Using simulation to manage project supply chain in the offshore oil and gas industry

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This paper is aimed at comparing simulation against spreadsheets as decision support tools to properly manage project supply chain in the offshore oil and gas industry. The paper presents a case study related to the problem of sizing a chain for pipeline laying from an offshore field in the Barents sea to the Russian coast. Results obtained through a spreadsheet developed by an oil and gas company have been compared to the ones gathered from an ad hoc simulation model. A simulation model with no stochastic variable has been introduced: results are quite similar to the ones of the spreadsheet, which allowed to validate the simulation model. However, the spreadsheet cannot take into account the con-tinuous move of the pipe-lay vessel while laying the pipes and it does not consider stochastic variables whose effect in real life is not negligible. Both weaknesses above are discussed.

Keywords: simulation; project supply chain; oil and gas; offshore

1. Introduction

Offshore oil and gas industry is at the same time relevant from the economic perspective (e.g. Sagers 2007), and complex from the construction viewpoint (Brimberg et al. 2003; Brykalov et al. 2007). Building an offshore drilling plant or a pipeline is a project by itself. Although many construction projects involve a given set of process stages, each project has to be regarded as unique: the site is different, hence the project is like some sort of prototype (Wegelius-Lehtonen 2001). A challenging task within the construction of drilling plants and pipelines is in properly managing project supply chain. Actually, project supply chain management encompasses the definition of the required resources to allocate to the project (e.g. machinery and materials), as well as planning and programming all the activities related to construction materials supply (e.g. pipes) and building activities (e.g. pipes laying).

Decision-making in project supply chain requires a deep understanding of its impact on project performance (Fouché and Rolstadas 2010), for instance efficiency in terms of cost, quality, time (Sobotka and Czarnigowska 2005) and risk (Cigolini and Rossi 2010a; Dey 2012), and the ability to manage project changes and dynamics (Weck 2005). Particularly, both eventual random disruptions (Wagner et al. forthcoming) and supply chain operational risks – i.e. according to Tapiero (2004) and Tapiero and Grando (2006), the risks connected to the daily disturbances of materials and information flows – may result in significant efficiency losses (Blackhurst et al. 2005) and, ultimately, to unpredictably high costs (Riddalls and Bennett 2002).

Within the oil and gas industry, project supply chain deals with sizing the elements of logistics system, which in turn requires the definition of e.g. the number and type of barges, and the size of pipe-laying ships. This is particularly true whenever the construction project requires the transhipment: sizing a transhipment system is a challenging task for several reasons.

First, a significant number of decisional variables must be considered: the number of cranes and their charging and discharging rate, the number of feeder vessels, their capacity and speed and, finally, the number of port cranes that can be potentially used and their charging and discharging rate.

Second, constraints are both static and dynamic. Static constraints are represented by the number of piers; by the manoeuvring times, the feeder vessels have to spend in hauling at piers and; in the case of a river port, by the characteristics of the access channels (i.e. one-way or two-way channel, the minimum distance between two feeder vessels which navigate along the channel in the same direction, channel depth, maximum speed allowed along the channel, locks characterising the channel and time necessary for passing each of them). Dynamic constraints are given by the feeder vessels planned maintenance, by the arrival plan of mother vessels, by the port traffic and, in the case of a river port, by the traffic in the channels due to other boats and by the channels draught as well as by the height of the bridges (which

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pass over the channels) whose values vary according to the flood tide.

Third, there are many sources of variance: they are represented by the failures of feeder vessels, of port cranes etc. and by weather conditions which can prevent the feeder vessels from navigating. Due to the complexity of the project supply chain management problem, a decision support tool which helps oil and gas companies in shaping the characteristics of feeder vessels and port equipment is needed.

The remainder of the paper is organised as follows. Section 2 is devoted to the background, while Section 3 presents the case study along with the simulation model developed and the actually used spreadsheet. Section 4 compares the results obtained with either approach, by outlining their strengths and weaknesses. Finally, Section 5 presents some concluding remarks and suggests future research paths.

2. Background

A plethora of approaches has been developed over the years to manage projects and to plan operations in the oil and gas industry, starting from static cost models to support the evaluation of feasible transportation options. Haugen et al. (2009) debated the trade-off among different CO_2 storage options under two power plant locations. Aspelund et al. (2006) presented a tool to evaluate – from the economic viewpoint – ship transport against pipeline transport to bring CO_2 to offshore platforms.

Linear programming has been widely applied to plan operations in oil and gas industry, although some attempts have been done to apply simulation-based tools: Dempster et al. (2000) developed a deterministic and stochastic model of strategic planning for logistics operations in the oil industry, based on DROP – Depot and Refinery Optimization Problem. Later, Kuo and Chang (2008) proposed a Mixed Integer Linear Programming (MILP) model to coordinate different planning and scheduling decisions that prevent from infeasible schedules, by taking into account detailed scheduling constraints since the early phases of production planning. Cheng and Duran (2004) developed a decision support tool based on the integration of a discrete event simulation tool with a stochastic optimal inventory control to assist decision-makers through the study, the design and the control of inventory and transportation system in a worldwide crude oil supply chain.

To plan project supply chain, models based on project management techniques are widespread (Ala-Risku and Kärkkäinen 2006). The principles of project management tools for construction projects lie in creating short-term schedules for project tasks based on a constraint analysis of project resources. Unfortunately, such tools require high visibility on project schedules and inventory levels (Ballard 2000), seldom available in practice (e.g. Caridi et al. 2006). Yeo and Ning (2002) developed a stochastic model to effectively deliver materials to a building site so to ensure a continuous construction process.

