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Simulation Model for Strategical Fleet Sizing and Operational Planning in Offshore Supply Vessels Operations

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Abstract

One of the most costly resources used in offshore supply logistics are offshore supply vessels, so-called platform supply vessels (PSVs). They are used to carry out regular supply functions, i.e. transport cargo to and from offshore installations. The data for this study was provided by the company StatoiHydro. StatoilHydro does not own supply vessels, they are hired from the shipping companies. There are basically two types of hire contracts: long-term and spot (short-term). Spot rates are normally significantly higher than the long-term ones, and spot vessels are typically hired when there is a shortage of long-term ones. Due to some uncertainty factors like weather conditions, demand variation and delays on the supply base, the number of supply vessels currently performing supply trips may vary. Moreover, different operational strategies can be used by supply vessels to handle the uncertainty factors. The objective of this thesis is to design a simulation model for offshore supply process that can serve as a tool for strategical fleet sizing and operational planning.

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Contents

1 Introduction

The Norwegian petroleum production started in 1971, when the Ekofisk field was developed, and since then it has grown rapidly. In 2006 Norway was the world's fifth largest oil exporter and the third largest gas exporter. The petroleum sector has become important for the economical growth and stability in times of Global Financial Crisis. The income from the petroleum sector increased significantly the standard of living in Norway and still keeps it on one of the highest levels in Europe. Taking all the above mentioned into account, it is important to keep petroleum production effective and thoroughly planned. A lot of researches concentrate on theoretical support of petroleum production all over the country. Oil and gas companies has financed considerable research to improve their operations. This shows that petroleum related operations are an important subject for research and study.

Statoil and Hydro played a significant role in the Norwegian oil industry since the early 1970s. Both companies have made key contributions to the development of Norway into a modern industrial nation. On October 1, 2007 Statoil and Hydro's oil and gas division merged into a new company – StatoilHydro. StatoilHydro had several projects together with Molde University College, providing necessary data and other related information for researches and students. As the company grows, it needs more thorough planning of performed operations. The offshore activity is extensive and getting more complex. Optimization of production processes has become an issue of big concern for the oil companies operating on the Norwegian continental shelf, including StatoilHydro. The complexity of problem and the scope of operations has made the logistic planning a subject of interest for research.

Logistics of oil and gas production is divided into two parts: downstream and upstream logistics. Downstream logistics is defined as bringing oil and gas to onshore customers. Supplying the offshore drilling and production units with necessary supplies is defined as upstream logistics.

The supply of offshore installations is a challenging logistics task: the installations must be supplied regularly to ensure a continuous production. One of the most costly resources used in upstream logistics are offshore supply vessels, so-called platform supply vessels. They are designed to carry regular supply functions, i.e. transport cargo to and from offshore installations. This involves the transportation of pipes, individual items in containers on deck and a variety of different bulk products both dry and wet in separate tanks. Cost-effective supply service requires thorough planning and well coordinated operation of platform supply vessels. The routes and schedules of vessels are planned, optimized and have to be operated consistently. Major focus points and issues include good demand estimation, operational and strategical fleet planning and routes and schedules optimization.

The problem treated in this thesis is related to upstream logistics of StatoilHydro. More specifically, the strategic fleet sizing and operational planning for supply vessels. The company does not own supply vessels: these are hired from the shipping companies. There are basically two types of hire contracts: long-term and spot (short-term). Spot rates are frequently significantly higher than the long-term ones and spot vessels are usually hired when there is a shortage of vessels on long-term contracts. The option of a platform waiting for long-term supply vessels to become available is not considered as it can lead to interruption of the production and much higher loss than vessel costs. Deciding the number of supply vessels to hire on the long-term basis is an important part of the strategic fleet size planning. This decision has a heavy economic impact as platform supply vessels are among the most expensive ones.

Weekly vessel schedule is usually decided in advance to cover planned demands from the platforms. This schedule is decided several times a year. Due to some uncertainty factors like weather conditions, demand variation and delays on the supply base the number of supply vessels currently performing supply trips may vary (as some might not be back to the base on time to start the next trip; this trip will then have to be performed by an extra vessel). This variation can be reduced by using more efficient operational strategies for supply vessels.

The dependence of supply operations on weather conditions adds considerably to the problem complexity. Normally these operations cannot be performed when the wave height exceeds a certain threshold. Additionally, the delays on the supply base can occur due to the late arrival of goods to the base. As a result supply vessels can be late on their schedule and the company should have enough supply vessels to cover scheduled demands. Calls for extra deliveries for the platforms also add variation to the number of supply vessels in use. The unpredictability of weather conditions, demand variations and delays makes the problem highly stochastic. Moreover, as later analysis will show, probability distributions best describing stochastic phenomena inherent to the problem are non-trivial and quite complex to handle through analytical approaches. For these reasons discrete-event simulation has been chosen as a methodology.

The objective of the work described in this thesis is to design and develop a discrete-event simulation model for offshore supply operations performed by supply vessels. This model will be used to evaluate alternative platform supply vessel fleet size and operational strategies for supply vessels. The remaining part of the thesis is structured as follows. Section 2 discusses the literature on the topic relevant to this thesis. In Section 3 the detailed problem description is given. Section 4 describes the simulation as a research methodology with relevant definitions. Research objectives and plan are presented in Section 5. General assumptions for the model, input specifications and modeling considerations are discussed in Section 6. Section 7 gives a short guided tour through Arena simulation software, describes the implementation of the model, its verification and validation. Output analysis is presented in Section 8. Section 9 describes the implementation of delays on the supply base and extra trips to the platforms. Conclusions are drawn in

Section 10.

2 Literature review

Presence of stochastic elements in offshore supply operations justifies the use of simulation approach. Therefore, in the literature review we will look into some applications of discrete-event simulation to problems involving fleet sizing decisions and operational planning in maritime and other applications. We will focus on major uncertainty factors, included in the model, and efficiency measures used to evaluate the performance of simulation. Some of such applications are relevant to our study. In such cases we will try to relate them to our problem, if this is possible.

Within maritime sector application one of the recent surveys has been done by Christiansen et al.(2004). The majority of discussed papers use analytical methods to solve fleet sizing problems. However, several publications have been mentioned, that used discrete-event simulation for decision support in fleet sizing and operational planning. As for operational planning, only research on scheduling and routing of ships has been reviewed. No any studies mentioning operational strategies as part of operational planning are mentioned in the review.

Darzentas and Spyrou(1996) have developed a simulation of ferry traffic in the Aegean Island. Developed simulation model is a decision aiding tool for transport system design and regional development. Main uncertainty factors are demand variance and weather conditions. Using the simulation model the authors have compared several combinations of different vessel types, harbour layouts, routes, passenger and vehicle demands, and even the establishment of new ports. The main measures of efficiency were the fraction of covered demand, the maximum number of ships queueing in ports, as well as vehicle and passenger delays. Even though the main uncertainty factors are similar to our study, the types of effect these uncertainties can have on the system are different. For example, weather conditions are described by the strength of the wind, and may cause the delays in departure from the port or slower speed of the vessel, while in our model the weather is described by the wave heigth and may cause the delays in loading/unloading operations. Also the model is used for strategic planning and does not mention any operational planning apart from routing, which is not of interest in our study.

Richetta and Larson(1997) have described an application of discrete event simulation to model the increased complexity of New York city's refuse marine transport system. Waste trucks unload their cargo at land-based transfer stations where refuse is placed in barges and then towed to the Fresh Kills Landfill in Staten Island. An advanced dispatching module was incorporated into the simulation model. Season- and site-dependent refuse inflow rates were major randomness factors. The authors demonstrated that the model reasonably well tracked the behavior of the real system. The system was used to evaluate different barge and tug fleet sizes, travel times and some other operational characteristics of network elements. Efficiency measures of interest were deferred refuse tonnage and tug utilization rates. This work is an extension of an earlier study by Larson(1988).

Simulation model, used for strategic fleet size planning of refrigerated containers is presented by Imai and Rivera(2001). In their study the simulation was used to determine the most convenient composition of owned and leased refrigerated containers for the transpacific cargo trade. Simulations are performed with five different owned container fleet sizes and 5 different demand patterns. Cost evaluation analysis is carried out for each simulation run and the results are compared to each other. If a given fleet size is insufficient to cover the cargo demand, additional containers are leased from the spot market — a provision shared with our model.

Fagerholt and Rygh(2002) have performed a simulation analysis on the design of a sea-borne system for fresh water transport from Turkey to Jordan in the Middle East. In this paper, the authors describe a problem faced by a major international shipping company. Fresh water is to be transported with high regularity at sea from Turkey to discharging buoys by the coast in Israel, then in pipelines from the buoys to a tank terminal ashore, and finally through pipeline from Israel to Jordan. Breakdowns of ship, buoy and pipeline facilities were identified as stochastic elements. The analysis aimed at answering questions regarding the required number, capacity and speed of vessels, the capacity and number of discharging buoys, the design and capacity of pipelines and the capacity of the tank terminal. Total waiting hours of the vessels, maximum storage use, number of pipeline flow stops and total amount of delivered water were the main efficiency measures.

