QATAR UNIVERSITY

COLLEGE OF ENGINEERING

WORK FORCE ASSIGNMENT AND PLANNING FOR ONSHORE OIL AND GAS WELLS CEMENTING OPERATIONS

BY

MOHAMED MOHSEN A. HAFEZ KHALIL

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Committee

The members of the Committee approve the project of Mohamed Mohsen A.Hafez Khalil defended on 30th of May,2016.

Dr. Fatih Mutlu

Thesis / Dissertation Supervisor

Name

Committee Member

Name

Committee Member

Name

Committee Member

ABSTRACT

In oil and gas well cementing operations, workers are exposed to long consecutive hours of work and irregular off times due to the nature of such service and inefficient workforce assignment. Overloading human resources increases the potential of errors during service execution, which is mostly considered catastrophic in this field of services. Efficiency of human resources overall reduces as they become over utilized. Finally, loyalty of employees to the company becomes unstable.

The objective of this project is to develop a more efficient workforce assignment policy for oil and gas well cementing operations. Cementing operation is critical and vital in a life cycle of any oil or gas well. Operating companies consider this operation as one of the most critical operations during the construction of a well and they explicitly place a zero margin of error in this operation.

A case study from the land field of Dukhan is examined in this project. An international oil field services provider is the current service provider for cementing services. The main deficiency of the existing planning policy is the overloading of resources performing the service operation. The project ultimately aims to reduce the average positive deviation from the maximum shift duration for each member of the service team. A sub-objective of the project is limit the maximum waiting time a drilling rig spend waiting on crew members to execute the job to 24 hours.

Methodology of the project starts by studying the current personnel deployment policy and defining the problem. Following that, previous operational data is collected over the span of 1 year and probability distributions are determined for uncertain variables. Finally, the new proposed planning policy is simulated in AnyLogic Multimethod Simulation software to examine its efficiency, where generated data is collected, analyzed and compared to the existing planning policy.

The combination of both the project methodology and the relevant literature review provide strong bases for developing alternative personnel assignment policies. Methodology in general is considered a good foundation for staff assignment problems, while literature review gives insight for the possibility of improving current assignment policy in order to have a more balanced work load distribution.

Obtained results confirm superiority of proposed planning policy. Average positive deviation dropped considerably compared to the current assignment policy. Drilling rig waiting time remains below pre-set maximum waiting time. Thus, proposed policy enhanced personnel assignment without compromising the integrity of operations.

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1. INTRODUCTION

Staff assignment is one of the most critical factors for oil and gas upstream service providers. The criticality of the operations performed along with its cost related impacts imposes a great focus on the staff assignment aspect. Service personnel are essential to any service operation, where their contribution cannot be reduced or eliminate form the work environment.

In this project, we are addressing the staff assignment problem at Schlumberger Well Cementing Services in Qatar. Schlumberger Cementing Services is one of the largest service providers for well construction operations globally and locally. It has provided service to several high profile clients in Qatar including Qatar Petroleum, Ras Gas, Qatar Gas, Dolphin Energy and Shell.

Recently and due to the limited resources available, Cementing Services is facing a resources overloading problem. This project analyses the current assignment policy and proposes a new one to overcome this issue.

1.1. Historical Background

Schlumberger was established in 1926 by the French brothers Conrad and Marcel Schlumberger. They introduced the idea of electrical resistivity well log into the industry. Their first attempt was in 1927 on a 500 meters deep well in the Alsace region of France. Prior to their attempt, scientists relied on core samples and cutting from the well bore to able to model the geology of a well and locate oil reservoirs. However, this method was unreliable. (1920s: The First Well Log, 2016)

Well logging was the first step for the Schlumberger brothers into the exploration industry. Over the years, Schlumberger continued the development and acquisitions to enrich their portfolio. They’ve invested heavily in research in development of upstream services, with a budget of more than 1 billion dollars in 2014 only.

Today, Schlumberger is the world largest oil & gas upstream services provider. It provides a wide range of services including:

- Directional Drilling
- Drilling & Measurements
- Wireline Logging
- Coil Tubing
- Well Cementing
- Well Stimulation & Fracturing
- Well Testing
- Well Completions

1.2. Workforce

Currently, Schlumberger has over 100,000 employees from 140 different countries. This workforce operates in 80 different Geo-Markets. Each member of this workforce is assigned a job-specific intensive training and development program. This program involves various types of training material and hands-on tasks. At the end of each training phase, an employee receives an assessment from direct management where he/she gets promoted to higher employment grade. (Background, 2016)

1.3. Facilities & Assets

Type of facilities and amount of assets depends on the type of service Schlumberger is providing in a specific Geo-Market. In Qatar, the available facilities are:

- Main Office, located in West Bay area.

- Workshops, located in Industrial Area
    - Drilling & Measurements Workshop
    - Well Services Workshop
    - Wireline Workshop
    - Testing Workshop
    - Completion Workshop
- Dry chemicals storage yard in Zekreet
- Liquid chemicals storage yard in Ras-Laffan Industrial City

Each segment has its own support utilities or facilities. For instance, Well Services has a laboratory for preparation and testing of cement slurries and stimulation fluids.

1.4. Financial Records

Table 1 details some of the financial data of Schlumberger over the past 5 years.

Table 1:Financial Data in Millions USD

	2014	2013	2012	2011	2010
Revenue	$48,580	$45,266	$41,731	$36,579	$26,280
Working Capital	$10,518	$12,700	$11,788	$10,001	$7,233
Total Assets	$66,904	$67,100	$61,547	$55,201	$51,767

Schlumberger had accumulated revenue of 48.58 billion dollars in the year of 2014 itself. This is a significant growth compared to 26.28 billion dollars in 2010. Global assets had also grown from 51.76 billion dollars to 66.90 billion dollars between 2010 and 2014, which is about 29.25% growth in their total assets. Also, new technology sales contributed to about 27% of the total revenue of the year 2014. That is a direct consequence of strong focus on R&D (Limited, 2014)

1.5. Health, Safety and Environmental Performance

On HSE side, Schlumberger have always shown a continues commitment to Health, Safety and Environment. There are several standards and policies incorporated in company's structure that ensures that all daily activities are safe to personnel and to the environment. (HSE Policy Statement, 2016). There are 21 HSE standards established by Schlumberger, which are:

- Journey Management & Driving

- Event Reporting & Management
- Personal Protective Equipment
- Business Continuity, Emergency & Crisis Management
- Training & Competency
- Auditing
- Environmental Standard
- Loss Prevention Teams
- Management of Change & Exemption
- Employee and Asset Security
- Contracting
- Mechanical Lifting
- Pressure Standard
- H_2S Standard
- Fire Prevention & Mitigation
- Injury Prevention
- Radiation
- Explosives
- Hazard Analysis & Risk Control (HARC)
- Customer Data Standard
- Dropped Objects

Journey management received a lot of attention in 2014, which resulted in a total of 16% reduction in driving related accidents, where Schlumberger faces the majority if its accidents. All work related trips are recorded and monitored through journey management system, that has specific rules to be applied for each trip, including speed limits, weather conditions and trip time.

All hazardous situations, near accidents and accidents are reported in QUEST, that is Schlumberger reporting portal. Each report is categorized depending on severity and frequency of the event. Depending on each category, event notification is escalated to higher levels of management, including CEO Pal Kibsgard. Figure 1 below illustrates the severity matrix.

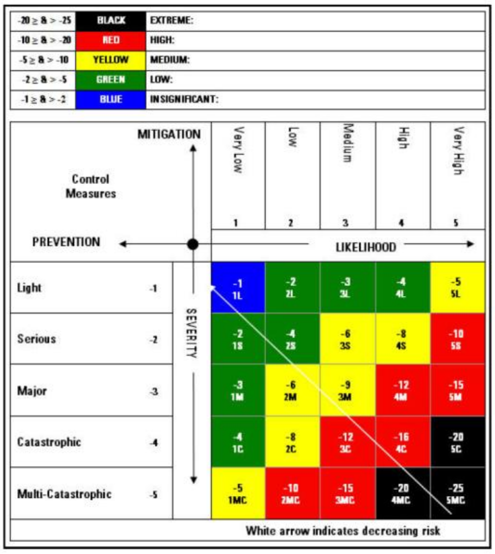

Figure 1: Severity Matrix

One important aspect related to this project from an HSE prospective, Schlumberger developed a fatigue management technique that defines the common signs of body fatigue and also estimates the time intervals where the human body is usually is not on full alert. The fatigue management technique is part of Schlumberger Injury Prevention Program. The main objective of this program is reduce the likelihood of risks associated with the daily operations. Fatigue management system also limits the maximum hours of duty to 16 hours as a worst case scenario, of which after that higher management approval is required.

1.6. Well Cementing

Well cementing is the introduction of cementitious material in the annulus between the drilled hole and the casing. This process is performed by mixing liquid cement slurry and pumping it downhole using high pressure positive displacement pumps. This operation requires a crew of personnel with different skills and qualifications. A typical crew consists of a supervisor, equipment operator, batch-mixer operator and a service helper. All service crews remain on standby until a request for service is received.

1.7. Personnel Assignment Issues

Current personnel assignment policy is inefficient in terms of resource overloading. Typically, personnel are set to work for long hours exceeding the maximum shift duration in the fatigue management policy. This is mainly due to the nature of the operations itself and the inadequate personnel planning practice.