In the end, MILP models and spreadsheets are the decision support systems mostly used to size project supply chain. Even the interviewed practitioners of one of the biggest oil and gas company worldwide confirmed that in day-by-day real life, managers use spreadsheets to size fleets, i.e. the number of barges needed to build offshore drilling plants and pipelines, and, in more general terms, to design and manage supply chain (Cigolini et al. 2011). However, models based on either MILP or spreadsheet neglect dynamic variables (e.g. Cigolini and Rossi 2004; Creazza et al. 2012) such as weather conditions, tide, waves and the fact that – while laying a pipeline – the pipe-laying ship moves forward along the projected pipeline route.

Indeed, the variables above might affect the feasibility of project plans even strongly, thus leading managers (supported by static tools only) to over-dimension or under-dimension project supply chain. Simulation allows to take into account dynamic variables, to perform sensitivity analyses and to build scenarios: e.g. while laying a pipeline, to test several alternative locations for the transhipment point by taking into account the distance covered by the barges to reach the pipe-laying ship. Moreover, the effect of bad weather days on project completion time can be properly figured out: several studies demonstrate that simulation can be successfully employed either in the oil and gas industry (Cheng and Duran 2004; Tao and Li 2007) or to support project supply chain (Sobotka and Czarnigowska 2005; Hatmoko and Scott 2010; Cigolini and Rossi 2010b; Cigolini et al. 2011).

However, simulation is not widely applied to project supply chain in the oil and gas industry and, for this reason, this paper is aimed at showing the benefits of simulation against popular static tools (mainly spreadsheets), by also bridging the gap between theory and practice in the field.

3. Case study

A case study has been introduced here to compare simulation and spreadsheets as decision support tools to properly shape project supply chain in the offshore oil and gas industry. The case refers to the problem of sizing a system for pipeline laying from an offshore field in the Barents sea to the Russian coast. Results obtained through the spreadsheet developed by an oil and gas company have been compared to the ones gathered from a simulation model. The spreadsheet developed by the oil and gas company is based on Excel™, while the simulation model is based on Arena™. Due to confidentiality reasons, more information cannot be provided about the company-used spreadsheet.

3.1. *Context*

The problem under study is focused on defining the number of feeder vessels and where to locate the onshore transhipment point. Both vessels and transhipment point are required to enable the construction of a pipeline designed to connect an offshore gas field in the Barents Sea with the Russian coast in the neighbourhood of Murmansk. The pipeline covers a distance of 550 nautical miles (around 1019 km) along the course depicted in Figure 1. Each pipe of the pipeline is about 12-metre long; its external diameter is about 1.4 metres and its weight accounts for about 20 tonnes (2×10^4 kg). The system is composed by three types of vessel.

(1) The J-lay pipe-lay vessel: it lays the pipes with a laying rate of 5.2 min per pipe (which corresponds to 0.0867 h/pipe). The pipe-lay vessel moves along the growing pipeline starting from the offshore field.

(2) The feeder vessel: a fleet of feeder vessels provides the pipe-lay vessel with pipes. The number of feeder vessels is a decision variable: each feeder vessel performs a there and back service between the pipe-lay vessel and an onshore transhipment point where the mother vessel downloads the pipes and the feeder vessels upload the pipes to be carried to the pipe-lay vessel. Each feeder vessel is characterised by about 3.500 deadweight tonnes (3.5×10^6 kg) that correspond to a capacity of 168 pipes, by a full-load speed of 10 knots (around 5.14 m/s) and by a speed when empty equals to 12 knots (around 6.17 m/s).

(3) The mother vessel: it feeds the pipes buffer at either transhipment point. It is characterised by a 25,000 deadweight tonnes (2.5×10^7 kg) – that correspond to a capacity of 1200 pipes – and by a full-load speed of 10 knots (around 5.14 m/s) and by a speed when empty equals to 12 knots (around 6.17 m/s). The mother vessel performs a there and back service between either transhipment point and the port of Arkhangelsk, on the Northern Dvina river near its outlet into the White Sea, in the far north of European Russia. The mother vessel sails first along the river channel, then from the river outlet to the onshore transhipment point. The loading (or unloading) rate of the crane on the mother vessel is 3.56 min per pipe, which correspond to 0.0593 h/pipe.