Simulation modeling of crude oil lightering in Delaware Bay was proposed by Andrews et al.(1996). Crude oil destined for Philadelphia- area refineries is transferred to lighters from the tankers in Big Stone anchorage offshore in Delaware Bay because the channel in the Delaware River is too shallow for fully loaded tankers. Uncertainty factors that influence the operation are arrivals of the tankers and service times. The random element in service times include the amount of crude to lighter and the weather at the time of lightering. Weather uncertainty is accounted for by assigning each barge a weather sensitivity parameter, which measures to what extent weather conditions influence lightering operations. The authors have developed a simulation model to study the effects of various policies on service levels. The results were used by a provider of lightering services and its largest customer to examine ways in which they could improve their working relationship. The customer was considering alternative lightering solutions, including doing its own lightering. The results of the simulation study showed that acquiring a separate fleet would be costly and allowed both parties to evaluate other alternatives for reducing costs and improving response times.

Vis et al.(2005) have described a model for a fleet size minimization for the vehicles transporting containers between unloading buffer areas and storage areas at a maritime container terminal. Each container in the buffer area has a time window in which the transportation should start. The objective is to minimize the vehicle fleet size such that the transportation of each container starts within its time window. The authors have developed an integer linear programming model to solve the problem of determining vehicle requirements under time-window constraints. Discrete-event simulation was used to validate the estimates of the vehicle fleet size by the analytical model. Parameters described stochastically in the simulation model include crane cycle times, release times of containers and vehicle travel times. The objective of the simulation is to examine how many vehicles are required to transport all the containers in such a way that the unloading time of the ship is minimized. A close agreement between the results of the analytical and simulation models was observed.

A simulation model for offshore anchor handling operations related to movement of offshore mobile units was proposed by Shyshou et al.(2008). The operations are performed by anchor handling tug supply (AHTS) vessels, which can be hired either on the long-term basis or from the spot market. The stochastic elements are weather conditions and spot- hire rates. The requirements on the weather conditions are similar to our model. The annual vessel hiring cost, consisting of long-term hire cost and spot hire cost, is used as an efficiency measure. Future spot rates for AHTS vessels and number of vessels on long-term hire are regarded as experimental design factors. Number of vessels on long-term hire is an experimental design factor, common for our model as well.

Application of simulation approach for fleet sizing outside the maritime domain is described by Godwin et al.(2008). Developed simulation model is a decision support tool for locomotive fleet sizing and associated deadheading policy. A railroad system in which *a priori* freight train schedule does not exist is considered. Random order arrival rates at each station considerably complicate locomotive fleet size planning. Simulation is therefore chosen as a solution approach and the study shows that the throughput increases with the number of locomotives up to a certain level. After that the congestion caused by the movements of a large number of locomotives in the capacity constrained rail network offsets the potential benefit of a large fleet.

To the best of our knowledge the application we consider is original and the problem has not been previously studied.

3 Problem description

The problem, described in this thesis, is the case of StatoilHydro. Therefore in this section we will give a short description of StatoilHydro upstream logistics. Upstream logistics is defined as supplying the offshore drilling and production units with necessary supplies. This thesis focuses on the supply process from onshore base to the offshore installations, performed by supply vessels.

3.1 Offshore operations of StatoilHydro

Offshore operations of StatoilHydro in the Norwegian Sea and the Barents Sea are mostly performed in four offshore operation regions: the North Sea region, the Western region, the Northern region, and the Barents Sea region. These operations are performed by different kinds of offshore installation units, like drilling and exploration units and production platforms.

Offshore oil production and drilling installations of StatoilHydro heavily depend on supplies (food, equipment, etc.), which are periodically delivered by supply vessels. Supplies are normally brought to an onshore supply base by trucks, to be later loaded on supply ships and delivered to offshore installations.

Supply vessels are loaded with necessary supplies at eight onshore bases: Hammerfest, Sandnessjøen, Brønnøysund, Kristiansund, Florø, Bergen, Mongstad and Stavanger. Spot vessels in most cases arrive from the British Sector, namely from Aberdeen. The Norwegian continental shelf onshore bases and offshore operation regions are depicted in Figure 1.

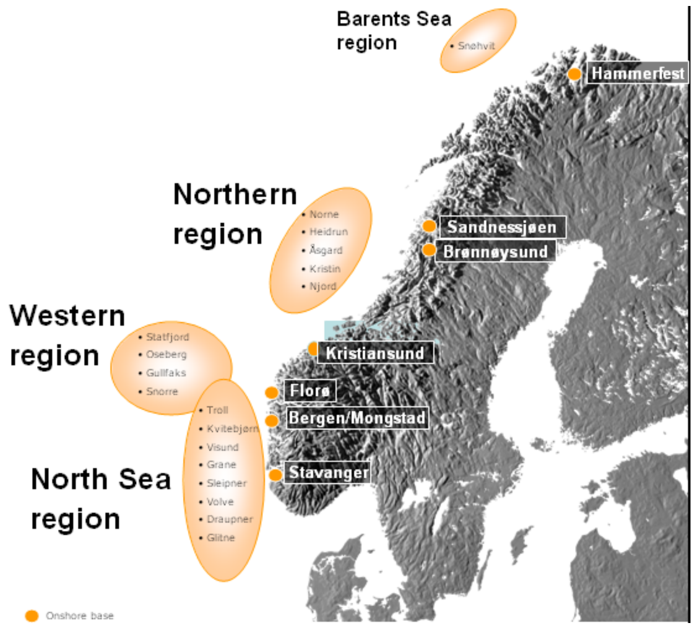


Figure 1: StatoilHydro onshore bases and operation clusters.

Loading/unloading operations between a supply vessel and an offshore installation are performed by cranes.

The detailed description on the upstream logistics in Offshore petroleum production can be found in Ph.D. thesis by Bjørnar Aas (2008), where one of the papers is dedicated to the role of supply vessels in offshore logistics.

3.2 Mongstad supply base

The problem treated in this thesis is a case of supply operations performed from Mongstad base.

Mongstad supply base was established in 1984 as a supply base for Norsk Hydro operations on the Norwegian continental shelf. Later, in 1999, Mongstad became an independent company providing port services to their clients. Today Mongstadbase AS is a modern and service-oriented supply base for installations of StatoilHydro on the continental shelf with a short sailing distance to a number of key North Sea oil and gas fields. Located 60 kilometers north of Bergen, Mongstadbase AS is the largest offshore supply base in Norway, based on volume/tonnage with total area of more than 400 000 square meters. It is a modern harbour, fully equipped with cranes, transport equipment and ample storage facilities, for both indoor and outdoor storage.

3.3 Installations

There are sixteen StatoilHydro offshore installations supplied from Mongstad. Six of them are mobile and ten other belong to three different clusters in Western and North Sea regions. Location clustering and mobile platforms are presented in Table 1.

	Clusters			
	Oseberg	**Troll**	**Heimdal**	**Mobile Installations**
	Oseberg A & D	Troll B	Grane	Deep Sea Delta
	Oseberg B	Troll C	Heimdal	T.O.Winner
	Oseberg C			B.Dolphin
	Oseberg Sør			Stena Dee
	Oseberg Øst			Deep Sea Trym
	Brage			West Venture

Table 1: Locations Clustering and Mobile Installations supplied from Mongstad base

3.4 Supply vessels

A Platform supply vessel (often abbreviated as PSV) is a ship specially designed to supply offshore oil platforms. These ships range from 65 to 350 feet in length and accomplish a variety of tasks. The primary function for most of these vessels is transportation of goods to and from offshore oil platforms and other offshore structures. Supply vessels are used to transport supplies between the supply base and the installations and the supplies can be divided into two main categories: deck cargo and bulk cargo. Deck cargo are pipes and individual items in containers, that are transported on deck of a vessel, while bulk cargo can be a variety of different products transported in separate tanks below the deck.

Supply vessels are multi-task vessels and might have other duties. e.g. fire-extinguishing or oil spill preparedness.

StatoilHydro does not own supply vessels, they are hired from the shipping companies. There are basically two types of hire contracts: long-term and spot (short-term). Spot rates are normally significantly higher than the long-term ones, and spot vessels are typically hired when there is a shortage of long-term ones.

3.5 Weekly vessel schedule.

Supply vessels normally operate according to a fixed weekly sailing plan, which contains the following information:

- Number of vessels leaving the base on a given day, and vessel departure times.
- A sequence of installations to be visited by each vessel with approximate timings for each visit.

Weekly sailing plan is periodically updated. For example, the time allocated for the same trip during the winter will be larger than during the summer to account for rougher weather conditions. The plan is decided depending on planned demands of the platforms. Some of the platforms have to be visited several times a week, while some of them require only one visit a week. Additionally, some of the installations are mobile. And when a mobile installation is moved to a new position, the sailing plan is updated.