1.8. Project Objectives and Methodology

The main objective of this project is to propose an alternative personnel assignment policy aiming to:

- Achieve more balanced utilization of workers over the planning horizon.
- Cover additional tasks that should be accounted for during utilization estimation.
- Limits the rig waiting time for a crew member to a maximum of 24 hours.

Beyond the 24 hours waiting period, the operating company Qatar Petroleum starts charging operations delay charges. These charges are placed to compensate for the time spent waiting for cementing service crew, while other resources on site are idle and cannot proceed with other operations because casing cementing is not yet complete.

The project will first address the current assignment issue in details, followed by collection of operational data over the span of 1 year. The collected data will be used to develop another assignment policy that fulfills the project objectives. Proposed policy model will be validated against the actual data and the simulation model of the current assignment policy. Finally, a comparison between the current and the proposed policy is demonstrated.

1.9. Report Organization

Chapter 1 is an introductory chapter, briefing historical, workforce, facilities and assets, HSE and well cementing information. It also contains a brief description about the current assignment issues and project methodology, where both will be explained in details in another chapters.

Chapter 2 details well cementing operations from technical prospective. Chapter 3 explains the current issues in personnel assignment along with the potential impacts associated with it. Chapter 4 explains the project methodology in details. Chapter 5 demonstrates the reviewed literature relevant to this project. Chapter 6 presents the operational data collected from the year 2014. Chapter 7 illustrates how the current assignment policy is modeled in AnyLogic simulation software and what are the assumptions and parameters associated with the code. Chapter 8 details the proposed personnel assignment policy. Similarly, it also details how the code is constructed in AnyLogic and the associated assumptions and parameters. Chapter 9 presents simulation results and results analysis. Chapter 10 is the report conclusion and recommendations.

2. WELL CEMENTING SERVICES

Cementing services is one of the critical operations in the life cycle of any well. Operating companies consider cementing jobs one of the services that requires zero failure probability. That is due to the major consequences that follow an inappropriate cement job. These consequences could reach up to millions of dollars in cost.

Well cementing is divided into Primary & Remedial cementing. Each of them has its own different objectives. In order to understand the basic cementing process, it's necessary to visualize the well bore schematic first.

2.1. Well Schematic

The below figure illustrate the basic schematic of an oil well.

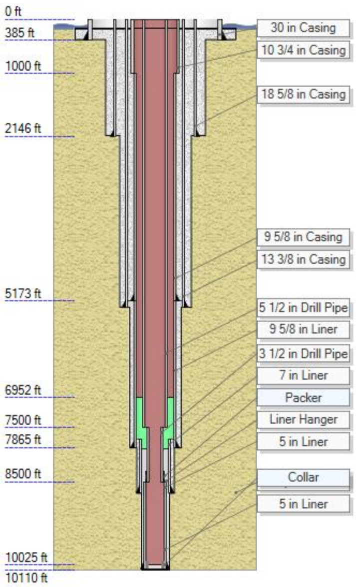

Figure 2: Well Bore Schematic

Any oil or gas well is composed of a set of tubes or pipes. These pipes range in size from 42" up to 4 ½ "diameter. Size or diameter of each drilled section depends on how packed the formation at that zone. In other words, the stronger the formation at the target zone, the harder to drill with larger size drill bit due to the increased resistance. Another factor controlling the casing size and type is the expected hydrostatic pressure inside the well and corrosivity of well fluids.

2.2. Primary Cementing

Primary cementing is defined as the introduction of cementitious material into the annulus between a casing and a drilled hole, a previous casing or both of them. The main objectives of primary cementing are:

- Provide isolation between different zones.
- Protect the casing or pipe against corrosion.
- Support axial load of the casing itself and following strings as well.
- Prevent wellbore from caving in.

As explained earlier, poor cement job which leads to poor zonal isolation could lead to extremely dangerous consequences. A good example of well failure due to poor zonal isolation is the Macondo disaster in the Gulf of Mexico. 11 people were lost in this incident and another 17 were injured. Approximately 5 million US barrels of oil were spilled into the Gulf of Mexico. (CSB, 2014)

Figure 3: Macondo Disaster

2.3. Conductor Section

This section is the first section in the drilling phase. After the drilling rig is positioned as per the drilling program, drilling starts up to a 700 ft deep. After that the conductor casing is positioned into the hole and cemented. The basic objective of this section is to provide the necessary support for the drilling rig for the upcoming drilling operations of the following sections. It also prevents the drilled hole from collapsing under the rig, as the shallow formations are usually unconsolidated at this depth.

2.4. Surface Section

Following the conductor section, surface section is drilling between 100 ft – 3000 ft. Casing size in this section ranges between 13-3/8” and 16” in diameter. The purpose of a primary cement job in this section is to protect surface water formations from contamination by drilling fluids or by hydro-carbons in a later stage. It also provides competent mechanical support for subsequent operations (Blow Out Preventer, Following Casings, etc…)

2.5. Intermediate Section

A section between the surface section and the target production section. Mainly, the objective at this section is to seal off any non-productive high pressure zones above the zone of interest. This zone usually requires more than one cement slurry system to cement the casing. Casing size typically ranges between 13-3/8” to 9-5/8”.

2.6. Production Section

Also called the pay zone, this section is the ultimate target of the entire drilling operation. Specific operations are performed on this zone, depending on the purpose of drilling the well. Scientists use core samples from the zone to analyze the formation contents and estimate the feasibility of investing in this particular field. That is in the case of drilling an appraisal well. In case of a production well, field assessment was performed earlier and the operating company is ready to produce from this well.

A production casing is place at this zone after drilling the section. Casing is cemented in place to provide necessary support and corrosion resistance. Some operators place a production liner instead of a production casing at this section in order to save on cost, since the casing is considered the most expensive part of a well. The only difference is between liners and casings is it does not extend all the way to surface. A typical size of production casing or liner ranges between 9-5/8” to 4-1/2”

After the casing or liner is cemented in place, a production tube is also placed all the way from surface down into the production casing. The annulus between the production casing / liner and the production tube is sealed off at the bottom using a production packer. The packer prevents hydro-carbons from flowing anywhere except inside the production tube, where it’s delivered to the surface. Commonly, the production tube is 3-1/2” diameter.

2.7. Cementing Equipment

A set of equipment is used in each cement job on the field. Each equipment is operated by one or two skilled operators. The set of equipment depends on the type of each job. In general, any cement job requires one cement pump unit and one cement bulk delivery truck.

2.7.1. Cement Pump Unit

Pump units are composed of two positive displacement pumps. Each pump has a different pressure rating and they're connected to two independent diesel engines. Each PD pump is associated with a centrifugal pump to assist the flow of cement slurry and other fluids to the suction manifold of the PD pump. Both PD pumps are connected to a high pressure (15,000 PSI) discharge manifold, where the flow can be directed down to the well bore.

Each unit is equipped with a slurry mixing and density control systems. Density controller maintains the dry cement to mix fluid (Chemicals & Water) ratio. In some sophisticated models, a pump unit can be operated remotely. The basic specifications of a pump unit are:

- Two caterpillar diesel engines, 325 BHP each
- Two FMC HP piston pumps, 5,500 and 10,000 PSI rated
- Total of 500 HHP (Hydraulic Horsepower)

Figure 4: Cement Pump Truck

Figure 5: Cement Pump Skid

2.7.2. Slurry Mixing System

Commonly, a slurry mixing system is attached to each pump unit. A slurry mixing system allows mixing of cement slurry on the fly in situation where large volume of slurry is required. A mixing system consists of an 8 US barrels capacity mixing tub, 16 US barrels capacity averaging tub, a chief mixer and a surge (buffer) can.

Mixing fluid is pushed through a centrifugal pump into the chief mixer where dry cement is added and mixed in the mixing tub. An NRD (None-Radio Active Densitometer) is attached to the mixing tub, which is part of the density control system.

Figure 6: Slurry Mixing System

2.7.3. Batch Blender

Batch blenders are used to pre-mix cement slurries before pumping starts. This is limited to slurry volume up 200 US barrels only. Operators prefer this method of preparing cement slurries because it ensure that the entire slurry density is homogenous prior to pumping it downhole. Dry cement is added to the pre-mixed water and chemicals until the required density is reached. Centrifugal pumps are used to circulate slurry from the bottom of each tank back to the top. This is to ensure the slurry remains dynamic until pumping.

Figure 7: Batch Blender

2.7.4. Cement Head

Cement Heads are extremely important in any cementing operation. They’re used as a barrier between the pump unit and the wellbore and to lunch mechanical separation plugs. Mechanical plugs (Commonly made from drillable aluminum and rubber) are used to separate fluids pumped inside the casing from each other. A Cement head is installed on top end of the casing through a cross-over and then connected to the pumping unit through a high pressure pipe line.

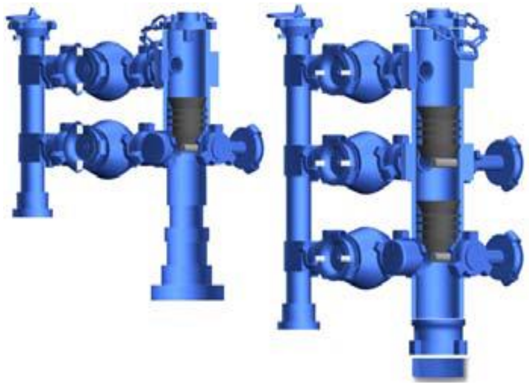

Figure 8: Single and Double Plug Cement Head

2.8. Single Stage Cementing Operation

2.8.1. Preparation

A client communicates with the dedicated technical engineer in headquarters to request for a cement job as per the existing contract. The technical engineer receives the request along with all the necessary information required to design an appropriate slurry system.