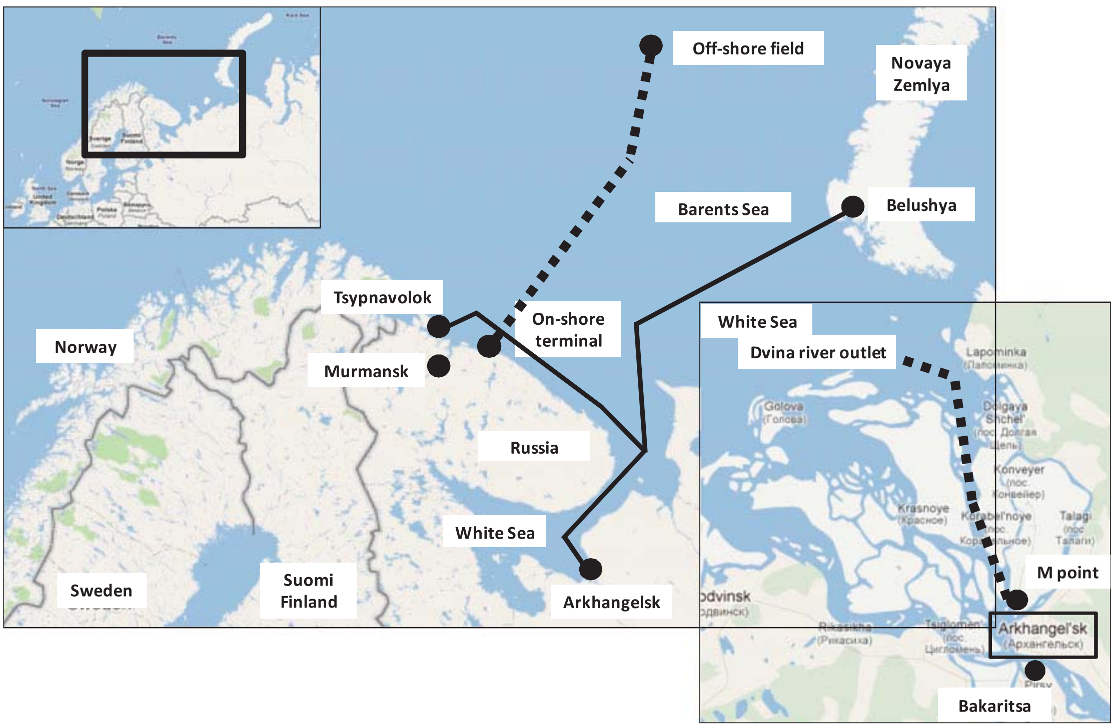

Figure 1. Map of the area.

The mother vessel and the feeder vessels, respectively, feeds pipes and take pipes from a stock located in the onshore transhipment point. The location of the onshore transhipment point is another decisional variable. The onshore transhipment point can be selected between two alternatives: (i) the port of Tsypnavolok in the Rybachy Peninsula, hereinafter named as Tsypnavolok and (ii) the port of Belushya in the southwest of the Southern Island of the Novaya Zemlya arctic archipelago, hereinafter named as Belushya (see again Figure 1). Both transhipments are equipped with cranes which are able to handle 20 tonnes (i.e. 2×10^4 kg) pipes. The loading (or unloading) rate of the cranes is 3.56 min per pipe, which correspond to 0.0593 h/pipe.

The mother vessel route to reach Tsypnavolok from the port of Arkhangelsk is composed of two stretches: (i) a 18.6 nautical miles (i.e. around 34.5 km) length river channel, which is a two-way channel going from the port to the Dvina outlet; no bridge crosses the channel and the maximum speed allowed in the channel is 3.5 knots (1.80 m/s) and (ii) a 494 nautical miles (around 915 km) length open sea stretch.

The mother vessel route to Belushya from the port of Arkhangelsk is composed of two stretches: (i) the above-mentioned river channel and (ii) a 605 nautical miles (around 1121 km) length open sea stretch. In the port of Arkhangelsk, a crane which is able to handle 20 tonnes pipes and with a loading (or unloading) rate of 3.56 min per pipe is always available. The map of the area is outlined in Figure 1 together with the main topological elements of the problem. The process flow of the activities performed by the mother vessel, and the feeder and the J-lay pipe-lay vessel are depicted, respectively, in Figures 2(a) and 2(b), using IDEF0 formalism.

The simulation model of the above-described context has been developed using ARENA™ software. The described activities and constraints have been modelled in the simulation model. For further information, the logical model is described using Petri nets, a formalism commonly used for this purpose (e.g. Pero et al. 2010), and it is presented in Appendix 1.

3.2. *Experimental campaign*

The (unknown) decision variables of the experimental campaign are the number of feeder vessels and the location of the transhipment point. Since all the project parameters are deterministic, only one simulation run has been performed for each configuration of the project supply chain, i.e. for each combination of transhipment location and number of feeder vessels.

The oil and gas company (through the spreadsheet) found that six (i.e. int(5.7) + 1) feeder vessels were needed in the case of Tsypnavolok, whilst eight (i.e. int (7.3) + 1) feeder vessels were needed in the case of Belushya. Therefore, the number of feeder vessels considered in the experimental campaigns are five, six and seven in the case of Tsypnavolok and seven, eight and nine in the case of Belushya. The length of each simulation run has been set to 398 days (corresponding to 9552 h), i.e. the time for completion defined in the contract. Finally, no sensitivity analysis has been performed to test the robustness of the solutions against environmental sources of variance (e.g. weather