Moreover, some of the platforms are closed during the night and therefore the supply operations cannot be performed at the time of closure. Those platforms are specially marked in the weekly vessel plan and their opening time has to be taken into consideration when delays in supply take place. A small fragment of the weekly schedule plan is presented in Figure 2

Weekly vessel plan

HYDRO

		MONDAY						TUESDAY					
DEP.MONGSTAD		17:00		17:00		19:00		17.00		To Shall 17:00		19:00	
BRAGE	Arr.	Mo. 23:00	1									We. 09:30	1
"BRGA"	Dep.	Tu. 01:30										We. 11:30	
GRANE	Arr.	Tu. 15:00	4					We. 05:00	1				
"HRMA"	Dep.	Tu. 18:00						We. 07:00					
DEEP SEA DELTA	Arr.	Tu. 09:30	3					We. 09:30	2				
	Dep.	Tu.12:30						We. 12:00					
T.O.WINNER	Arr.			Mo. 21:30	1					Tu. 21:30	1		
	Dep.			Tu. 00:00						We. 00:00			
HEIMDAL	Arr.												
"HEDP"	Dep.												
B. DOLPHIN	Arr.			Tu. 00:30	2					We. 00:30	2		
"BIDE"	Dep.			Tu. 03:00						We. 03:00			
OSEBERG A & D	Arr.											We. 12:00	5
"OSUF"	Dep.											We. 15:00	
OSEBERG B	Arr.	Tu. 02:30	2					We. 18:30	4				
"OSUB"	Dep.	Tu. 05:00						We. 20:30					

Figure 2: A fragment of Weekly Vessel Plan

3.6 Weather conditions

Loading/unloading operations between a supply vessel and an offshore installation are weather-dependent operations. Significant wave height (SWH) is a measure used to quantify weather conditions for supply operations. It is defined as the average height (trough to crest) of the one-third largest waves. Current safety norms and supply vessel characteristics disallow loading or

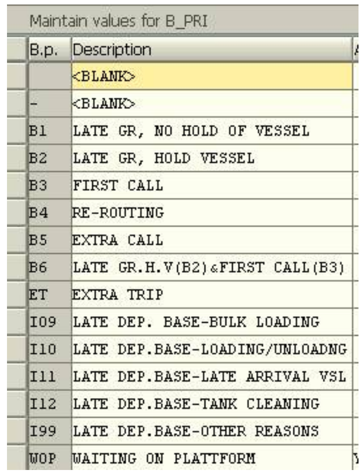
Figure 3: A supply vessel in heavy weather

unloading operations when SWH exceeds 4 meters. The time period, during which the SWH is less then 4 meters is referred to as Low-sea period; the time period, during which the SWH exceeds 4 meters is referred to as High-sea period. The duration of the Low-sea period should not be less then expected time of the loading/unloading operation. The time period during which a supply vessel is waiting for a weather window to perform a loading/unloading operation is referred to as wait-on-weather (WOW). Figure 3 shows the example of supply vessel in heavy weather.

Weather conditions are not the same for every location. When SWH disallow load operation on one installation, vessel can be sent to another installation, where weather conditions are better.

3.7 B-priorities

The variation in the weekly vessel plan can occur due to delays on the supply base or some extra requirements from the platforms. These kinds of situations are called "B-priorities" and there are several types of them. The classification of B-priorities is presented in Figure 4 .



Maintain values for B_PRI

B.p.	Description
	<BLANK>
-	<BLANK>
B1	LATE GR, NO HOLD OF VESSEL
B2	LATE GR, HOLD VESSEL
B3	FIRST CALL
B4	RE-ROUTING
B5	EXTRA CALL
B6	LATE GR.H.V(B2)&FIRST CALL(B3)
ET	EXTRA TRIP
I09	LATE DEP. BASE-BULK LOADING
I10	LATE DEP.BASE-LOADING/UNLOADNG
I11	LATE DEP.BASE-LATE ARRIVAL VSL
I12	LATE DEP.BASE-TANK CLEANING
I99	LATE DEP.BASE-OTHER REASONS
WOP	WAITING ON PLATTFORM

Figure 4: Possible values for B-priorities: screenshot from SAP.

B1 - This is the situation, when some goods have been late to be delivered to the supply base, but the vessel is still sent to the route according to schedule. In this case, late goods must be delivered with the next or additional vessel.

B2 - Again, the supplies are delivered late on the supply base, but the supply vessel is held until all required supplies are loaded.

B3 - One of the platforms requests to be visited first on the route.

B4 - One of the platforms requests to change the position in the visiting sequence.

B5 - The platform calls for some extra deliveries, and it can be delivered on the regular schedule, if the capacity of the vessel allows extra load.

B6 - This is the combination of B2 and B3 situation: the vessel has been delayed on the base, that led to the platform requirement to be visited first.

ET - One of the platforms requests extra visit by additional vessel.

I09, I10, I11, I12, I99 - The delays on the supply base due to other reasons than in B1 and B2 situation.

WOP - The vessel is delayed on the platform.

Situations B2, ET, I09-I12, I99 are considered to have the biggest impact on the number of vessels that are currently in use, and therefore are the ones considered in this thesis.

4 Simulation as a methodology

In this section some important definitions related to simulation as a methodology are provided. Every definition is given in a formal way with some explanations related to this thesis.

Simulation is one of the most widely used operations-research and management-science techniques. One indication of this is the Winter Simulation Conference, which attracts 600 to 700 people every year. Most complex, real-world systems with stochastic elements cannot be accurately described by a mathematical model that can be evaluated analytically. This is one of the main reasons for such popularity of simulation.

The major impediments preventing simulation from becoming a universally accepted and well-utilized tool are model-development time and the modelling skills required for the development of a successful simulation. All mentioned shows that this study is not only modern and interesting, but also rather complex and demands time as well as certain skills to be successful and useful.

Simulation is a technique for using computers to imitate (simulate) the operations of real-world facilities or processes. The facility or process of interest is usually called a system. In order to study it scientifically it is often required to make some assumptions about how it works. These assumptions take form of mathematical or logical relationships and constitute a model that describes the behavior of the system. If the relationships are simple enough, it may be possible to use mathematical methods to analyze the system. However, most of the real-world systems are too complex to be analyzed analytically, and these systems have to be studied by means of simulation.

According to Kelton et al.(2004) simulation refers to a broad collection of methods and applications to mimic the behavior of real systems, usually on computer with appropriate software. A system is defined to be a collection of entities (vessels in our case) that act and interact together towards the accomplishment of some logical end. With respect to the definition, the supply process for the offshore installations is the system studied in this thesis. The supply vessels during their routes are seen as entities that act and interact together. And the goal is the successful delivery of supplies to the platform over the year.

The state of a system is a collection of variables necessary to describe a system at a particular time, relative to the objectives of a study. All the state variables for the system will be described in Section 6. As an example here, the number of vessels in use will be one of the state variables for our system.

Systems can be of two types: discrete and continuous. A discrete system is the one in which the state variables change instantaneously at separate points in time. In a continuous system state variables change continuously over time. Few systems in practice are completely discrete or continuous; but since one type of change predominates for most systems, it is usually possible to classify a system as being either discrete or continuous. Our system is a discrete system as state variables, e.g. the number of vessels in use, change only when the vessel starts its route or when it arrives back to the base.

According to Law and Kelton(2000) discrete-event simulation concerns the modeling of a discrete system as it evolves over time. The points in time, when state variables change, are the ones at which an *event* occurs, where an event is defined as an instantaneous occurrence that may change the state of the system. Each event starts at a discrete point in time and triggers a set of operations changing major state variables. The state of the system is defined by the values of major state variables. The description of major state variables and event for our system is given in Section 7.

Experimenting with a simulation model requires systematic approach, which is referred to as Experimental design. Experimental design is the way to decide the configuration of inputs (usually referred to as *experimental design factors*) before the simulation run in a systematic way and examine respective changes in certain outputs (also called *efficiency measures* or *responses*). Experimental design factors and efficiency measures are defined in Section 8.

5 Research Objectives and Plan

A big amount of stochastic elements in upstream logistics of StatoilHydro operations makes it difficult to describe and analyze the system of offshore supply by mathematical model that can be evaluated analytically. At the same time, offshore supply system has to be estimated under some projected conditions. This leads to the conclusion, that the appropriate way for the analysis is simulation.

The objective of this thesis is to design and develop a discrete- event simulation model for evaluation of alternative supply fleet size configurations. The model has to represent offshore supply operations performed by supply vessels according to the weekly vessel plan, the influence of weather conditions, delays on supply base and extra calls from platforms on scheduled routes, and usage of spot-vessels for extra deliveries. As supply operations include many factors and are rather complicated, it was also important to make the model transparent and intuitive for the users without the problem background. This will be achieved through creation of an advanced animation for the model.

In order to make a simulation model adequate and useful, following steps must be performed:

- As a base for the final model, a basic simulation model will be created.

The basic model will simulate all deterministic elements of the model. These elements are: weekly vessel plan (performance of supplies on a basis of weekly plan), loading and unloading operation on offshore installations and opening hours of the offshore installations. This basic model will also include advanced animation of all mentioned operations.

- When all the deterministic elements are modelled, the uncertainty factors will be included. To quantitatively describe possible uncertainty factors, it is required to analyze the nature of uncertainty, possible distributions and suitable models. All these includes historical data collection and analysis, which will provide an information about the way to describe these factors.

- As a next step, the simulation of uncertainties will be included in the basic model.

- The appearance of uncertainty will lead to some delays or changes in weekly vessel plan. Therefore, the model has to be adapted to adequately simulate these possible changes. Several operational strategies can be used when the vessel faces the uncertainty, like heavy weather. These strategies has to be evaluated in terms of usage of the spot-vessels, and the best strategy will be determined.

- On the last stage the analysis of created simulation model will be carried out. Different number of vessels on long- term contracts and different operational strategies will be evaluated based on number of spot- hire days, which is the main efficiency measure.

The important part of the simulation is the continuous verification of simulation model. Some changes in the model may lead to the behaviors that are not possible for the real-life system, as in real life there is also a human factor and some decisions are made by vessel captain or dispatcher on the supply base considering the circumstances. Therefore, the model has to be adequate for the real world and verified on every change.