After designing a slurry system as per the provided data, technical engineer generates a complete cement job program that includes the slurry properties, type and quantities of chemicals to be added, laboratory test reports and detailed job procedures.

Client reviews the program and approves it or requests further clarifications or modifications. Approved finalized program is then communicated to the client's representative on site and the cementing service supervisor.

Service supervisor starts preparing the required equipment and material to perform the operations. Each piece of equipment undergoes a detailed pre-job inspection. This procedure is called STEM inspection. All materials and equipment required for the job is transferred to the well site approximately 12-24 hours before the actual treatment.

2.8.2. High Pressure Line Rig-Up

Commonly, land rig operations require high pressure lines to be connected and disconnected before and after each job. On average, each rig up take between 3 to 5 hours and it does not require any special skills. Required personnel are 3 or more.

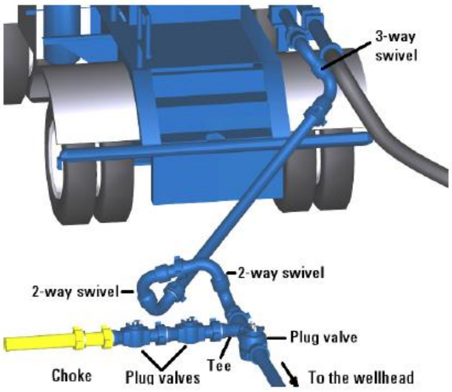

Figure 9: HP Rig Up from Pump Unit

Figure 10: HP Rig Up to Wellhead

Figure 11: Cement Head Rig Up to Casing

2.8.3. Job Procedures

Procedures of primary cement jobs are mostly similar for each section. Main differences are usually the pumping rates, slurry density and slurry volumes. As a result of these variables, pumping pressure differs from each job.

Step One: Pumping Chemical Wash / Spacer

First fluid pumped is always a chemical wash or a higher density spacer or both. A chemical wash is used to thin up the existing drilling fluid inside the well bore. Cement slurry cannot be contaminated with drilling fluid under any circumstances. Any contamination with drilling fluid will induce a loss in the mechanical properties of the cement to a point that it will not set and will remain in a gelled phase.

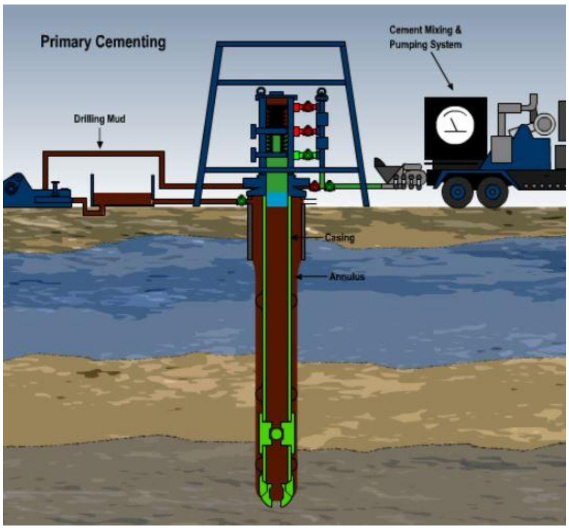

Figure 12: Pumping Wash / Spacer

A chemical wash is followed by a higher density spacer that is used to displace the thinned up drilling fluid out of the wellbore. Spacer also acts as a buffer between the drilling fluid and the following cement slurry. This is an additional precaution to prevent slurry contamination.

Step Two: Dropping Bottom Plug

A bottom mechanical wiper plug is released after the wash or spacer to act as an additional barrier between drilling fluid / spacer and cement slurry. Plugs are made of drillable material (Aluminum) and wiper rubber. Plugs are pre-loaded in the cement head before starting the operation.

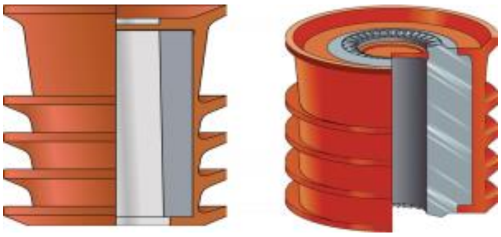

Figure 13: Bottom Wiper Plug

Step Three: Pumping Lead Slurry

A lead cement slurry is pumped after dropping the bottom plug. A lead slurry is always heavier than the spacer and lighter than the following tail slurry. A job is designed in such a way to avoid fingering phenomenon of the fluids.

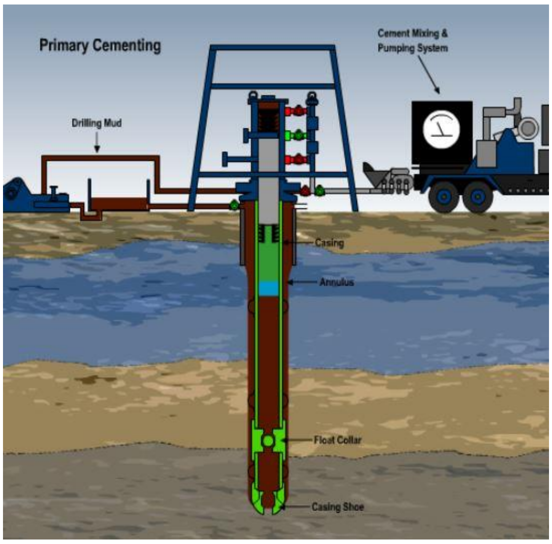

Figure 14: Pumping Lead Slurry

Step Four: Pumping Tail Slurry

A tail slurry is pumped behind the lead slurry without any sort of separation between the two fluids. Contamination between the two slurries is not considerable.

Step Five: Dropping Top Plug and Displacement

After pumping all the cement slurries down hole, the top plug is dropped and the displacement process starts. Another fluid is pumped after that, usually a drilling mud, to displace the cement slurry from inside the casing to the annulus between the casing and the open hole. This is the final position of the slurry where it will be allowed to set and gain compressive strength. Cement is given a certain time to set and solidify that ranges between 10 to 24 hours.

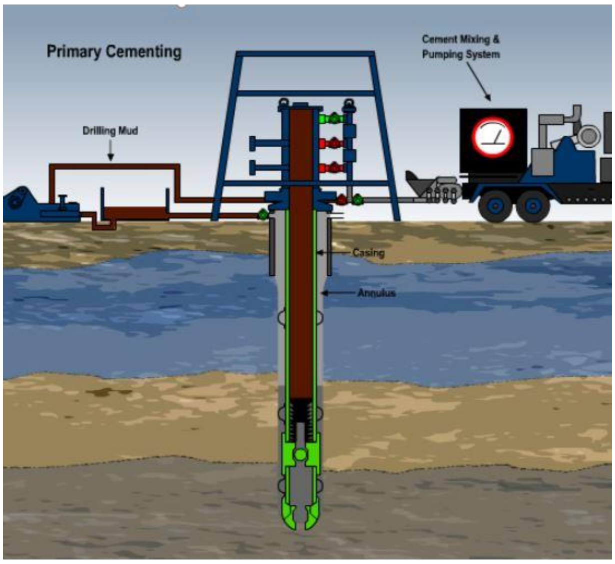

Figure 15: Displacement

3. PROBLEM DESCRIPTION

In each phase of oil field development, well construction services play an essential rule. A case study from the land field of Dukhan is considered in this report. The field of Dukhan is operated by one of the lead operators in Qatar, where it placed 6 drilling rigs on location. Each drilling rig is operating independently from the others. Each rig is positioned based on exploration and seismic surveys data. The rig moves to another location after constructing a complete well and starts over again.

Cementing services provider Schlumberger assigned 3 complete crews for the cementing operations of those 6 rigs during the duration of the existing contract. Each crew consists of:

- Cementing Supervisor
- Equipment Operator
- Batch Blender Operator
- Helper
- Cement Pump Unit
- Batch Blender
- Bulk Truck

Each crew receives a call for a job after the drilling phase is complete. A call for a job is assigned to a crew based on its turn to service. That is, the crew who finished first gets the new service request. An assigned crew stays on duty until completion of the job, regardless of job duration. Usually the job duration ranges between 8 and 40 hours depending on the status down the hole.

3.1. Process Flow Diagram

Process flow diagram in figure 16 is based in the actual contract signed between the field operating company and the well construction contractor.