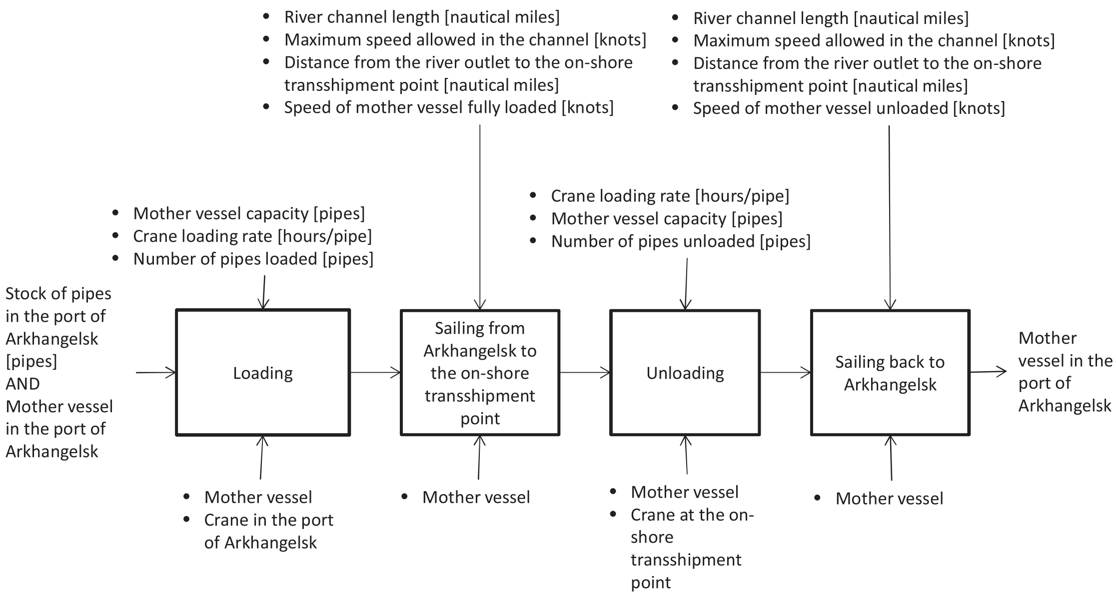

Figure 2a. Process flow of the mother vessel.

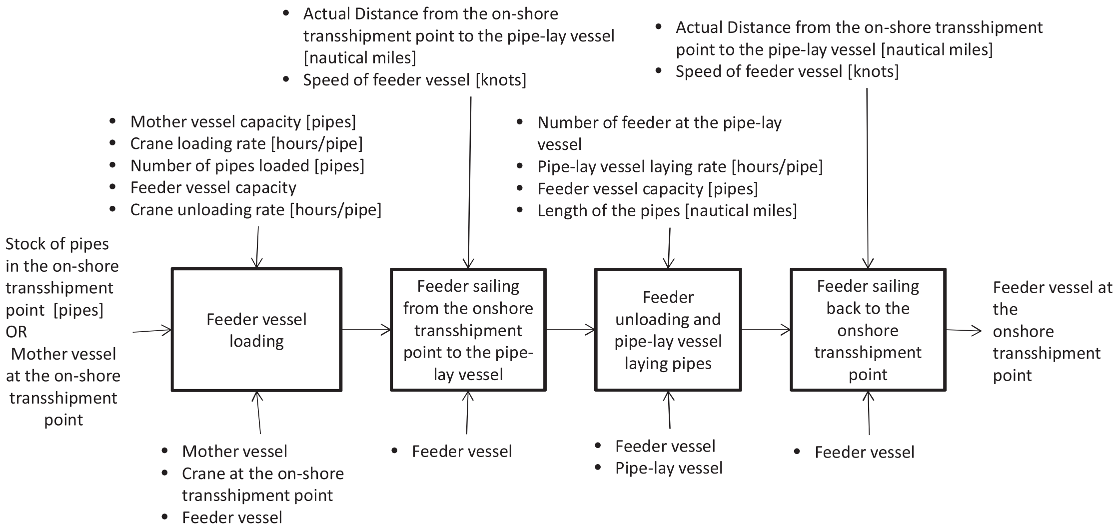

Figure 2b. Process flow of the feeder and the J-lay pipe-lay vessel.

conditions, traffic along the river channel, etc.) since the oil and gas company did not provide data on such exogenous variables.

Table 1 summarizes the output in terms of pipeline length at the end of the simulation run (i.e. after 9552 h) and of the hours required to complete the pipeline under each run of the experimental campaign.

4. Results

Results obtained through the simulation model confirm the ones through the spreadsheet. Indeed, as supposed by the oil and gas company, six feeders are needed to lay all the pipes under Tsypnavolok and eight under Belushya. In this way, on the one hand, the simulation model has been validated while, on the other hand, the tool used by the oil and gas company proved to be sound and sophisticated as a simulation model where no stochastic variables are considered.

However, a more in-depth analysis of the results highlights two main weaknesses of the static spreadsheet-based approach: first, it cannot take into account that the pipe-lay vessel moves while laying the pipes, i.e. the fact that the distance between the transhipment point and the pipe-lay vessel varies continuously. Second, to reduce the complexity, a set of simplifying hypotheses have been set.

Table 1. Results of the experimental campaign.

	Characteristics		Output	
Experiment	Feeder vessels (number)	Transhipment location	Pipeline length (in miles)	Time required (h)
1	5	Tsypnavolok	490.04	10,357.07
2	6	Tsypnavolok	550.00	8797.16
3	7	Tsypnavolok	550.00	8591.65
4	7	Belushya	526.30	10,061.47
5	8	Belushya	550.00	9545.25
6	9	Belushya	550.00	9374.39

As far as the former weakness is concerned, the spreadsheet changes the distance between the transhipment point and the pipe-lay vessel every time the pipe-lay vessel has installed 50 nautical miles (corresponding to around 92 km) of pipes. Figure 3 and Table 2 show the sections in which the pipeline was divided. Each letter (from A to L) indicates the different places where the pipe-lay vessel is located while laying the pipes. In Table 2, the corresponding distances from the transhipment points can be read.