6 Input specification

This section contains basic model assumptions and general data considerations. We also describe the modeling of major inputs: weekly routes for the vessels, high-sea and low-sea period durations and strategies in case of uncertainties. Weather durations will be described by random probability distributions. Relevant distributions are displayed in Table 2 (refer to Law and Kelton(2000), whose notation we follow, for a more detailed description of these distributions).

Notation	Description	Probability density function
Expo(β)	Exponential distribution with mean parameter β	$f(x) = \begin{cases} \frac{1}{\beta}\ e^{-\frac{x}{\beta}} \text{ for } x > 0 \\ 0 \text{ otherwise} \end{cases}$
Gamma(β, α)	Gamma distribution with shape parameter α and scale parameter β	$f(x) = \begin{cases} \frac{\beta^{-\alpha} x^{\alpha-1} e^{-\frac{x}{\beta}}}{\Gamma(\alpha)} \text{ for } x > 0 \\ 0 \text{ otherwise} \end{cases}$
Beta(β, α)	Beta distribution with shape parameters β and α	$f(x) = \begin{cases} \frac{x^{\beta-1}(1-x)^{\alpha-1}}{B(\beta,\alpha)} \text{ for } 0 < x < 1 \\ 0 \text{ otherwise} \end{cases}$
Weibull(β, α)	Weibull distribution with shape parameter α and scale parameter β	$f(x) = \begin{cases} \alpha\beta^{-\alpha} x^{\alpha-1} e^{-(x/\beta)^{\alpha}} \text{for } x > 0 \\ 0 \text{ otherwise} \end{cases}$
LN(μ_l, σ_l)	Lognormal distribution with scale parameter $\mu = \ln(\mu_l^2/\sqrt{\sigma_l^2 + \mu_l^2})$ and shape parameter $\sigma = \sqrt{\ln\left[\left(\sigma_l^2 + \mu_l^2\right)/\mu_l^2\right]}$	$f(x) = \begin{cases} \frac{1}{x\sqrt{2\pi\sigma^2}} e^{-\frac{(\ln(x)-\mu)^2}{2\sigma^2}} \text{for } x > 0 \\ 0 \text{ otherwise} \end{cases}$

Table 2: Notation for random probability distributions

6.1 General assumptions and data considerations

Weekly vessel plan for 2007/2008 was used as a primary source of information. There are two weekly vessel plans: from 12th of May 2007 until 30th of November 2007, and from 1st of December 2007, until 11th of May 2008. Each weekly vessel plan has a schedule for the vessels over the week with platforms to visit. The first weekly plan (from 12.05.2007) specifies starting time from the supply base Mongstad, time of arrival to every offshore installation, time of departure from each visited installation and time of arrival to the base for each route. The plan also contains the information about the sequence in which platforms are visited. Second plan (from 01.12.2007) shows a departure and arrival times from and to Mongstad. It also shows the platforms to visit on every route, but does not specify the time or sequence of platform visits. The fragment of the weekly vessel plan from 12.05.2007 was shown in Figure 2. The fragment of Weekly vessel plan form 01.12.2007 is shown in Figure 5

This weekly vessel plan differs from the first one by the departure times from Mongstad and by deletion of some platforms from some routes. Therefore, it was assumed that travel times between platforms and times spend on the platform are the same as in first plan.

Some of the offshore installations are closed from 19.00 until 7.00. These platforms cannot be visited at this time, and if so, the vessel has to wait until morning to perform the supply. On the weekly vessel plan these installations are marked blue. However, according to the weekly vessel plan some of the platforms, that are marked blue, are still visited during the night. It means some kind of supplies can be performed during the night as well.

As our model does not include demands specifications for the platforms, the following assumption was made: if, according to weekly vessel plan, "blue" platform is visited at night, it is considered to be open 24 hours a day like a regular platform. Other "blue" platforms, where the rule is not

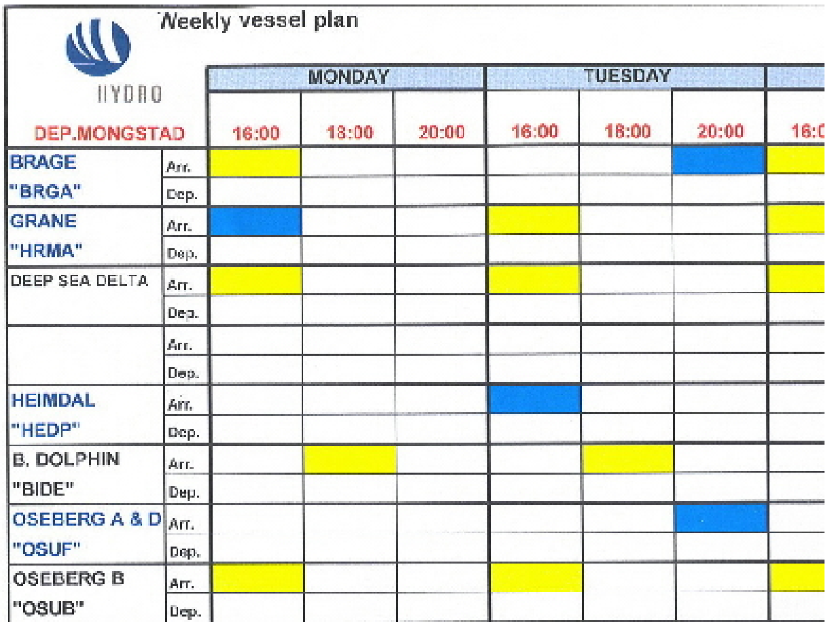


Figure 5: The fragment of Weekly vessel plan from 01.12.2007

violated, are assumed to be closed down for supplies from 19.00 until 07.00.

It is also assumed, that in case there are no vessels available to start the planned route, the spot vessel is hired to perform the operation.

6.2 Loading/Unloading operation durations

The duration of loading and unloading operations usually depends on the amount of supplies that have to be loaded/unloaded. However, the arrival and departure times to every platform are specified in the weekly vessel plan from 12.05.2007. The difference between these times was assumed to be the duration of loading operation. These times were also applied to the weekly vessel plan from 01.12.2007. Even though in real life the duration of supply operation will depend on the vessel and the amount of supplies, in this model we assume that it depends on the platform. Therefore, every offshore installation will have their own loading/unloading times, which will not change from vessel to vessel.

6.3 Weather modeling

The Norwegian Meteorological Institute maintains a grid of sensors in the Norwegian sea, which, among other information, register SWH. These data are occasionally of unacceptable quality (e.g. due to sensor breakdowns) and were therefore not used. However, the data "hind forecasted" with the help of a meteorological model are available for each grid point from January, 1955 to December, 2006. The SWH data is discretized and reported on a six-hour basis.

The requirements on the weather conditions described in Shyshou et al.(2008) are of similar pattern, which provided the information on possible weather modeling approach. In Table 1 the clustering of the platforms was presented. All the mobile platforms were assigned to Oseberg cluster, as it is located more centeral with respect to other clusters. We have identified the nearest grid point for each of 3 offshore operation clusters and transformed the data into month-specific durations of high-sea and low-sea periods using linear interpolation between neighboring six-hour measurements. These durations were then used to fit theoretical distributions for high-sea and low-sea period durations for each month and each grid point, yielding a total of 2(high and low)$\times$4(number of clusters)$\times$12(number of months) $= 96$ distributions.

To generate the durations of high-sea and low-sea periods during simulation we fit probability distributions to the historical data. As a general rule in such situations the distribution expression minimizing the square error of the fit was chosen. To illustrate, the fitting of a theoretical probability distribution for the duration of high-sea periods in January in Oseberg cluster is depicted in Figure 6.

Table 3, whose entries are calculated based on the 52-year period ($1955-2006$) of "hind forecasted" data for the grid point nearest to the Oseberg cluster (60.40 northern latitude, 2.73 eastern longitude), is helpful in under-

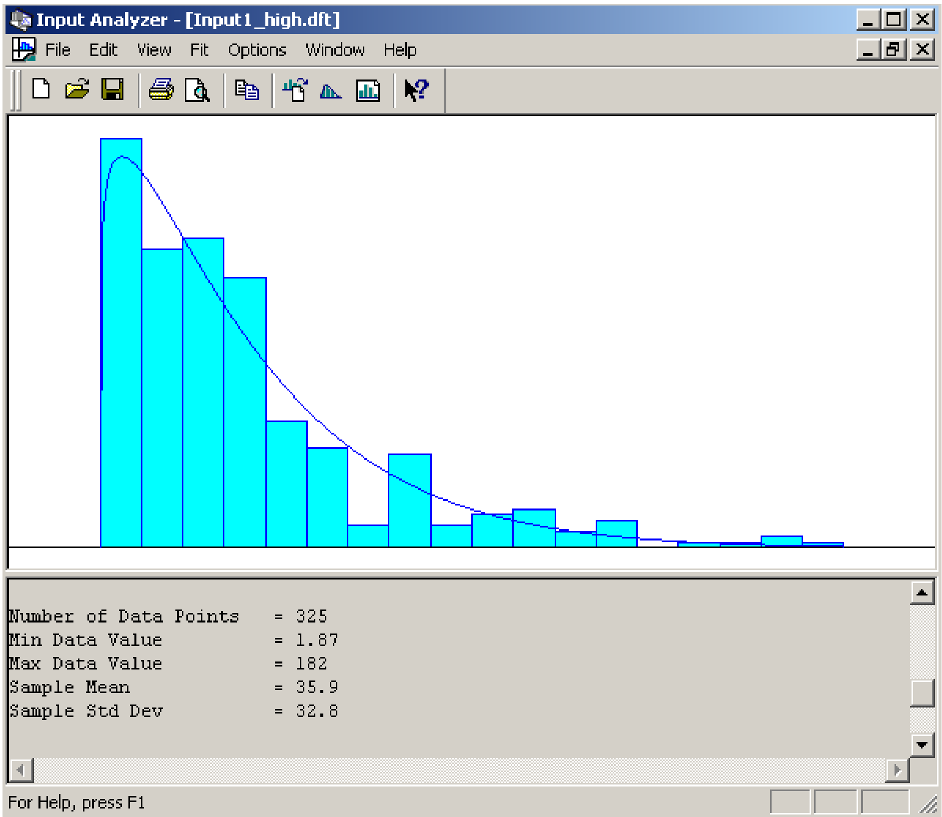


Figure 6: Fitting data to the probability distribution by Arena InputAnalyzer

standing SWH modeling.