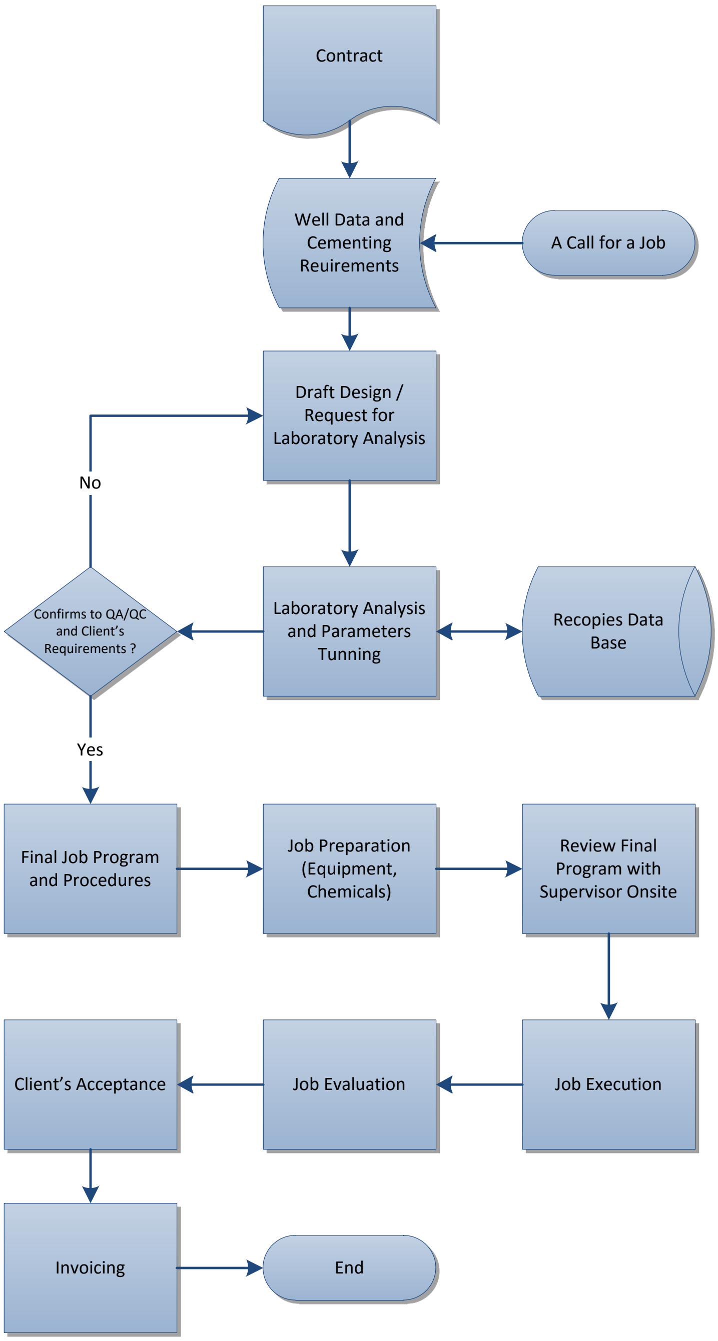

Figure 16:Cementing Process Flow

A contract is established between field operator and well construction contractor. Typically, basic rates are defined for basic materials and standard operations. A contractor would receive a call from the client requesting for a cement job with some given well parameters such as depth, temperature, formation information, …etc.

A contractor as an expert drafts an initial job program with some specific parameters for the cement slurry to be used that would satisfy the requirement of the client. An analysis request is then forwarded to the laboratory to confirm the validity of the design. Laboratory personnel will perform a series of conformance tests and forward the final slurry recipe back to the job designer. The engineer or the designer will prepare a final job program and review it with the client for a final go ahead to start the job.

From that point, the field personnel will start preparing the necessary equipment and material for the job. Prepared equipment and material would then be transported to well site. Well site preparation usually starts 24 hours before execution. A set of equipment is lined up and tested prior to the job.

Once well site preparation is complete, cementing supervisor conducts a job review with the engineer and service manager to ensure his awareness of all job aspects along with any HSE concerns.

The final go ahead call is given by client's representative on site. Once received, contractor's personnel will execute the job and remove all equipment from well site back to the stand by area. Job is evaluated between the client and the contractor and invoices are issued upon client's acceptance.

The process flow is the same for primary and remedial cementing

3.2. Current Problems in Workforce Assignment

In any service project with high uncertainty, resource utilization and resource leveling are known to be a common problem. The main issue is the over-utilization of human resources due to the uncertainty of operations and the continuous demand to reduce overall operational costs. Many service providers do not pay enough attention to this issue, although it could be solved or improved with simple resource management systems.

The current assignment policy is based on queuieing the service crews to wait for a service request. The crew that finished a service goes to the end of the queue and first crew in the queue takes the next service request and so on. This policy neglects the variation in treatment or service duration. In other words, a crew will be working continuously until the service is complete and then returns back from the worksite. Treatment duration could last up to 40 hours in some cases depending on the well conditions and performance of the drilling rig.

In general, the current policy violates the internal policy of Schlumberger that limits the total shift duration of any service crew member to 16 hours as a worst case scenario. On the other hand, the implemented utilization monitoring system at Schlumberger takes in account only the service time as productive time. Other operations like equipment maintenance for example is not taken into account as productive time, which is, in our opinion, gives an inaccurate personnel utilization figures.

In general, over-utilization of human resources in oil & gas field services has several negative impacts including:

- Reduced resource efficiency.
- Reduced quality of service provided to a client.
- Service provider may encounter additional costs due to human errors during service execution, which in many cases result in a complete loss of profit.

- Risk of reduced service provider reputation.
- Loyalty of employees may become questionable, which might lead to additional costs for the service provider in case of hiring new workforce.

4. PROJECT METHODOLOGY

Methodology of this project is based on analyzing the previous operational records that contain service execution dates and operation durations. From this data, the average positive deviation is calculated. As a following step, a new assignment policy is proposed to improve current deficiencies in the present planning policy.

4.1. Estimating the positive deviation from maximum duty hours under current policy

The first step in this project is to estimate the current utilization of workers and the average positive deviation from the maximum pre-set shift duration. The maximum number of hours is set to 16 hours which is the worst case scenario set by the fatigue management policy. This step requires collection of previous operational data from the year of 2014. This data will be also used to create a simulation model based on the current assignment policy for validation purposes.

4.2. Proposing an alternative assignment policy

As a second step, a new assignment policy is proposed. The new policy aims to reduce the positive deviation from the maximum working hours for each worker. This alternative policy is based to utilizing the idle resources when the maximum allowed working hours for an active resource is reached. An idle resource will move immediately to replace an active resource on worksite. For simplicity, travel time for the replacement worker is neglected at this point and shall be considered for further improvement to the new policy.

Equipment is considered to be available during service execution all the time. No replacement equipment to be provided.

4.3. Comparing proposed assignment policy with the existing policy

As a final step, both the current and proposed policies are modeled and simulated through AnyLogic software. The performance matrices evaluated in order to prove the enhancement provided by the new policy are:

- Average worker utilization
- Average positive deviation from the maximum allowed duty hours for a worker
- Maximum allowed waiting time a drilling rig spends waiting for a crew member to start an operation

The input parameters for the simulation are based on the data collected from operations of year 2014. These parameters are

- The number of sections drilled in each well
- The probability distribution for the duration taken by the drilling rig to finish drilling a section
- The probability distribution for the duration taken by a cementing crew to complete a service job
- The average number of days a drilling rig takes to mobilize from one location to another

The same parameters estimated from previous operational data will be used to simulate the proposed and the current assignment policies.

5. LITERATURE REVIEW

Work force assignment in different demand environments has been widely studied in the literature, but the studies in stochastic demand environment are limited. The main purpose of the literature review is to understand how such problems are approached and what are the preliminary steps taken to achieve a feasible solution.

Mieke Defraeye and Inneke Van Nieuwenhuyse (Inneke Van Nieuwehuyse, 2016) provided a fine literature review on staffing and assignment methods for non-stationary demand patterns, particularly service environments. They've divided the staff capacity planning into four different steps:

1. Forecasting the demand or generating demand patterns
2. Estimating the staffing requirements
3. Shift scheduling
4. Rostering: Assigning employees to shifts

They've classified the relevant literature into different categories. These categories were based for example on the number of articles written in a specific time interval, system assumptions, …etc.

One interesting classification was based on the performance matrices addressed by a certain article. Large portion of the literature used discrete event simulation method to evaluate performance matrices including resource utilization as a function of time, server idle time over a time horizon, number of hours where workload exceeds a certain percentage and the maximum allowed waiting time.

A.T. Ernst, H. Jiang, M. Kirshnamoorthy and D. Sier discussed staff assignment and rostering different applications and models. (Ernst, Jiang, Krishnamoorthy, & Sier, 2004)

They have stated that optimized personnel schedules can provide a large number of benefits, but requires a careful implementation of decision support systems.

The first step of the assignment process is to determine the number of staff required to meet the demand requirements. This step is also constrained by the local regulations, actual human capabilities and cost objectives.

Authors suggested a rostering problem classification divided into 6 different modules:

1. Demand Modeling

As described earlier, the first module of the rostering process is to determine the number if staff required over certain planning horizon. Authors defined the demand modeling process as translating a predicted pattern of incidents into specific duties and then build staff requirements. They've also classified these incidents into three different categories:

- Task Based Demand: Demand is obtained from lists of individual tasks to be executed. These tasks are usually defined in terms of starting time and duration for each.
- Flexible Demand: In this case, the demand requirements are not firmly known and requires some forecasting techniques. This appears in service environments where the service requests starting times and durations are not completely known but can be predicted.
- Shift Based Demand: Demand is obtained directly from the specifications of the number of staff directly required to be on duty on a particular shift.

2. Days Off Scheduling

This module aims to determine how rest days are distributed between work days for different lines of work. This problem is commonly arising during the rostering process of flexible of shift based demand

3. Shift Scheduling

This module deals with the problem of selecting from a pool of resources the number of personnel required for each shift along with which shift to be worked in order to meet the existing demand.

4. Line of Work Construction

In this module, lines of work or work schedules for each staff member is created. This process depends on the basic construction blocks, which could be shifts, duties or stints. This module is also called tour scheduling when we are dealing with flexible demand.

5. Task Assignment

It might be necessary to assign one or several tasks in one shift that require specific skills. This module deals with this process.