The simulation model allows a better approximation of the pipe-lay vessel position since it changes the distance every nautical mile (i.e. 1.85 km) instead of every 50 (i.e. around 92 km): this better approximation prevents from overestimating or underestimating the need of feeders. In particular, according to the spreadsheet, the number of feeders is a continuous variable – e.g. 7.3 in the case of Belushya – while in the simulation model, the number of feeder vessels is a discrete variable, so the output of the spreadsheet can be compared only with the mean value of feeder vessels used in the simulation model. Moreover, in the case of Tsypnavolok, the number of needed feeders according to the spreadsheet is greater than the average number of feeder vessels used per week resulting from the simulation model, and the opposite is true in the case of Belushya. In the case studied, this has not affected the solution, however – broadly

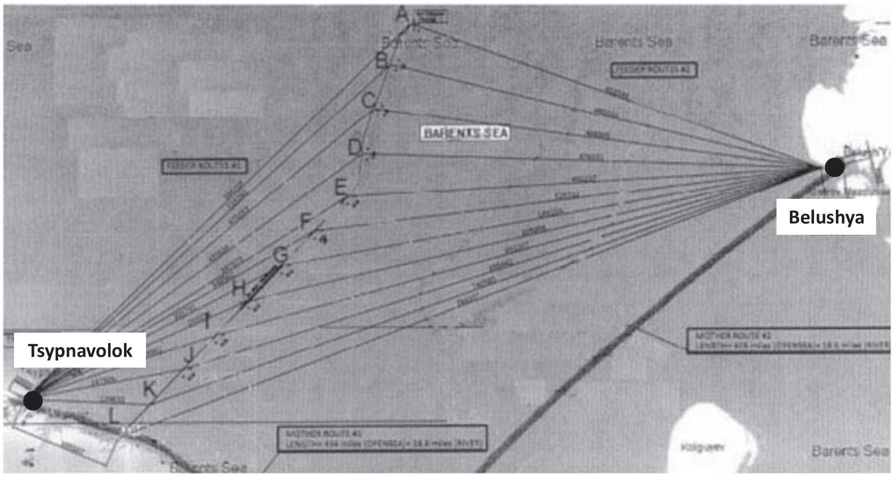

Figure 3. Sections of the pipelines.

Table 2. Distances from transhipment points to the points where the pipeline is was divided.

Point	Distance from Tsypnavolok [nautical mile]	Distance from Belushya [nautical mile]
A	564.26	452.53
B	519.26	460.32
C	475.25	468.37
D	435.63	476.63
E	397.57	492.24
F	349.36	529.72
G	301.74	569.10
H	255.08	610.00
I	209.90	652.21
J	167.51	695.44
K	129.88	740.59
L	105.51	783.11

speaking – it might result in overestimating or underestimating the fleet of feeders.

As far as the latter weakness is concerned, both the spreadsheet and the experimental campaign performed with the simulation model have been built under some simplifying assumptions. (1) Feeders, cranes, ships, etc. are always available, i.e. they are not subject to breakdowns. (2) There is always at least 10 meters of depth, i.e. tide effect can be disregarded. (3) There is no traffic in the channels and the port facilities are always available. (4) The river port from which the mother vessel leaves is located in a place (highlighted by letter M in Figure 3 and 4) different from the one where the real outward port of Arkhangelsk is located, i.e. Bakaritsa; in this way the oil and gas company avoids the problem of modelling (through the spreadsheet) the bridge located in between point M and Bakaritsa, where navigation is interrupted for some hours per day.

The hypotheses above have been introduced due to the hurdles risen in including dynamic variables in the spreadsheet. However, by removing the hypotheses above, the feasible region is likely to widen: e.g. although no breakdowns are assumed (see assumption 1 above), the crane of the pipe-lay vessel is not characterised by 100% availability. This fact can prevent the pipe-lay vessel from unloading the feeder vessels and laying pipes, thus causing longer pipes-laying time. The simulation model allows quite easily to take into account the breakdown phenomenon concerning the pipe-lay vessel crane, its stochastic nature and its impact on the number of feeder vessels needed. In particular, in the case of Belushya, Table 3 shows the pipes-laying time against the mean of the mean time between failure (MTBF) and the number of feeder vessels, under the hypotheses that the MTBF of the pipe-lay vessel crane is drown from an exponential distribution and the mean time to repair (MTTR) is assumed as a stochastic variable normally distributed with mean and standard deviation equal to 24 and 12 h, respectively. The results depicted in Table 3 have been obtained by performing on the simulation model 6 experimental campaigns of 10 replication runs each.

From Table 3, it is clear that, in the case of Belushya, if breakdowns of the pipe-lay vessel crane are taken into account, eight feeder vessels cannot be sufficient to complete the pipeline on time. In particular, nine feeder vessels are needed if the mean of the exponential distribution from which the MTBF is drown is equal or lower than 1500 h (in the case of MTTR drawn from a normal distribution with mean 24 h and standard deviation 12 h).

Finally, the location of the port (see assumption 4 above) has been found to affect the number of feeder vessels in case of Belushya. Actually, the real outward

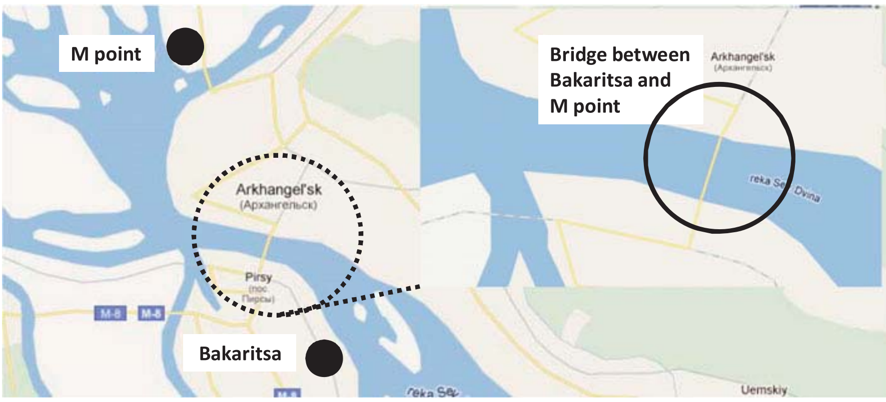

Figure 4. A detail of the area.