Month	# of Obs.	Mean	St.Dev	Min	Max	Distribution expression
1	325	35.9	32.8	1.87	182	$1 + Weibull(36.6, 1.13)$
2	273	29	27.1	2.2	148	$2 + Expo(27)$
3	274	25.9	24	2.2	149	$2 + Expo(23.9)$
4	157	23.4	21.2	1.33	127	$1 + 126 * Beta(0.74, 3.43)$
5	81	22.3	18.3	1.7	89.1	$1 + Weibull(22.9, 1.24)$
6	51	18.4	15.6	2.05	66	$2 + Expo(16.4)$
7	22	19.9	15.5	2.75	53.3	$2 + 52 * Beta(0.533, 1.01)$
8	39	17.6	14	2.19	66	$2 + LN(19.5, 35.5)$
9	144	21.3	16.5	1.35	84	$1 + Gamma(14.2, 1.42)$
10	245	25.4	22.3	1.21	174	$1 + 173 * Beta(0.885, 5.38)$
11	283	27.8	27.3	2.46	263	$2 + Gamma(20.7, 1.25)$
12	339	33.4	28.5	2.05	169	$2 + Gamma(23.9, 1.31)$

Table 3: High-sea period durations for Oseberg cluster $(60.40N,\ 2.73E)$

The “Mean” and the “St.Dev” columns contain average duration (in hours) of the high-sea period starting in a given month and its standard deviation respectively. The “Max” and "Min"columns reveal the longest and shortest continuous high-sea period starting in a given month during the 52-year period. The number of high-sea periods starting in a given month during the 52 years is found in the “# of Obs.” column. This is the number of observations we have used to fit a probability distribution expression given in the “Distribution expression” column. Not surprisingly high-sea period durations tend to be longer in winter and shorter in summer. There is a pair of such tables for each cluster. High-sea and low-sea periods for each cluster are sampled one after the other (high-sea period, then low-sea, then high-sea again, etc.) from identified month- and location-specific distributions.

6.4 Operational strategies

As far as the weather conditions are in the low-sea state, the vessel just follows the initial weekly vessel plan. There are no delays or changes in the supply process. Once the weather turns into high-sea period, when the supply operations cannot be performed, the vessel that arrives to the platform with heavy weather has to make a decision on the actions to be taken in this situation. There can be different ways for the vessel to react to the weather conditions.

"Waiting strategy". The simplest way is to keep the vessel waiting until the weather turns into low-sea period for long enough to perform the supply operation. Once the loading/unloading operation has been completed, vessels proceeds on the assigned route.

"**Skip strategy**". If the vessels arrives to the platform with bad weather conditions, it checks forecasted duration of such conditions, and if the duration is longer than acceptable WOW time, vessel skips the platform and sails to the next one on the route. Initial acceptable WOW is defined for each platform separately, depending on the number of visits the platform has during the week. If the platform is supposed to be visited five or six times a week, the WOW time can not be longer than 24 hours. This is done to avoid the situation when more than one vessel are kept next to the platform. If the platform has only one visit a week, the WOW time should not exceed the average duration of the routes on weekly vessel plan, which is 34 hours. This means that instead of waiting, the vessel can complete another route and then come back to this platform with necessary supplies. However, WOW is an experimental design factor, and initial WOW might be not optimal with respect to spot-hire days.

An additional assumption is that weekly demand of any platform can be delivered by one vessel. So once there have been platforms not visited due to heavy weather, the supplies will be delivered by separate vessel when the low-sea period starts.

7 Model implementation, verification and validation

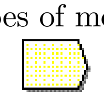
In this section we will discuss the implementation, verification and validation of the simulation model in Arena 9.0.

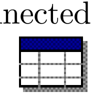
7.1 Implementation software

Arena is a general-purpose simulation package by Systems Modeling Corporation. Arena was chosen for three reasons:

- It combines the ease of use of high-level simulators with the flexibility of general-purpose programming languages. This enables convenient modeling and a more efficient implementation using Arena's Object Model and writing out the outputs for later analysis.
- It includes dynamic animation in the same work environment, which was very helpful in model verification and validation.
- It provides integrated support for statistical design and analysis. Most of the input probability distributions were identified with the help of Arena Input Analyzer.

To build models with Arena, modeling shapes called "Modules" are used. These modules are grouped into several panels (Templates). There are two types of modules on a panel: Flowchart modules and Data modules.

 - Flowchart module shapes are placed in the model window and connected to form a flowchart, describing the logic of the process.

 - Data modules are not placed in the model window. Instead, they are edited via a spreadsheet interface.

The Arena model-building panels are:

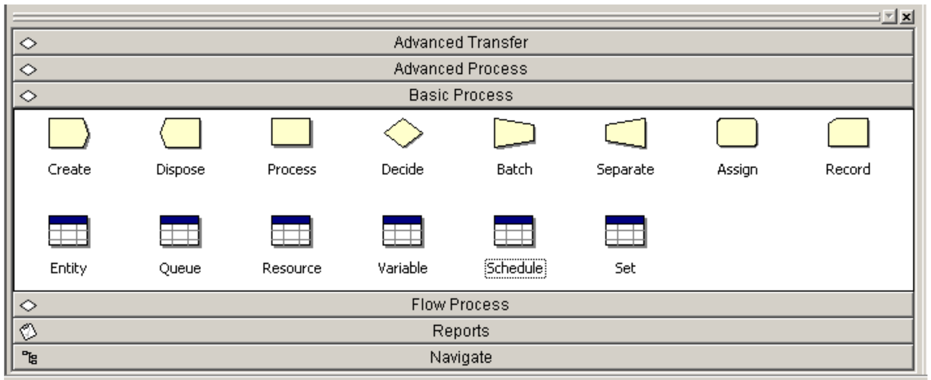


Figure 7: Basic Process Template with included modules

- **Basic Process**. This panel is used most commonly and as the basis for most models. It includes such flowchart modules as Create (to create entities like vessels or weather entity), Dispose (to dispose entity from the model), Assign (to assign different characteristics to the entity or variables, like route to the vessel, vessel type etc.), Process (to describe the characteristics of the process like Loading operations) and others. There are also some basic data modules, like Variables, Entities, etc. Figure 7 shows the Basic Process Template with all included modules and list of other Templates included in Arena.

- **Advanced Process** . Most important flowchart modules in this template for our model are: Delay (delays the entity for specified time) and Hold (holds the entity until specified condition or signal). Data modules that will be used in the model are: Advanced Set (defines set of objects of the same type, e.g. routes) and Expression.

- **Advanced Transfer.** Used to simulate different kinds of transfers. From this Template we will use Station and Route flowchart modules, and Sequence and Distance data modules.

A model is constructed by dragging and dropping modules into the model window, connecting them to indicate the flow of entities through simulated system, and then detailing the modules using dialog boxes or Arena's built-in spreadsheet.

The results of the simulation run can be viewed through automatically generated report. By default the report contains the following information:

- entities: times, number in, number out, work-in-process
- queues: Waiting times and Number waiting
- resource: usage
- User specified parameters.

Other information can be requested to be present in the report.

A short summary on Arena software can be found in Law and Kelton(2000). For more detailed information Kelton et al.(2004) can be used.

7.2 Implementation

A top-level flowchart for the simulation model is depicted in Figure 8.

Major state variables for our system are *Number of vessels currently in use* and *Total number of spot-hire days*. With respect to defined state variables, major events are *Departure of the vessel from the supply base* and *Arrival of the vessel to supply base*.

Starting simulation time is set to 14.05.2007, as this is the time the weekly vessel plan is available. There are 4 possible entities in the model: Weather entity, Vessel, LongTermVessel and SpotVessel. Weather entity is used to generate high-sea and low-sea periods. There is one such entity for each cluster. Entity of the type Vessel is used before the contract is assigned to the vessel. This entity is used only in Create Submodel and is assigned with another type: LongTermVessel or SpotVessel - depending on availability of

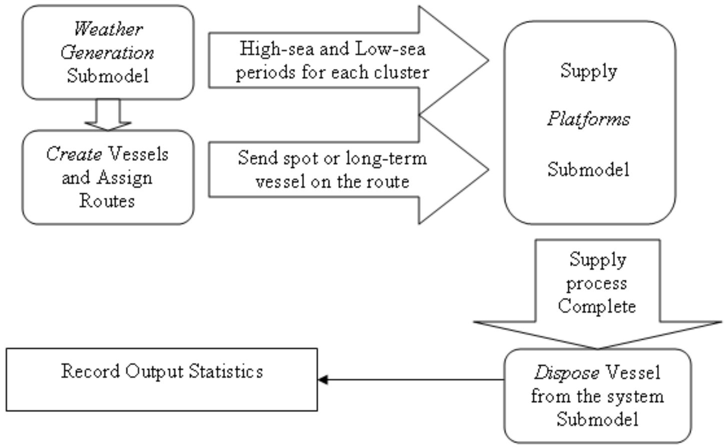


Figure 8: Arena Implementation Flowchart

long-term vessels. LongTermVessel and SpotVessel are entities that travel through the system. It is important to know how many vessels are currently in the system. For such information Work-In-Process parameter is used:

WIP(EntityType) -Work-In-Process - Number of vessels of the type EntityType currently in the system.

