

Figure 5: Material Barge Routes

Table 1: Travel Speed of Equipment

Travel Speed	Knots per hour
Sea Buoy to LBxx (Loaded Barge)	6.0
LBxx to Sea Buoy (Empty Barge)	7.0

4.2 Results and Comparisons

Two sets of cases were investigated: Set 1, which used estimated lay rates for LB30 as presented in Table 3, and Set 2, which used the actual rates as presented in Table 4 for days 1 through 33 and an estimated rate of 210 joints/day for day 34 till the end of the project. In each

simulation case 15 replications were run; this was tested to be a sufficient number of replications.

Set 1 Cases.- In this set of cases three routes were analyzed as presented in Fig. 5, i.e., the Mississippi route, the ICW route with shallow drafted 3000 tugboats and the ICW route with deep drafted 3000 tugboats. The Coating Yard for all cases was operated for 24 hrs.

The three cases analyzed are summarized in Table 5. For these three cases, the usage of the equipment has been determined so the downtime of the LB30 is always zero which implies minimum risk. As can be seen in Table 5, Route 1 (Mississippi) requires slightly shorter time of the LB30 operations; however, the cost of transportation is higher by \$18,000 compared to Route 3 (ICW with deep drafted 3000 hp tugs). Route 2 is the most expensive route. Route 1 could be chosen over Route 3 because of the shorter operating time of LB30 and the lighter river traffic as it has been experienced by the tugboat captains. The variation of the LB30 joint inventory is presented vs. the material barge load number in Fig. 6. In particular, the dots represent the simulation replications, while the solid line represents the mean value across the replications.

Set 2 Cases.- In Set 1 Cases, Mississippi route was determined to be the preferred one. That conclusion confirmed the experience and expectation of the operations personnel. During the execution of the project due to several reasons, the actual rates for the first 33 days of Table 4 were quite smaller compared to the estimated rates of Table 3. The obvious consequence would be an increase in the duration of the project; therefore, it was decided to conduct further analysis using the actual rates of Table 4 for the first 33 days and an estimated daily rate of 210 joints for the remaining portion of the project. This additional analysis comprised the Set 2 Cases. These cases are summarized in Table 6. Here it should be noted that the simulation model using the actual conditions for the first 33 days confirmed the progress of the project up to that point. This was a good validity check for the simulation model.

The four cases of Table 6 have the same number of fleet equipment with the same arrival times as in Set 1 Cases except for the number of material barges that are four instead of five; the arrival times for these four material barges are the same with the arrival times of the first four barges in Set 1 Cases. Furthermore, the cases of Table 6 differ from each other with regard to: (a) the Coating Yard loading rates and (b) the Coating Yard operating hours with overtime. The variation of the LB30 inventory for these four cases is shown in Fig. 7.