Table 3. Results when failures of the pipe-lay vessel crane are considered.

MTBF (h)	Number of feeder vessels	Average pipes laying time (h)
2000	8	9547.45
	9	9374.39
1500	8	9557.41
	9	9376.89
1000	8	9562.32
	9	9374.50

port is placed six nautical miles (i.e. around 11 km) far from the hypothesised position and there is a bridge in between the real port (i.e. Bakaritsa) and point M. A simulation model has been developed to include the actual place of the port from where the mother vessel leaves and the bridge. Due to the tide, the height of the bridge becomes lower than the mother vessel air draft, thus preventing the mother vessel from under-passing. Simulation runs have shown that if the water level is 11 meters even for just 1 h per day, only 545.48 nautical miles (corresponding to around 1011 km) of pipes – instead of the targeted 550 nautical miles (corresponding to around 1019 km) – are installed in the allotted time (i.e. 9552 h), and the oil and gas company is heavily penalised in the case the pipeline installation does not meet the due date.

5. Conclusions

Within the oil and gas industry, project supply chain deals with sizing the elements of the logistics system, which requires the definition of e.g. the number and the type of barges, and the size of pipe-laying ships. This is particularly true whenever the construction project requires the transhipment: sizing a transhipment system is a challenging task for at least three reasons. First, a significant number of decisional variables must be considered. Second, there are both static and dynamic constraints. Third, there are many sources of variance: they are represented by the failures of feeder vessels, of port cranes etc. and by weather conditions which can prevent the feeder vessels from navigating. Due to the complexity of the project supply chain management problem, a decision support tool which helps oil and gas companies in defining the features of both feeder vessels and port equipment is needed.

MILP models and spreadsheets are the decision support systems mostly used to size project supply chain. However, models based on either MILP or spreadsheets neglect dynamic variables such as weather conditions, tide, waves and the fact that – while laying a pipeline – the pipe-laying ship moves forward along the projected pipeline route. Indeed, the variables above might affect the feasibility of project plans even strongly, thus leading managers (supported by static tools only) to overestimate or underestimate the requirements of the project's supply chain.

On the other hand, simulation can be successfully employed to support project supply chain by taking into account dynamic variables, by performing sensitivity analyses and by building scenarios. E.g. while laying a pipeline, several alternative locations for the transhipment point can be tested by taking into account the distance covered by the barges to reach the pipe-laying ship; also the effect of bad weather days on project completion time can be properly figured out.

As a consequence, simulation has been applied to the case of defining the number of feeder vessels and where to locate the onshore transhipment point for pipeline laying from an offshore field in the Barents sea to the Russian coast. Results obtained through the spreadsheet developed by an oil and gas company have been compared to the ones gathered from a simulation model. Actually, the results from simulation confirm the ones through the spreadsheet, thus on the one hand, the simulation model has been validated while, on the other hand, the tool used by the oil and gas company proved to be sound and sophisticated as a simulation model where no stochastic variables are considered.

However, a more in-depth analysis of the results highlighted two main weaknesses of the static spreadsheet-based approach: first, it cannot take into account that the pipe-lay vessel moves while laying the pipes, i.e. the distance between the transhipment point and the pipe-lay vessel varies continuously. Second, to reduce the complexity, a set of simplifying hypotheses have been set.

So, in the end, it can be concluded that simulation represents a useful alternative to MILP and spreadsheets to size the elements of a logistic system when dealing with project's supply chains in the oil and gas industry. Future research paths are related to: (i) the development of a simulation model for more complex contexts; (ii) the development of a simulation meta-model for offshore oil and gas industry which allows for automatically build simulation models to size project supply chain systems for both pipelines and drilling plants.

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Appendix 1

Figure 5 represents the activities performed by the mother vessel, by feeders and by the pipe-lay vessel, when the transhipment point placed in the port of Tsypnavolok using the formalism of the Petri nets. The token in place P1 (which represents the mother vessel) and the token in P2, (which represents the crane in the port of Arkhangelsk) activate transition T1. T1 cancels the token in P1 and in P2 and, after a duration d_1 given by the time needed to fully load the mother vessel, T1 assigns the value of the parameter C_{MV} to the variable P_{MV}, and creates one token in P2 (i.e. it releases the crane) and one token in P3. Notice that: $d_1 = C_{MV}/LR_P$, where C_{MV} is the mother vessel capacity (i.e. 1200 pipes) and LR_P is the crane loading rate, which corresponds to the loading rate at port (i.e. 0.0593 h/pipe).

The token in place P3 activates transition T2 which represents the mother vessel sailing along Dvina river. T2 deletes the token from P3 and, after a duration d_2 given by the time needed to the mother vessel to cover the river channel, it creates one token in place P4. Notice that: $d_2 = L_{RC}/AS$, where L_{RC} is the length of the river channel (i.e. 18.6 nautical miles, which corresponds to around 34.5 km) – and AS is the maximum speed allowed in the channel (i.e. 3.5 knots or 1.8 m/s).