7.2.1 "Weather generation" submodel

For each operation cluster high-sea and low-sea periods are generated alternately from cluster- and month-specific distributions described in Section 6.3. As the high-sea and low-sea periods are generated, the times for the period to end are recorded in specially defined variables. So for each cluster, once the period of particular sea level has started, the model knows exactly when it is going to end and be changed to the opposite.

7.2.2 "Create" Submodel

The simulation model starts with Create modules, which generate entities of the type Vessel. From 14.05.2007 until 31.11.2007 the create modules generate vessel entities as following:

- 2 vessels start on Monday, Tuesday, Thursday and Friday at 17.00
- 1 vessel starts on Wednesday at 17.00
- 1 vessel starts on Monday, Tuesday, Wednesday, Thursday and Friday at 19.00
- 2 vessels start on Saturday at 16.00

From 01.12.2007 1 vessel starts every week day at 16.00, 18.00 and 20.00, and 2 vessels still start on Saturday at 16.00, according to weekly vessel plans.

As the vessel entity leaves the create module, it arrives to assign module, where route is assigned according to the creation time. For example, if the vessel arrives on Monday at 19.00 before 1st of December, the route assigned to the vessel will be: Stena Dee - Deep Sea Trym - Oseberg Ost - Oseberg C - Oseberg Sor - Mongstad.

After the vessel has been assigned with the route, the model checks if a long- term vessel is available to perform the operation. If WIP (LongTermVessel) is equal to the variable "Long Term Vessels", all long-term vessels are in use and Vessel entity is assigned with new entity type: SpotVessel - and new picture. Otherwise, entity type is changed to LongTermVessel through assign module. The vessel is then sent to Mongstad station, from where it follows assigned route.

Create submodel also generates vessels for missed visits to the platforms. These vessels are held in Hold module until the missed visit to the platform appears and the duration of low-sea period is enough to sail to platform with

Stations

	Beginning Station	Ending Station	Distance
1	Mong	Brga	360
2	Brga	Osub	60
3	Osub	Delta	270
4	Delta	Hrma	150
5	Hrma	Mong	720
6	Mong	Winner	270
7	Winner	Bide	30
8	Bide	Rig2	90
9	Rig2	Mong	240
10	Mong	Sdee	240
11	Sdee	Trym	30

Figure 9: Fragment of the Distance module in Arena

missed visit and perform supply. When vessel is released to supply missed platform, the checking on the availability of long-term vessels and assignment of vessel type is done as described above.

7.2.3 "Platforms" submodel

As the vessel leaves the Mongstad station, it proceeds to the platforms submodel. The distances between platforms are defined in terms of time it takes from one platform to another. These distances are taken from the Weekly vessel plan from 12.05.2007 and are converted to minutes (as the distance definition in Arena allows only integer inputs). Total of 56 distances had to be defined and calculated. Arena snapshot of the Distances module is shown in Figure 9

Once the vessel arrives to the station, the duration of load/unload operation is assigned to the vessel. Further modeling depends on the strategy, chosen for the vessels once they face heavy weather at the location. Two different strategies have been defined in Section 6.4.

"**Waiting strategy**". Once vessels arrive to the platforms, it is transported to the Hold module, where weather conditions in the location are checked. If high-sea period is forecasted to start before supply operation can be completed, or if high-sea period has already started, the vessel will be held in the Hold module until low-sea period starts. The duration of started low-sea period has to be enough to complete the supply operation.

"**Skip strategy**". After arriving to the platform, the expected and current weather conditions are checked.

- **Low-sea period is in place, and is expected to continue for the time required for load/unload operation.** In this situation vessels proceeds to the platforms, and occupies the crane for the loading/unloading for the time period, defined in weekly vessel plan. If the vessel arrives at night to the platform, which is closed during the night, it waits until the platform is open and then performs load/unload operation.

- **Low-sea period is in place, but high-sea period is expected to start before the load/unload operation can be completed.** The duration of the high-sea period cannot be forecasted before it actually started. Therefore, if the vessel doesn't have enough time to supply the installation, it doesn't know how long it will have to wait, and it skips current platform and proceeds to the next one on the route.

- **High-sea period is in place, and is expected to continue for longer than possible WOW time.** Here the vessel knows for sure that it will have to wait longer than WOW time, so it skips current platform and proceeds to the next one on the route.

- **High-sea period is in place, but is expected to finish within possible WOW time.** The vessel is send to the Hold Module, where it will stay until the weather conditions will be suitable for performing the supply operation.

Once weather conditions allow to supply the installation, vessel is sent to the Process module, where it occupies the crane for loading and unloading for the duration defined by the assigned Process time. Only one vessel can be supplied at a time, so if there are any more supply vessels next to the platform, they have to wait until the other vessel completes its operation.

If the platform missed the visit due to weather conditions, the special counter for missed visits for every platform will keep account on how many visits were missed. When the weather is good, and the duration of good weather is expected to be enough to reach the platform and supply it, the additional vessel will be sent to the platform. If platforms was not visited for two or more weeks, additional vessels will be send for every week of missed visits, according to made assumption, described in Section 6.4.

Once vessel completed the route, it comes back to Mongstad base, and is sent to Leave station in Dispose submodel.

7.2.4 "Dispose" Submodel

Dispose Submodel is used only to collect all necessary statistics and to dispose vessel entity from the system.

7.3 Verification

Robert G.Sargent (1999) defines model verification as “ensuring that the computer program of the computerized model and its implementation are correct... Computerized model verification ensures that the computer programming and implementation of the conceptual model are correct." Robert G.Sargent (1999) also defines two basic approaches for testing simulation software: static testing and dynamic testing. In static testing the computer program is analyzed to determine if it is correct by using such techniques as structured walkthroughs, correctness proofs, and examining the structure properties of the program. In dynamic testing the computer program is executed under different conditions and the values obtained (including those generated during the execution) are used to determine if the computer program and its implementations are correct. Both, dynamic and static testing is a part of the simulation model development. Though we more rely on the dynamic verification of our model.

To understand whether the model behaves the way it was meant, we will use animation as a major tool . It illustrates the behaviors of the vessels in the most transparent way. Figure 10 is an animation snapshot of the model.

The current date and time are displayed on the right from the Mongstad base. Each offshore installation is animated by a small square next to station and waiting spots next to the square. The square presents the Crane, that performs loading and unloading, and can be in 3 possible states: white - idle, green - seized and shaded - closed over night. The waiting spot next to station is used when vessel has to wait due to weather conditions. Weather conditions are presented by 3 circles, one for each cluster, that can be in 2 states: blue - low-sea period and red - high-sea period.

As Figure 10 demonstrates, there are five long-term vessels in use. As the simulated time is 6 a.m., offshore installations Troll B (Trub), Troll C (Truc), Heimdal (Hedp) and Oseberg A&D (Osuf) are shaded, meaning closed for the night. Platforms Oseberg Sør and Oseberg Øst are performing load/unload operation (marked with green square). The red circle near Troll B and Troll C shows the high-sea period in place on Troll cluster. The vessel near Troll C is displayed standing on the waiting spot, which shows that low-sea period is expected to start within 34 hours.

Through the animation it is easy to verify the model after any changes. Through the animation run, vessels sailing from one destination to another can be observed. The simulation clock shows what time vessels start from Mongstad, and it is obvious that the timing is consistent with one of the Weekly vessel plan. We can also see, that platforms that are supposed to be closed at night are simulated and animated as closed during simulated