6. Staff Assignment

This final module deals with the assignment of individuals to specific lines of work. This is usually done during the construction of work lines.

Peter Brucker, Rong Qu and Edmund Burke have proposed a mathematical model for personnel scheduling and planning (Brucker, Qu, & Burke, 2011). They've suggested that a general personnel scheduling problem can be formulated as:

$$Min \sum_{e \in E} \sum_{\pi \in P_e} C_{e\pi} X_{e\pi}$$

Where:

E: The set of available employees

e: An employee belongs to E

P_e: The set of feasible working patterns π: A working pattern represented by a binary vector

$C_{e\pi}$: The cost of assigning the working pattern π to an employee e

$X_{e\pi}$: A binary variable equal to 1 if and only if a working patter π is assigned to employee e

The above formulation is subject to the following constraints:

$$\sum_{\pi \epsilon P_e} X_{e\pi} \leq 1, \qquad e \in E$$

and

$$\sum_{e \in E} \sum_{\pi \in P_e} \pi(j,t) X_{e\pi} \geq D_j \;\; for\ all\ (j,t)$$

The objective of this formulation is to ensure that demand Dj(t) if all tasks j is covered over the planning horizon and the cost of assignment of employees is minimized. The first constraint guarantees that only 1 employee is assigned for 1 working pattern. The second constraint sets the number of employees assigned to a task j equal to the demand j at a particular period of time.

The paper presents the nurse rostering problem as a special case of the mathematical model, where the planning horizon consists of all days within a five weeks planning horizon.

Hongbo Li and Erik Demeulemseester (Li & Demeulemeester, 2015) addressed the problem of resource usage fluctuations over the time frame of a specific project, or also called an RLP. They described this problem as a project represented by activity on node representation. Each non-dummy activity duration is stochastic and denoted by the random variable d_i. They assumed di follows a known demand distribution. Furthermore, each activity i requires r_{ik} renewable resources of resource type k during time period t.

Li and Demeulemeseeter developed a genetic algorithm to solve this problem, with an objective of minimizing the expected positive deviation of both resource utilization and activity starting times.

Vile, Gillard, Harper and Knight addressed the problem of managing and scheduling emergency medical services in Welsh Ambulance Service Trust (WAST) (Vile, Gillard, Harper, & Knight, 2016). Their paper addressed the main capacity planning by developing a decision support tool that takes into account forecast, priorities and scheduling methods.

WAST uses response times as one of their KPIs. They've divided their demand into three different categories based on medical urgency:

- Category A: Immediately life-threatening condition
- Category B: Serious but not life-threatening condition
- Category C: Neither life-threatening nor serious condition

After forecasting the demand, the next step is to convert these demand figures into minimum staffing requirements by utilizing the queuing theory. Authers developed an ILP with an objective of minimizing the number of crews assigned to each shift, in such a way that guaranties a minimum number of employees is present all the time.

From a deterministic prospective, Iyer, Liu, Sadeghpour and Bernnan developed a fuzzy-logic resource leveling optimization tool (Iyer, Liu, Sadeghpour, & Bernnan, 2015). The developed tool does not examine the day to day activities, rather, it looks at the project as a whole and selects the days of activities that requires resource leveling. Their argument is by using this type of method, the tool implicitly yield an optimum solution all the time. Their tool was developed in MATLAB.

As a conclusion, several methods can be used to approach the personnel assignment problem. The selection of the correct method and performance matrices depend mainly on the nature of the demand. Commonly, the first step is estimating or forecasting the demand, which relies on studying the previous observation of the current system. Also, the literature provides a variety of performance matrices that can be used the evaluate a proposed solution to a given problem. As mentioned earlier, the performance matrices of interest in this project are positive deviation exceeding maximum working hours and personnel utilization over planning horizon.

6. DATA COLLECTION AND ANALYSIS

Data has been collected for primary cementing operations over the year of 2014 for the 6 drilling rigs operating in Dukhan field. Personal experience also had an input on the data organization specifically on the sequence of events. This combination allowed for determination of exact drilling duration of each section for each well serviced in the activity sheet.

The collected data has been organized and sorted in a descending order based on the date of execution. It has been also categorized based on the drilled and serviced sections. Section drilling duration and service or treatment duration has been analyzed using EasyFit software to find the most suitable probability distribution fit, that is used later on in the simulation models.

Drilling operations require mainly primary cementing services, basically casings and liners cementing. However, remedial cementing jobs may also be required in some cases.

The collected data consist of the type of operation, duration of each job and the well number. Based on the sequence of operations and well numbers, days required to drill a section has been estimated as well. 95% of the observed cementing operations were primary cementing, where only 5% were remedial. In order to simplify the problem, only primary cementing services is considered.

6.1. Primary Cementing

In the field of Dukhan, primary cementing operations were performed for the main sections, 13-3/8” casing, 9-5/8” casing and 7” casing. These were conducted in rigs number 1,2 and 4. The operations order follows the casing size. That is, 9-5/8” casing cannot be cemented before 13-3/8” casing. Once 7” casing cementing is complete, it takes the rig a certain amount of time to run production tubing, install the wellhead and move to another drilling location. This period is accounted for.

Collected data has been organized and examined to determine which probability distribution is the best fit for each set of data. EasyFit software has been used to complete this step. EasyFit provides a large number of continuous probability distributions fitness along with a ranking that demonstrates the fitness of each distribution based on the three different fitness tests.

6.2. Section Drilling Duration Probability Fit

6.2.1. Surface Section

Surface section data has been found to best fit a Pert distribution with a minimum value of X =3.4467 days, a maximum value of X=31.584 days and most likely value of X=13.358 days.

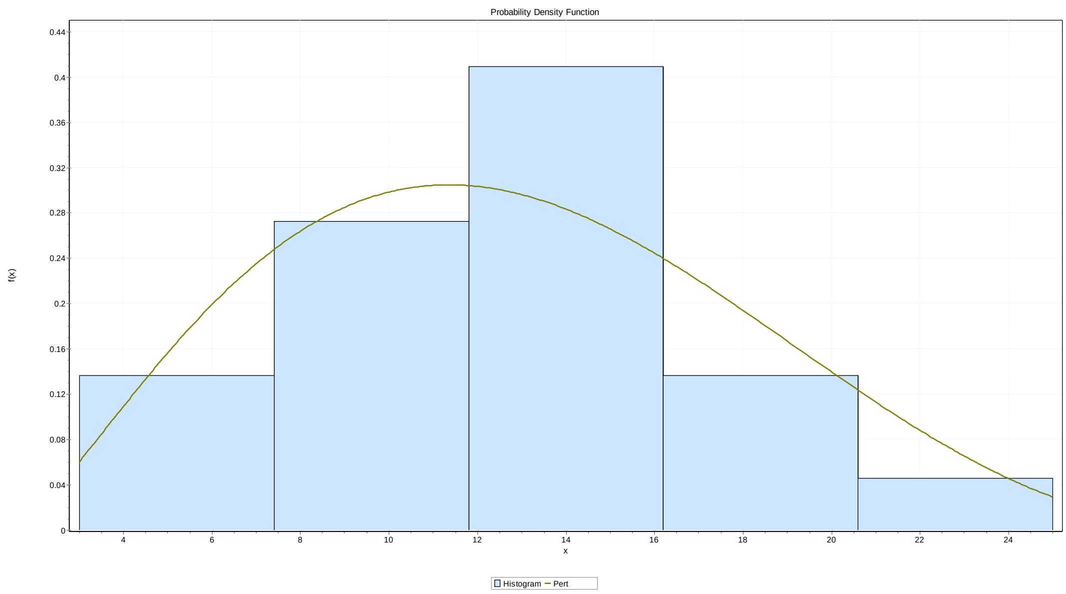

Figure 17: Surface Section Drilling Duration

6.2.2. Intermediate Section

The best fit distribution for intermediate section drilling found to be also a Pert distribution with a minimum value of X= 5.743 days, a maximum value of X=19.422 days and a most likely value of X=8.298 days.

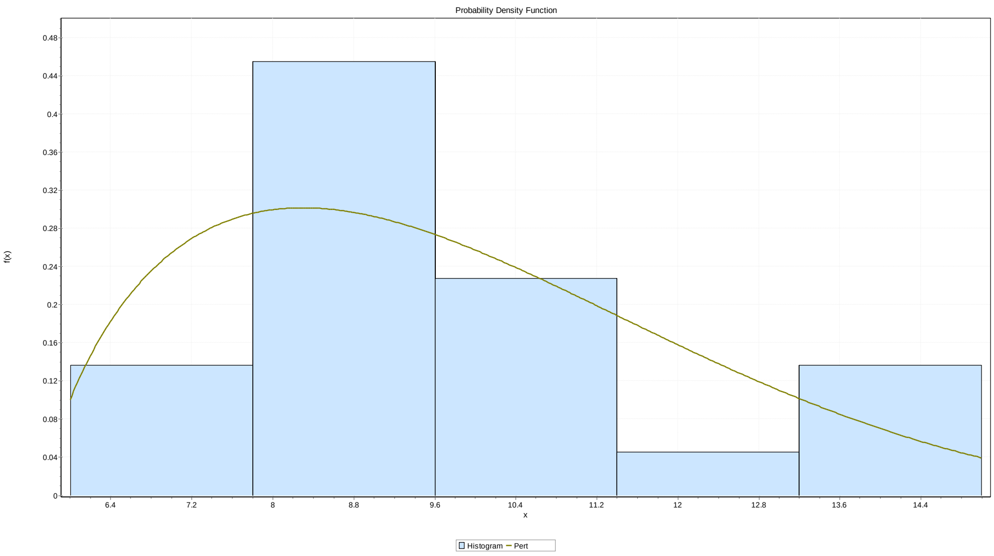

Figure 18: Intermediate Section Drilling Duration

6.2.3. Production Section

This section also fits a Pert distribution with a minimum value of X=5.9179 days, a maximum value of X=35.235 days and most likely value of X=7.3946 days.