The token in P4 makes active transition T3 which represents the mother vessel sailing along the open sea stretch, i.e. from the river outlet to Tsypnavolok. T3 cancels the token from P4 and, after a duration d_3 given by the time needed to the mother vessel to cover the open sea stretch, it creates one token in P5. Notice that: $d_3 = D_{RO-T1}/S_{MVF}$, where D_{RO-T1} is the distance between the Dvina river outlet and the port of Tsypnavolok (i.e. 494 nautical miles, which corresponds to around

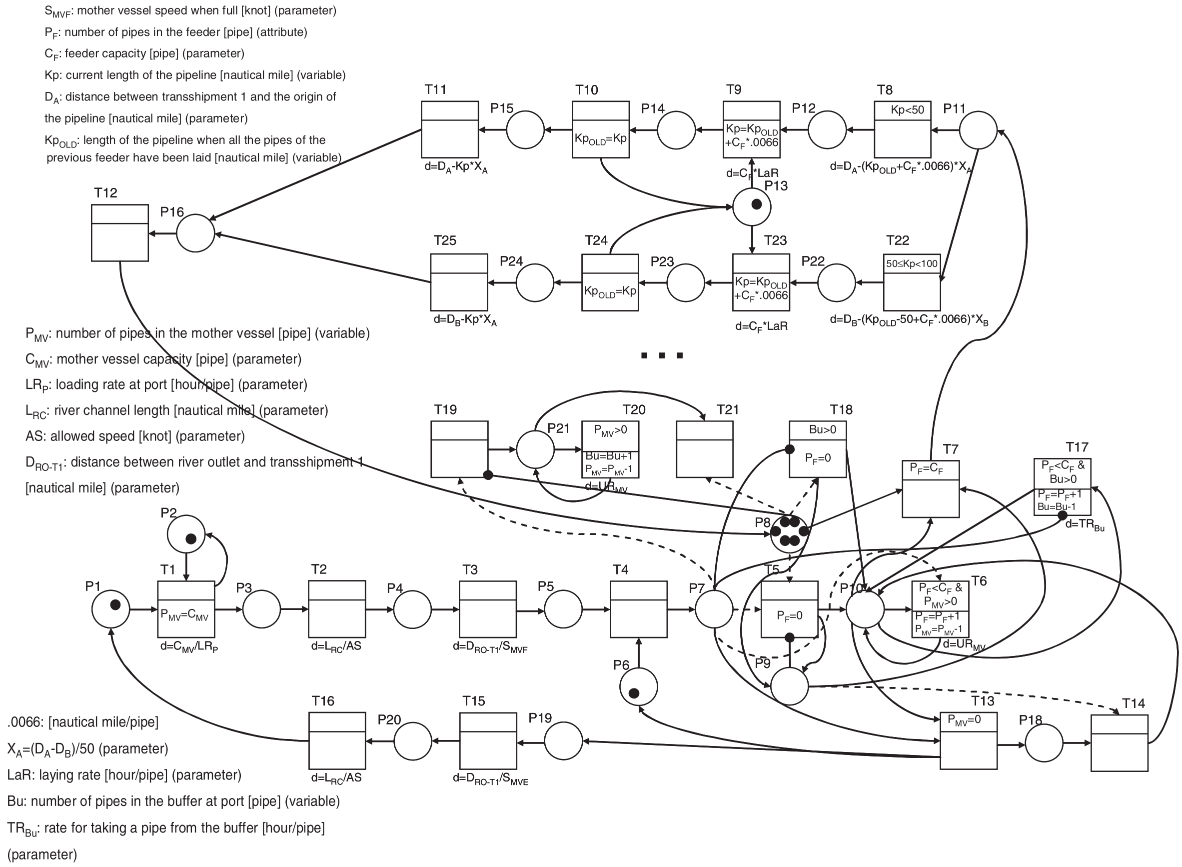

Figure 5. Petri net representing the simulation model.

915 km) and S_{MVF} is the speed of the mother vessel at full load (i.e. 10 knots, corresponding to around 5.14 m/s).

When one token is in P6 (which means that the mooring position at Tsypnavolok port is available for the mother vessel), the token in P5 activates transition T4. T4 cancels the token from P5 and the one from P6, and creates one token in P7. If at least one token is in P8 (which means that at least one feeder is at Tsypnavolok port) and no token is in P9 (which means that no feeder is awaiting for being completely loaded), transition T5 becomes active. T5 creates one token in P9 and one in P10, and initialises the token's attribute P_F, which represents the number of pipes in the feeder (i.e. T5 sets $P_F = 0$). If the number of pipes in the feeder (hereinafter referred to as P_F) is lower than the feeder capacity (hereinafter referred to as F_C, i.e. the feeder is not loaded at full capacity) and the number of pipes in the mother vessel (hereinafter referred to as P_{MV}) is greater than 0 (i.e. it can directly loaded by the mother vessel), the token in P10 activates T6.