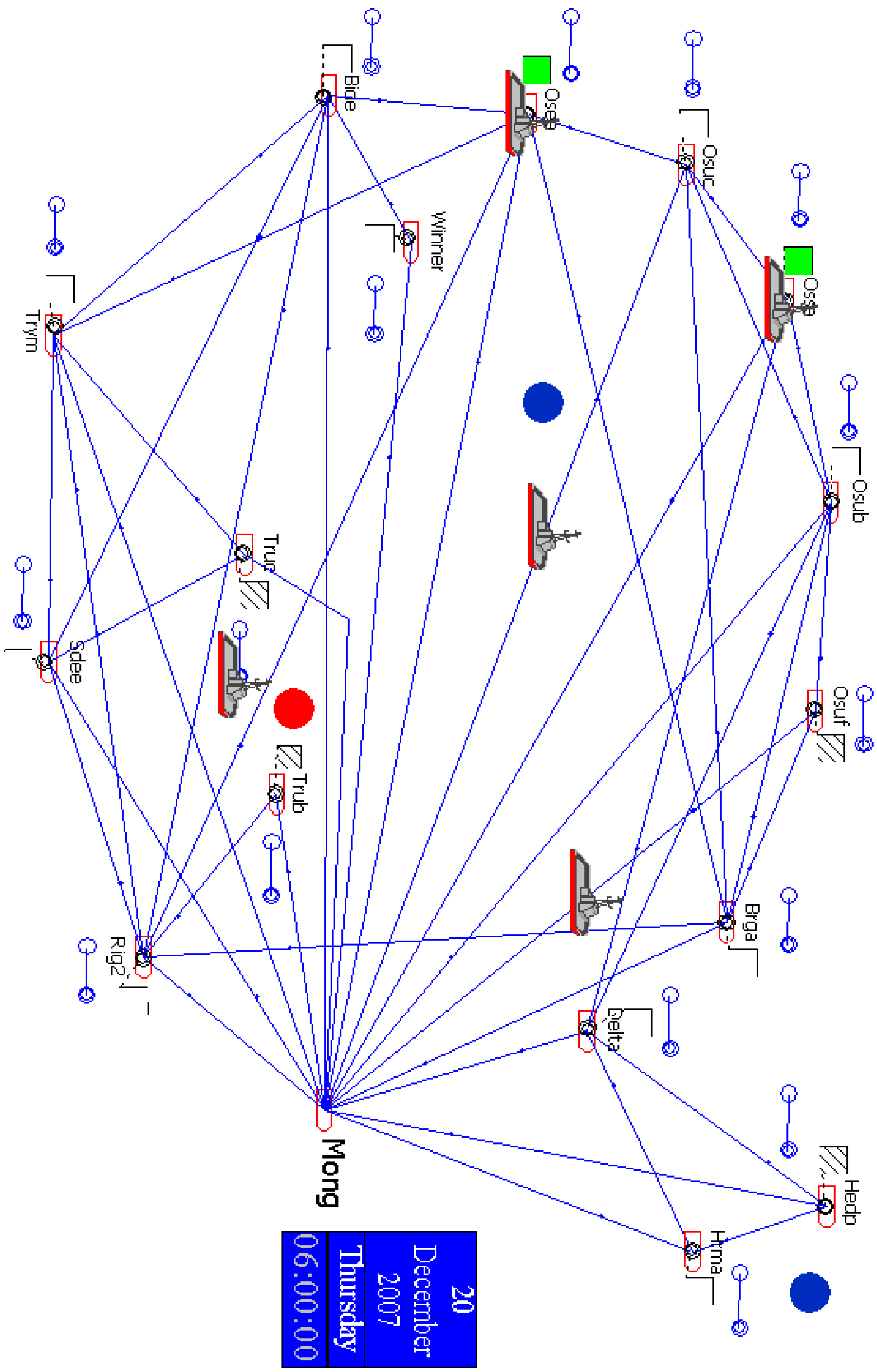


Figure 10: A snapshot of animation for the model.

nights.

Also the behavior of the vessels when facing the weather conditions are consistent with the strategies defined.

All mentioned above allows us to conclude, that the implementation of the model is correct.

7.4 Validation

For model validation we will again use the techniques of Robert G.Sargent (1999). Model validation is defined as "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model". It is often difficult to separate verification and validation, as these two processes are closely related, and often the same techniques are used for both. Various validation techniques are described by Robert G.Sargent (1999). Those used for validating our model are listed below.

- Animation. This technique was discussed in details in Section 7.3.

- Event Validity: The "events" of occurrences of the simulation model are compared to those of the real system to determine if they are similar. This technique was used to validate the fulfilment of Weekly vessel plan. Combining with Animation, it was determined that simulated events as vessel creation and vessel movements are consistent with provided data. Here it should be noticed that Data validity is of great importance for the successful model development. We assume that the data provided on Weekly vessel plan is the exact behavior of the system excluding uncertainty factors and can be used for validation of the model.

- Face Validity: "Face validity" is asking people knowledgeable about the system whether the model and/or its behavior are reasonable. This technique can be used in determining if the logic in the conceptual

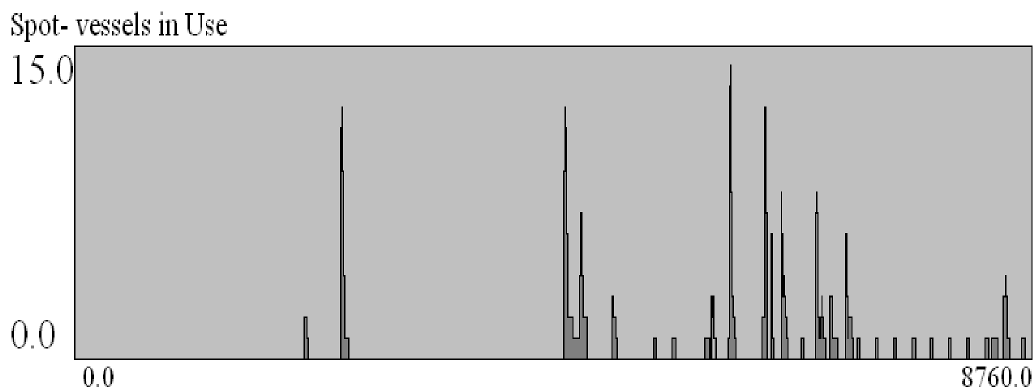


Figure 11: Graph created by Arena during simulation run

model is correct and if a model's input-output relationships are reasonable. Using this technique it was discovered that Waiting strategy is not valid for the real system, as it creates the queues in front of the platforms of up to 7 - 8 vessels, that can be waiting up to 1 week in the queue. This behavior of the model was considered unreasonable, and the "Waiting" strategy was excluded from further analysis.

- Operational Graphics: Values of various performance measures, e.g., number in queue and percentage of servers busy, are shown graphically as the model moves through time; i.e., the dynamic behaviors of performance indicators are visually displayed as the simulation model moves through time. We used such graphics for number of spot vessels in use. The graphic from one of the simulation runs is shown in Figure 11. As we can see, the usage of spot vessels increases in the third quarter of the simulation time. Considering that simulation starts in May, third quarter of simulation time is exactly winter time. As weather conditions during winter are usually worth than during the rest of the year, it can be concluded that the model is valid concerning the hiring of spot vessels.

8 Output analysis

In this section the results of the simulation run are presented and analyzed. The efficiency measure for the model is *SpotHireDays* - total number of days for which spot vessels were hired. The experimental design factors are *Number of vessels on long-term hire* and *WOW time* for "Skip" strategy.

We will define an experiment as a simulation run for defined number of replications with defined combination of experimental design factor values. For each experiment, the average and half width values for SpotHireDays will be presented. These values are used to present 95% confidence interval for the efficiency measure - the value of SpotHireDays belongs to the interval $(Average - Halfwidth, Average + HalfWidth)$ with the probability of 0.95.

8.1 Number of long-term vessels

Number of long-term vessels was changed from 0 till 10 and the output statistics were collected on SpotHireDays. Number of replications for each experiment was set to 100.

Also the results of the runs can be seen in Table 4 , where half widths are presented as well. As we can see from the Graph presented in Figure 12, when the number of vessels on the long term contract is between 0 to 5, the relation with SpotHireDays is almost linear. This effect is because first 5 vessels are almost fully utilized. Utilization of a vessel is defined by the amount of time the vessel spends on the routes. Every next vessel will be in use less then previous, and this is what the graph shows. There is almost no difference between 9th and 10th vessel, as expected utilizations of 9th and 10th vessels are low and on approximately the same level. This shows that it is not appropriate to hire 10th vessel on the long- term contract. However, the final decision must be taken depending on expected spot-rates.

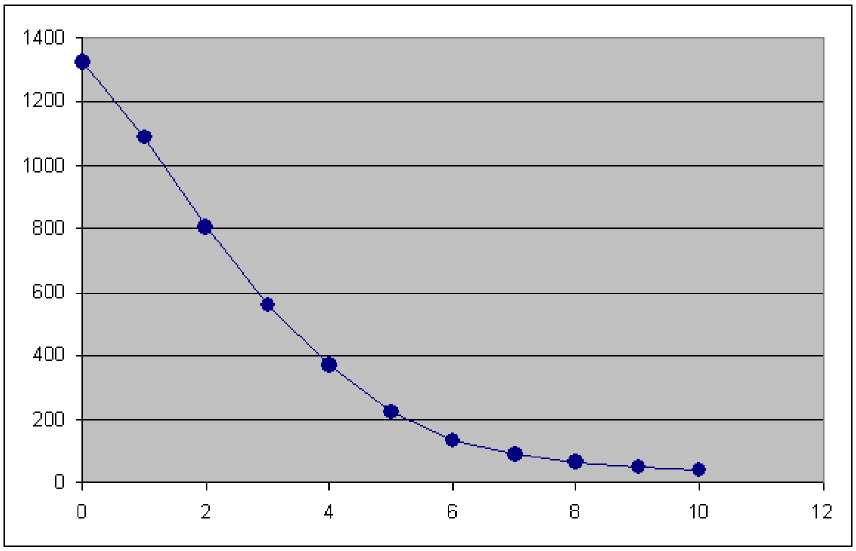


Figure 12: The relation between number of Long-term vessels and SpotHire-Days.

8.2 Operational strategies

Different operational strategies, when facing heavy weather, were defined in Section 6.4. As it was mentioned in Section 7.4, "Waiting strategy" didn't pass "Face" validation stage due to high queues in front of offshore installations, and therefore was excluded from further consideration. "Skip strategy" is appropriate to use, but WOW is an experimental design factor.