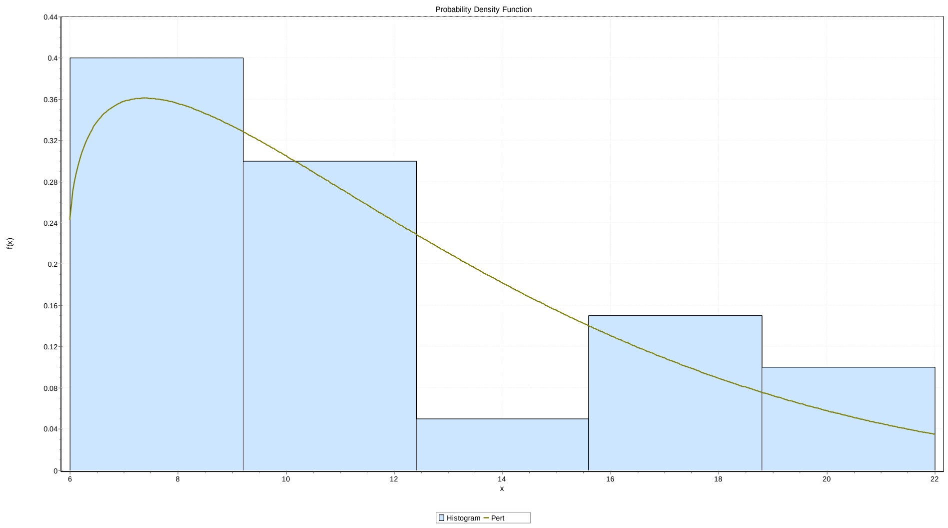

Figure 19: Production Section Drilling Duration

Selection of a best fit probability distribution is based on the goodness of fit as per Kolomogorov, Anderson and Chi-Squared fitness tests. However, selection is bounded by the available probability distribution functions in AnyLogic Simulation Software.

6.3. Section Treatment Duration Probability Fit

6.3.1. Surface Section

Similar to the drilling duration, the surface section found to follow a Pert distribution, with a minimum value of X=8 hours, maximum value of X=70.18 hours and a most likely value of X= 8 hours.

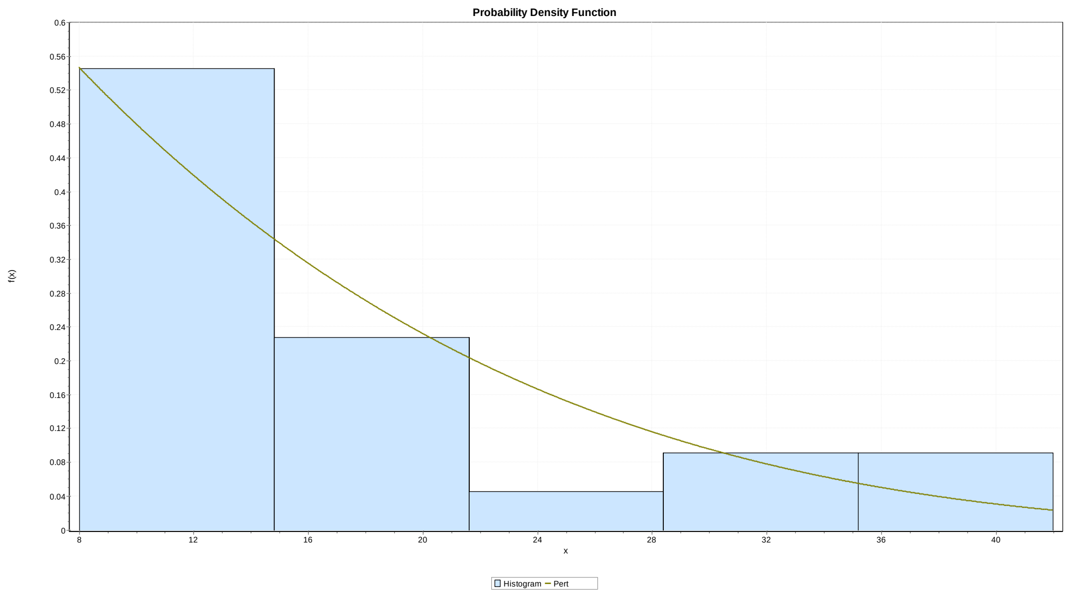

Figure 20: Surface Section Treatment Duration

6.3.2. Intermediate Section

Intermediate section also follows a Pert distribution with a minimum value of X=11 hours, maximum value of X=95.525 hours and a most likely value of X=11 hours.

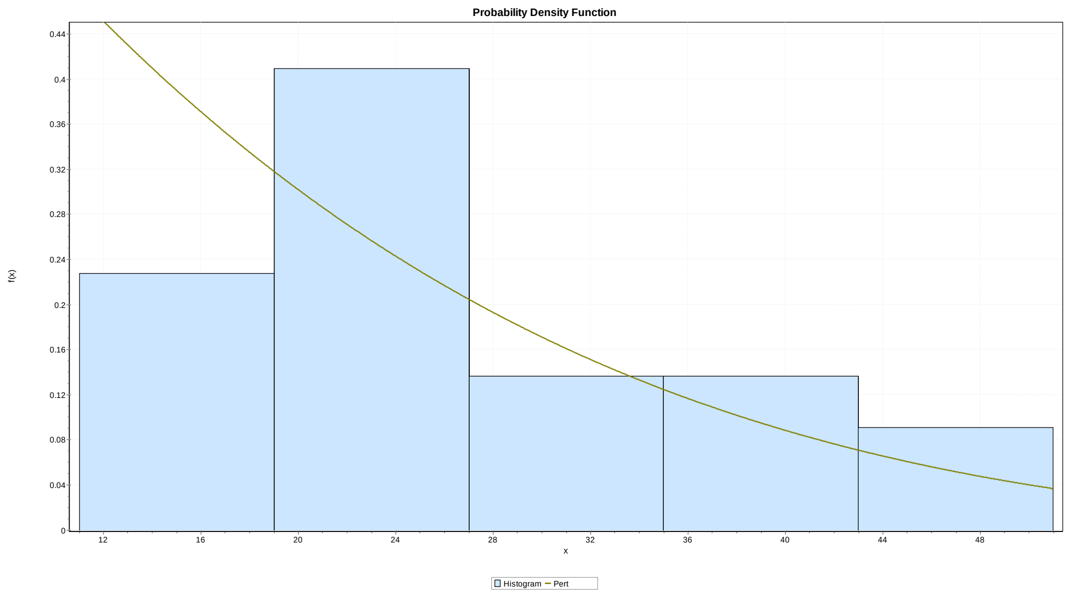

Figure 21: Intermediate Section Treatment Duration

6.3.3. Production Section

This section also follows the same Pert distribution, with a minimum value of X=12 hours, a maximum value of X=103.57 hours and a most likely value of X = 12 hours. The advantage of choosing Pert distribution in AnyLogic is the ability to define boundary limits.

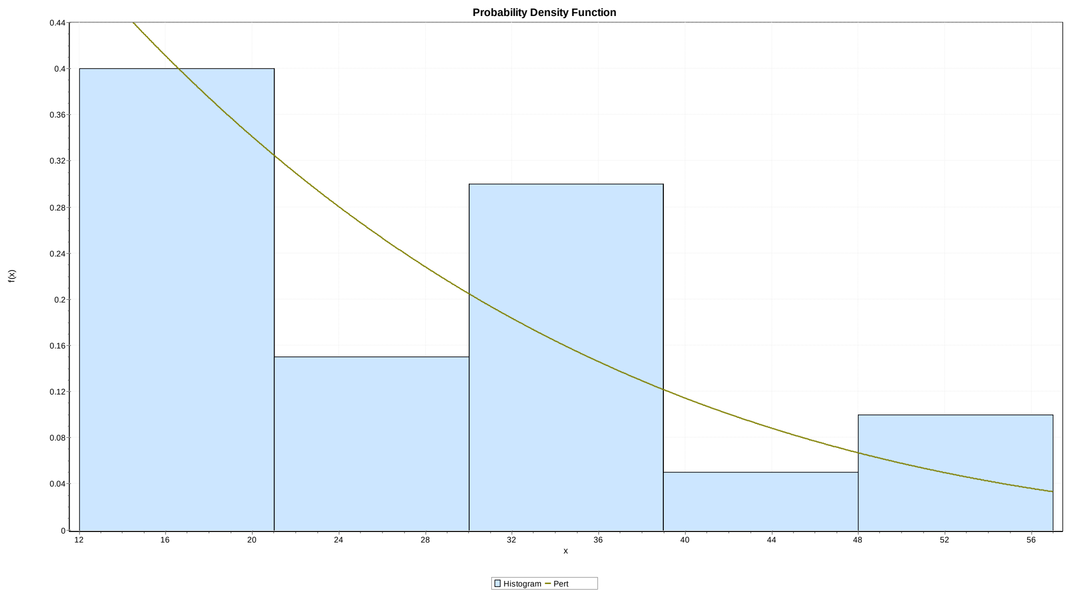

Figure 22: Production Section Treatment Duration

7. Current Assignment Policy

The current assignment policy is based on having 3 service crews serving 6 drilling rigs. The selection of a crew to perform a service depends on which crew completed a previous service first. That is the crew who is idle the most compared to all crews. The current practice does not into account maximum duty hours. A crew will remain active during operation regardless of how long it takes. For validation and analysis purposes, current policy simulation results are compared to the actual collected operational data.