T6 deletes the token from P10 and, after a delay given by time needed to unload one pipe from the mother vessel and to load it on the feeder (notice that this delay corresponds to the unloading rate of the mother vessel, i.e. 0.0593 h/pipe), it allows to create one token in P10, to increment the value of the token's attribute P_F (i.e. $P_F \rightarrow P_F + 1$) and to decrement the value of the variable P_{MV} ($P_{MV} \rightarrow P_{MV} - 1$). Such a cycle ends when either the feeder is full (i.e. $P_F = C_F$) or the mother vessel is empty ($P_{MV} = 0$). In the former case, the token in P10 activates transition T7. T7 cancels the token from P10, the one from P9 and one token from P8 and it creates one token in place P11. The empty place P9 allows transition T5 to be activated if, after the actions performed by T7, at least one token is still in P8, which means that the empty P9 (i.e. no feeder is awaiting for being completely loaded), allows another feeder (if any) to be directly loaded from the mother vessel. Depending on the value of the variable Kp, which represents the length (in nautical miles) of the portion of pipeline already laid, the token in P11 makes active one of the transitions it is connected to. If $Kp < 50$, T8 becomes active. T8 deletes the token from P11 and, after a duration given by the time needed to cover the distance between Tsypnavolok and the pipe-lay vessel, it deletes the token in P11 and creates one token in P12. If one token is in place P13, which means that the mooring position along the pipe-lay vessel is available, transition T9 becomes active. T9 it cancels the tokens from P12 and P13 and, after a duration d_4 given by the time needed to lay all the pipes transported by the feeder it assigns to Kp its previous value – let say Kp_{OLD} – and creates one token in P14. Notice that: $d_4 = C_F/\mathrm{LaR}$, where LaR is the pipe-lay vessel laying rate (i.e. 0.0867 h/pipe) and C_F records the pipeline length reached by means of the pipes transported by the previous feeder, plus the length (in nautical miles) of the pipes transported by the current feeder (i.e. 0.0066 C_F, where 0.0066 is the length of one pipe in nautical miles).

The token in P14 activates transition T10: T10 assigns to the variable Kp_{OLD} the value of the variable Kp, i.e. it sets $Kp_{OLD} = Kp$, deletes the token from P14 and creates one token in place P15. As a consequence, T11 becomes active. T11 deletes the token from P15 and, after a duration given by the time needed to reach Tsypnavolok from the position of the pipe-lay vessel, it creates one token in P16. The token in P16 activates transition T12. T12 cancels the token from P16 and creates one token in P8, which means that T12 makes available one feeder at Tsypnavolok.

Now, let go back to place P10. If – due to the cycle performed by P10 and T6 – the mother vessel is empty (i.e. $P_{MV} = 0$), T13 becomes active. T13 cancels the token from P10 and the one from P7, and creates one token in P19 (which represents the mother vessel sailing toward Arkhangelsk port) and one token in P18 (which represents the feeder still awaiting to be fully loaded). The token in P19 activates transition T15, which represents the mother vessel sailing from Tsypnavolok to the river outlet. T15 cancels the token from P19 and, after a duration d_5 given by the time needed to the mother vessel to cover the open sea stretch, it creates one token in P20. Notice that $d_5 = D_{RO-T1}/S_{MVF}$, where S_{MVE} is the speed of the mother vessel when it sails empty (i.e. 12 knots, which correspond to around 6.17 m/s).

The token in P20 makes T16 active. T16, which represents the mother vessel sailing from the river outlet to the port of Arkhangelsk, deletes the token from place P20. After a delay given by the time needed to the mother vessel to cover the river channel, transition T16 creates one token in P1. The token in P18 – due to the token in P9, since $P_F \neq C_F$ and T7 has not been activated – makes transition T14 active. T14 creates one token in P10, which represents the feeder that must finish to be loaded, provided that an adequate number of pipes is stored in the buffer at Tsypnavolok (hereinafter referred to as *Bu*). If no token is in P7 and if the number of pipes in the feeder is lower than the feeder capacity and the number of pipes in the buffer at Tsypnavolok is greater than 0 (i.e. $P_F < C_F$ and $Bu > 0$), the token in P10 activates T17.

Transition T17 deletes the token from P10 and, after a duration given by time needed to withdraw one pipe from the buffer and to load the pipe on the feeder (i.e. 3.56 min per pipe, which correspond to 0.0593 h/pipe), it allows to create one token in P10, to increment the value of the token's attribute P_F (i.e. $P_F \rightarrow P_F + 1$) and to decrement the value of the variable *Bu* ($Bu \rightarrow Bu - 1$). Such a cycle ends when the feeder is full (i.e. $P_F = C_F$) or when the buffer is empty ($Bu = 0$) or even when the mother vessel arrives at Tsypnavolok (i.e. one token is in P7). Notice that the same cycle is activated also when no token is in P7, at least one token is in P8 and the number of pipes in the buffer is greater than 0, i.e. when transition T18 becomes active. In other words, the cycle representing the feeder loading is activated also when the mother vessel is not at the transhipment point and the pipes buffer is not empty.

Finally, transitions T19, T20 and T21 and place P21 allow to represent the unloading of the pipes from the mother vessel and their loading on the buffer. When one token is in P7 (i.e. the mother vessel is at Tsypnavolok) and no token is in place P8 (i.e. no feeder is available at Tsypnavolok), T19 becomes active and it creates one token in P21. If the number of pipes in the mother vessel is greater than 0, the token in P21 makes active transition T20, which (i) deletes the token from P21 and, after a duration d_6 given by the time needed to unload a pipe from the mother vessel and to load the pipe on the buffer (i.e. the unload rate of the mother vessel, 3.56 min per pipe, which correspond to 0.0593 h/pipe), (ii) increments the value of the variable *Bu*, i.e. the number of pipes in the buffer, (iii) decrements the value of the variable P_{MV}, i.e. the number of pipes in the mother vessel and (iv) creates one token in P21. This cycle ends when a feeder is available at Tsypnavolok. As a matter of fact, when at least one token is in P8, transition T21 becomes active and deletes the token from P21.