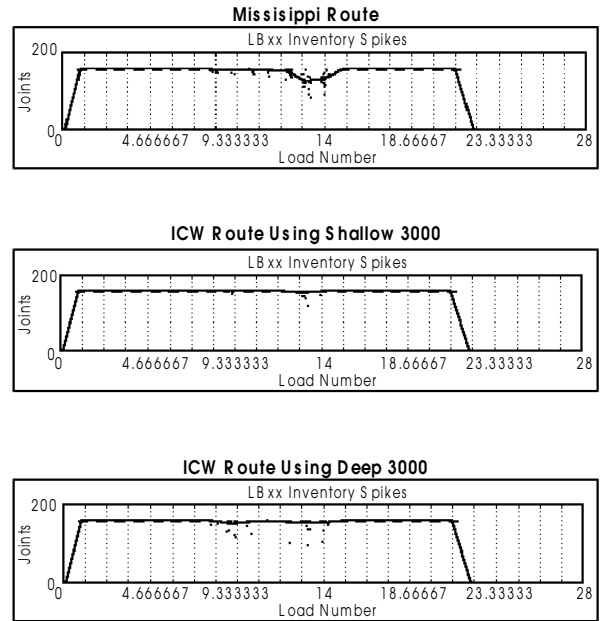


Figure 6: LB30 Inventory vs. Load Number Set 1 Cases

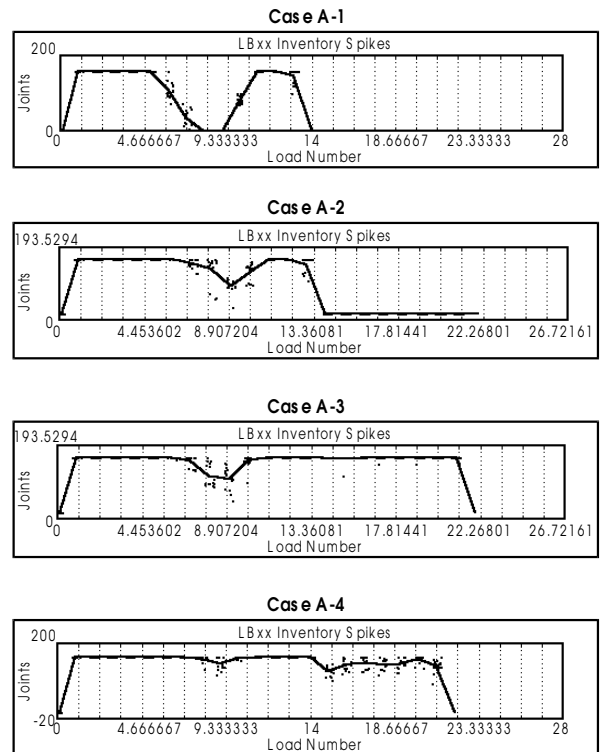


Figure 7: LB30 Inventory vs. Load Number Set 2 Cases

Table 5: Route Comparison using Estimated Pipelaying Rates

Route Number	Route Description	Number / Scheduled Start Day			LB30 Start Day	Cost (\$)	LB30 Days	LB30 Idle Hrs
		Barges	900	3000				
1	Mississippi	5/1,3,5,7,10*	2/1,2	3/2,4,7	4	924,460	31.3	0.0
2	ICW w/Shallow 3000	5/1,2,3,6,20	3/1,2,6	4/2,4,7,21	3	966,550	32.0	0.0
3	ICW w/Deep 3000	5/1,2,3,4,15	5/1,1,2,2,4	2/2,4	3	906,510	32.0	0.0

*Note: The notation 5/1,3,5,7,10 means the five barges arrived on day 1, day 3, day 5, day 7 and day 10 respectively. The same interpretation applies to the rest of the numbers.

Table 6: Analysis using Actual Pipelaying Rates during Project Execution (Mississippi Route)

Case	Yard Hrs + OT	Coating Yard Loading Rate		Cost (\$000)	LB30 Operations	
		Day	Joints/Hr		Days	Idle (Hrs)
A-1	0600-1800+2 OT	1	10	1,518	57.5	286
A-2	0600-1800+2 OT	1	10	1,476	57.7	246
		10	14			
A-3	0600-1800+6 OT	21	10	1,228	47.1	0
		1	10			
		10	14			
A-4	0400-2400+4 OT	21	21	1,209	45	0
		31	26			
		1	12			
		31	16			

In Case A-1 the loading rates of 10 joints/hr and yard operating hours of 6:00 am to 6:00 pm with 2 hours of overtime were used. As it can be seen, the inventory of LB30 dropped to zero for an extensive amount of time which implies shutdown of the LB30 operation for 286 hours. The operating time of LB30 is 57.5 days and the total transport cost is \$1,517,960.

To remove the inventory dip between material barge load numbers 6 and 10 the yard loading rate was increased to 14 joints/day between day 10 and 21. This is reflected in Case A-2. As it can be seen in Case A-2, the LB30 inventory drops to zero joints from material barge load 13 till the end of the project.

To remove the risk implied with the inventory drop at the latter part of the project and to reduce the LB30 downtime, Case A-3 was analyzed. In this case the yard overtime hours were increased from 2 to 6, and the yard loading rate was properly increased, as can be seen in Table 6. Case A-3 has a total LB30 operating time of 47.1 days and a transportation cost of \$1,228,470. Case A-3 is definitely an acceptable case in terms of risk.

Furthermore, Case A-4 was investigated. This case has longer operating hours for the yard and a fast loading rate. Case A-4 gave a LB30 operating time of 45 days and a total transportation cost of \$1,209,150; both these two numbers are favorable compared to Case A-3. The comparison of Case A-3 and Case A-4 demonstrates the importance of properly planning the operations of the coating yard with the objective being the minimization of the total cost to the customer (cost of transportation, cost of the LB30 operations, and cost of the coating yard).

In Set 1 Cases simulation is used as a planning tool, whether in Set 2 Cases simulation is used as a control tool to make proper adjustments during the execution of a project.

5 CONCLUSIONS

Simulation proved to be a very effective tool for analyzing the pipelaying operations considered in this investigation. The object-oriented environment, the hierarchical modeling capabilities, the connectivity with other programs like Excel, and other powerful features of the software “Extend” provided the right environment for developing in a short time a detailed, flexible to adapt to alternative scenarios, and easy to use model.

The simulation model developed addressed all the problem objectives set at the beginning of this paper. In addition, it revealed a very important issue: that it is cost effective for the initial inventory to be used as a source for pipe joints during normal operations and not only under exceptional conditions. Thus, the model suggested revision of existing practices.

The simulation model proved to be effective as a planning tool while using the estimated lay rates for the pipelaying vessel, and as a control tool during the execution of the pipelaying project. As a planning tool, it can be very useful during the bidding phase of a project as well as during the initial preparation of the project after the contractor wins the job. As a control tool, it can be used during the execution of a project to make proper adjustments in addressing unexpected delays or potentially shifting equipment to other projects. In both cases as a planning or control tool the simulation model can facilitate excellent communication among the interested parties: the contractor and the customer. Finally, the flexibility provided by the simulation model to consider alternative scenarios makes it an excellent decision making tool, and a tool for improvement of processes and operations. For all these reasons, the simulation model developed in this investigation passed very successfully the “credibility” test

by the operations people, i.e., the user of the model and sponsor of the development.

ACKNOWLEDGEMENTS

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