7.1. Model Structure

The current policy is modeled based on the below process flow chart in figure 23.

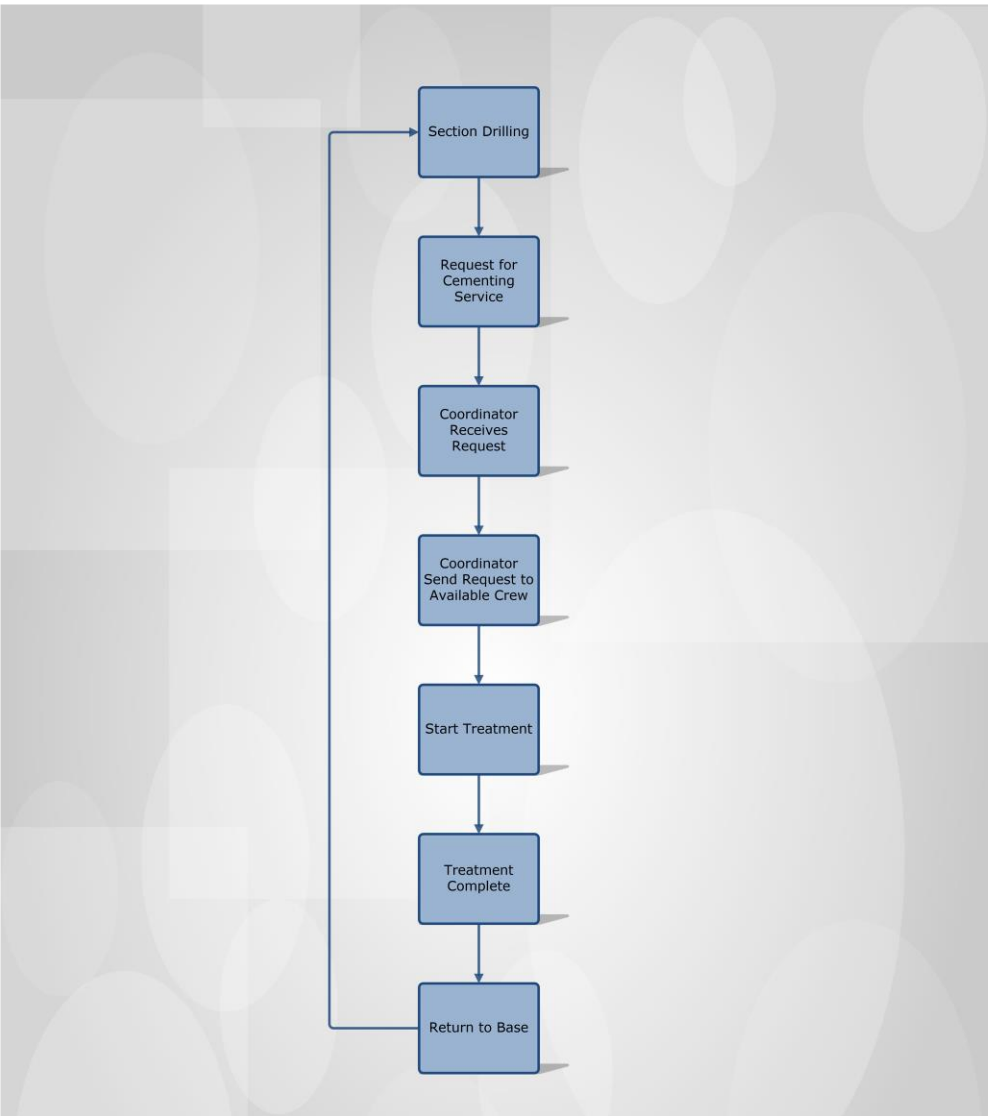

Figure 23: Current Policy Flow Chart

As can be seen, the process flow is quite simple and straight forward. A service request is received from the drilling rig by the operations coordinator and forwarded to the available crew. A crew moves to wellsite to perform the operation.

7.2. Model Assumptions and Parameters

AnyLogic model for the current assignment policy follows the below parameters and assumptions:

- Number of drilling rigs: 6
- Number of service crews: 3
- Number of sections drilled for each well: 3 sections
- Duration to drill surface section follows a Pert distribution with a minimum value of X =3.4467 days, a maximum value of X=31.584 days and most likely value of X=13.358 days.
- Duration to drill intermediate section follows Pert distribution with a minimum value of X= 5.743 days, a maximum value of X=19.422 days and a most likely value of X=8.298 days.
- Duration to drill production section follows Pert distribution with a minimum value of X=5.9179 days, a maximum value of X=35.235 days and most likely value of X=7.3946 days.
- Duration to complete cementing treatment for a surface section follows Pert distribution, with a minimum value of X=8 hours, maximum value of X=70.18 hours and a most likely value of X= 8 hours.
- Duration to complete cementing treatment for an intermediate section follows Pert distribution with a minimum value of X=11 hours, maximum value of X=95.525 hours and a most likely value of X=11 hours.
- Duration to complete cementing treatment for a production section follows the same Pert distribution, with a minimum value of X=12 hours, a maximum value of X=103.57 hours and a most likely value of X = 12 hours.
- A drilling rig will move to a new location to start drilling a new well in 5 days.
- At the beginning of any simulation, the probability that a drilling rig is currently working on a surface section, intermediate section or production section is equally likely.

- A treatment will not start unless a crew is available at wellsite.
- The crew which finishes the previous service the earliest is selected to perform the new service request.
- Transportation time for any member / equipment is neglected.
- All service crew members are at the origin point (Base) when at idle state.
- Drilling rigs are randomly positioned at the start of each simulation.

7.3. Simulation Model and AnyLogic Code

AnyLogic is a multimethod simulation software that allows for modeling of a wide variety of case studies in the field of logistics, transportation, resources planning, …etc. This platform provides a different modeling methods including process based modeling and agent based modeling. The case study in hand is modeled as agent based case. Agent based modeling is considered the easiest modeling method compared to the other modeling methods.

7.3.1. Drilling Rig Agent

The below figure 24 demonstrates how a drilling rig agent is constructed.

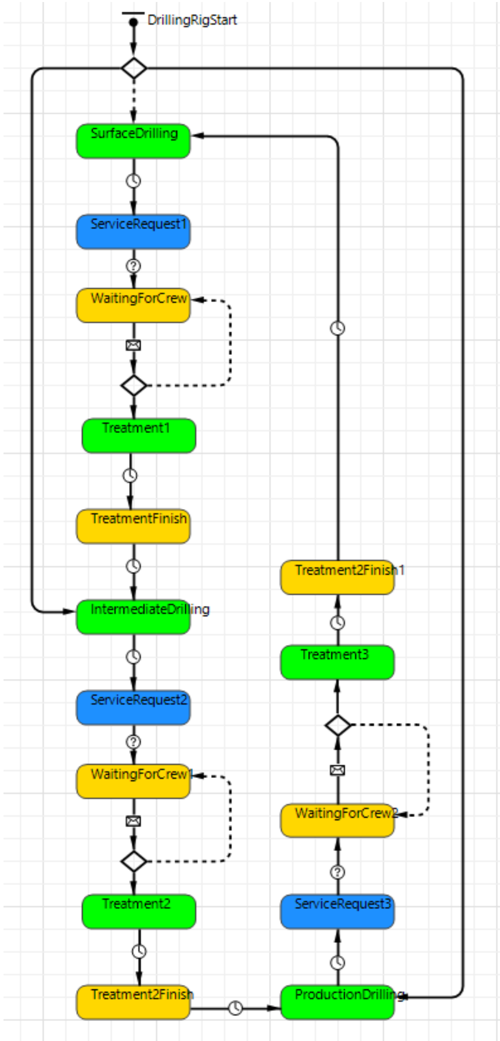

Figure 24: Drilling Rig Agent

Once a simulation starts, the probability to start at any of the 3 drilling section is equally likely to happen. As soon as section drilling is complete, a request is sent to the service coordinator for a cementing service. The service crew is mobilized to the wellsite to perform the treatment and the start of service is triggered by a specific message sent by the crew once it arrives at the site.

After completion of service, the crew moves back to the base and drilling continues. The drilling rig moves to another drilling sport after the completing the production section. This process takes 5 days.