Initial values for WOW were decided for each platform separately depending on number of visits during the week. It appeared that all the platforms are split in 2 categories:

- Visited 5 - 6 times a week. For all such offshore installation WOW time was defined as WOW1 and set to initial value of 24 hours.
- Visited once or twice a week. For these platforms WOW time was defined as WOW2 and set to initial value of 34 hours.

# of long-term vessels	Average	Half Width
0	1325	3.38
1	1087	3.26
2	806	3.31
3	560	3.34
4	372	2.97
5	221	2.88
6	133	2.5
7	90	2.27
8	66	2.03
9	51	1.98
10	40	1.92

Table 4: Average number of SpotHireDays with Half width for 100 replications

These values were used for the analysis in Section 8.1. In this Section we will experiment with the model and see, which values for WOW1 and WOW2 will minimize the efficiency measure - SpotHireDays. Number of long-term vessels was set to 6, as it is number of vessels required to perform weekly vessel plan without hiring spot vessels, if no delays occur. This is also the number of long-term vessels, used by the company during the simulatiuon period, according to actual data.

In the Table 5 the relation between WOW1 and SpotHireDays are presented. To build such relation, WOW2 was fixed to 34, WOW1 was assigned with different values, number of replications was set to 100, and the results of the simulation run were recorded. Column "WOW1" in Table 5 shows the values set for WOW1 in hours, "SpotHireDays" - average number of SpotHireDays for 100 replications, and "Half Width"- corresponding values for SpotHireDays half widths obtained from simulation run. Column "%" contains the percentage of improvement from initial values.

The graphical results are presented in Figure 13.

As it can be noted, the optimal WOW1 time appeared to be 0. This result

WOW1	SpotHireDays	Half Width	%
24	132.95	2.5	0
18	119.19	2.02	10.35
10	107.62	1.77	19.05
5	101.04	1.74	24
2	97.31	1.69	26.81
1	96.51	1.62	27.41
0	95.74	1.57	27.99

Table 5: Experiment results for parameter WOW1

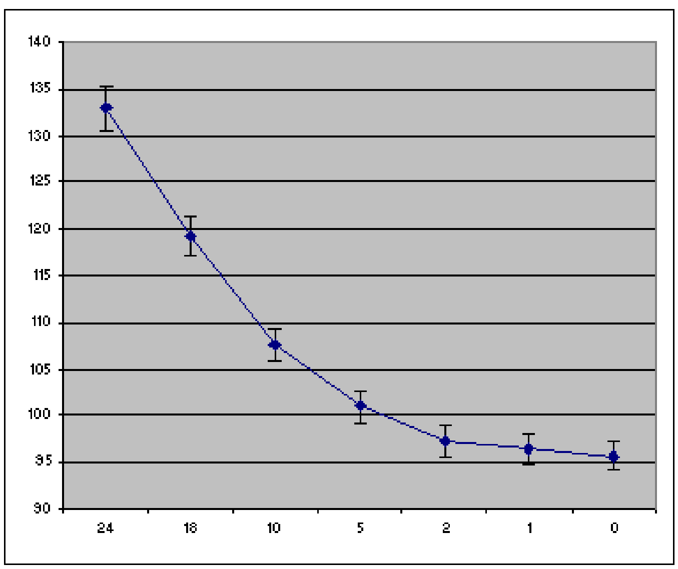


Figure 13: SpotHireDays with confident intervals depending on the WOW1.

leads to the conclusion, that it is appropriate to skip offshore installations with heavy weather conditions on the route without any delay, and send additional vessel to skipped platform during low-sea period.

Same procedure was done for WOW2, but WOW1 was fixed to 0, as it was the optimal result from the experiments with WOW1. The results are presented in Table 6 and Figure 14. As it can be seen in the tables, there is no significant change in SpotHireDays depending on WOW2. There are several reasons for that. First, there are only four offshore installations, for which WOW2 is applied: Troll B, Troll C, Heimdal and Oseberg A&D - so it may not have much influence on the SpotHireDays. Second, these platforms are visited only once or twice a week, therefore there are less chances that the vessel will arrive during high- sea period.

WOW2	SpotHireDays	Half Width	%
10	98.91	1.66	$-3,31$
15	97.77	1.62	-2.12
20	96.7	1.54	-1
34	95.74	$1,57$	0
50	95.15	1.59	0.62
60	95.32	1.51	0.44
80	96.08	1.53	-0.36
100	96.97	1.52	-1.28
150	97.98	1.65	-2.34

Table 6: Experiment results for parameter WOW2

Even though the changes in SpotHireDays between two consequent measures are within 95% confidence interval, clear trend can be noted in Figure 14. Therefore it can be concluded, that optimal value for WOW2 lies between 20 and 100 hours. Keeping in mind, that the shortest route on the weekly vessel plan is 18 hours, and the longest - 52 hours, we may conclude that the optimum will most possibly lie within minimum and maximum route duration. By looking at the graph in Figure 14 we can only assume that it will probably be the maximum route duration, that will give optimal value for

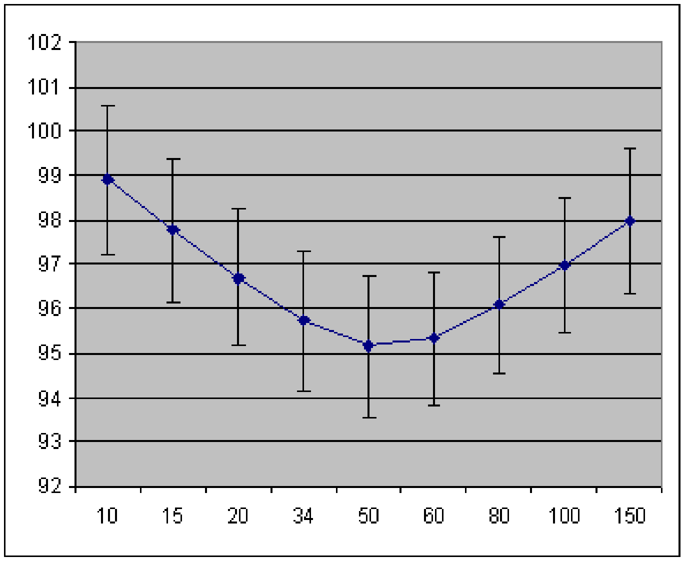


Figure 14: SpotHireDays with confident intervals depending on the WOW2.

WOW2, though no significant differenceses were found for WOW2 between 20 and 100.

9 Additional features

Soma additional features have been included in the final simulation model. This features will be discussed in this section. Due to the absence of data for considered base and considered offshore installations, it was not possible to validate the implementation. However, the verification was performed with satisfactory results.

9.1 Delays on supply base

Often delay in the vessel plan can be caused by late arrival of goods to the onshore base. If the supplies are late, the vessel must wait for the delayed goods, and therefore will be late on the assigned schedule. There are also other reasons for the vessel to be delayed from scheduled departure from the base. These situations and their formal classifications were described in Section 3.7. These delays have been implemented in the simulation model by adding Delay module in the model, after assigning the route to the vessel. As historical data about vessels delays on the Mongstad base will become available, it can be analyzed using Arena Input Analyzer, and the probability distribution for the duration of such delays must be entered as the Delay Time.

9.2 Extra trip to offshore installation

Occasionally, additional supplies are requested from the offshore installations, and these supplies has to be delivered as soon as possible. Such demands are classified as ET (see Figure 4), and require additional vessel sent to the installation.

ETs were also implemented in the model by adding Create modules. Create modules generate extra vessel with the same frequency, as ET demands arrive from each particular offshore installation. The data about the time between arrivals of ET demands for each offshore installation has to be analyzed and a probability distribution has to be fit. Once these distributions are defined, they can be entered in Create module in the field "Time between arrivals".

10 Conclusions

PSVs are one of the most costly resources in upstream logistics of oil and gas production. Therefore determining their fleet size requires thorough planning. Many stochastic factors, like weather conditions, delays of supplies on the onshore base, calls for extra visits from offshore installations, can influence weekly vessel plan, resulting in delays and PSV shortage. This shortage must be covered by vessels, hired from the spot market, which are normally more expensive than vessels on the long-term contracts. Uncertainties make it difficult to apply analytical methods.

The simulation model for the offshore supply process was created. The model can be used as a desicion-support tool for strategic fleet planning, as well as an evaluation tool for operational strategies that can be used by vessels when facing such uncertainty factors as heavy weather conditions, delays on the supply base or extra calls from the offshore installations. Using the simulation model different fleet sizes have been tested. It was noted that as the utilization of the vessels goes down, the contribution of every next vessel hired on the long-term contract becomes less visible in terms of spot-hire days. Moreover, two different strategies for the vessels facing heavy weather have been analyzed. It was observed that proposed "Waiting" strategy leads to high delays and long queues in front of the platforms. "Skip" strategy was tested with different WOW times. Output analysis shows that WOW should be smaller, or even close to 0, for the offshore installations that are visited more frequently (5 - 6 times a week). Different results were observed for the installations that are visited once or twice a week. It was noted that the system is less sensitive to WOW time on such installations. It was also observed that the optimal WOW time lies within the range of route duration on the weekly vessel plan.

On the final stage the model was extended with Delays on the supply base and calls for ET. These implemented features can be used for further analysis of offshore supply process.

The simulation model is seen as a tool for analysis of the behavior of the offshore supply system with many stochastic factors. It is transparent and does not require special knowledge to understand the outcome on any kind of changes that can be applied to the system. Moreover, the model can be easily extended with additional features to become even closer to the real life.

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