7.3.2. Crew Agent

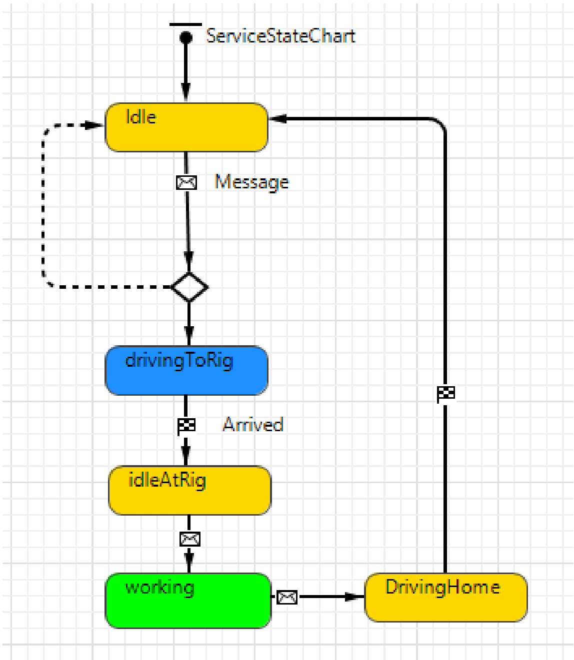

Figure 25: Crew Agent

The crew agent is constructed in such a way that allows it to receive a request from the service coordinator and mobilize immediately to wellsite to perform an operation. No shifts or maximum duty hours are considered in this agent construction.

7.3.3. Service Coordinator Agent

This agent controls the flow of work to all available service crews. The agent basically receives a service request and sends to a crew. The state chart in this agent checks for requests every 1 minute of simulation time.

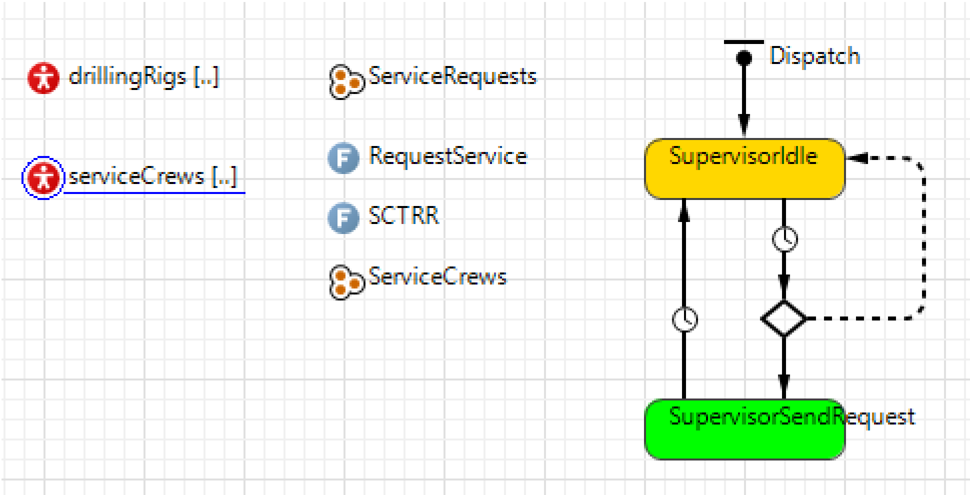

Figure 26: Service Coordinator Agent

The choice of service crew depends on the vector "ServiceCrews" that initially has all service crews lined up. Once a crew is selected to perform an operation, the crew index number is removed from the list and retuned back as the last element. This method ensures an even distribution of workload over all available crews.

8. Proposed Assignment Policy

The proposed assignment policy is based on having a dedicated dispatcher to monitor and organize personnel duties and assignments. Dispatcher function can be assigned to two employees working on 12 hours shift each. Each employee will be able to view current ongoing operations along with working hours of each field worker along with expected upcoming operations based on the planned operations provided by the operating company. Deviation from original plan is highly likely in drilling operations, where the proposed model is able to capture these deviations through human inputs.

8.1. Model Structure

The structure of the proposed assignment and planning policy is demonstrated in figure 27.

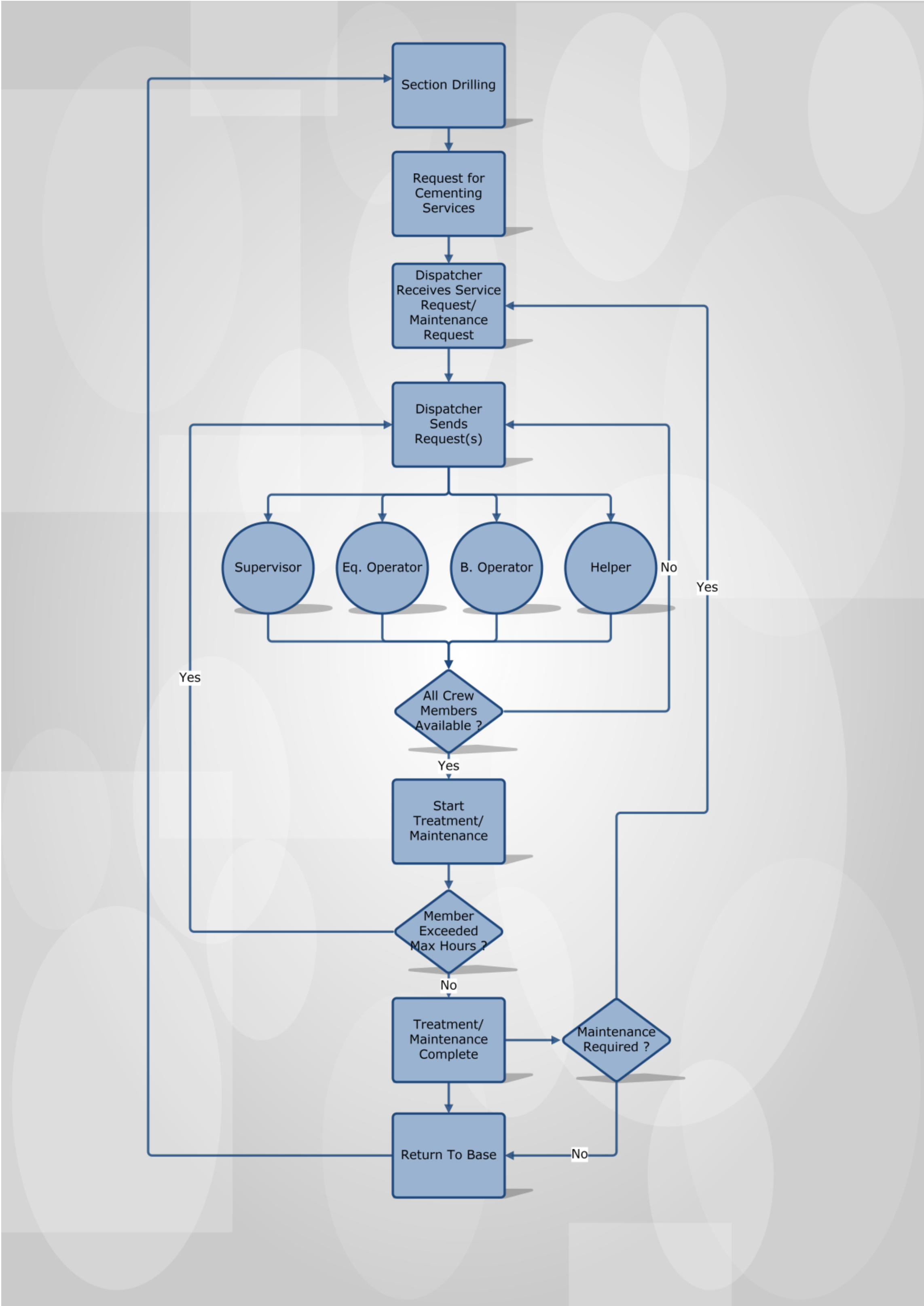

Figure 27: Proposed Policy Flow Chart

The model starts by observing the current ongoing drilling operations on a specific drilling rig. Once drilling is complete, the drilling rig sends a request for cementing service which is directly received by the dispatcher. The dispatcher points the available personnel to perform the treatment from the available pool of resources, based on a specific criterion. Treatment or operation will not start unless a crew is completely assembled and all the members required are available.

During the operation, dispatcher monitors the amount of hours worked by each member and once a member exceeds the allowed hours on duty, the dispatcher gets a notification to change that particular member with another available member from the pool of resources. Once the replacement member arrives at the worksite, the active member will go to resting state for a period of time and then becomes ready to work again.

If an equipment required maintenance after treatment is complete, the dispatcher receives a request for maintenance that requires a certain number of workers with some specific skills to perform the maintenance. An equipment will be out of service until the maintenance is complete. Meanwhile, the dispatcher continues to monitor the drilling operations and ongoing cementing treatments on all worksites.

8.2. Model Assumptions and Parameters

The proposed model incorporates the following:

- Number of drilling rigs: 6
- Number of service equipment: 3
- Number of available supervisors: 3
- Number of available equipment operators: 3
- Number of available batch operators: 3
- Number of available helpers: 3
- Number of sections drilled for each well: 3 sections

- Maximum allowed working hours: 16 Hours for each member
- Duration to drill surface section follows a Pert distribution with a minimum value of X =3.4467 days, a maximum value of X=31.584 days and most likely value of X=13.358 days.
- Duration to drill intermediate section follows Pert distribution with a minimum value of X= 5.743 days, a maximum value of X=19.422 days and a most likely value of X=8.298 days.
- Duration to drill production section follows Pert distribution with a minimum value of X=5.9179 days, a maximum value of X=35.235 days and most likely value of X=7.3946 days.
- Duration to complete cementing treatment for a surface section follows Pert distribution, with a minimum value of X=8 hours, maximum value of X=70.18 hours and a most likely value of X= 8 hours.
- Duration to complete cementing treatment for an intermediate section follows Pert distribution with a minimum value of X=11 hours, maximum value of X=95.525 hours and a most likely value of X=11 hours.
- Duration to complete cementing treatment for a production section follows the same Pert distribution, with a minimum value of X=12 hours, a maximum value of X=103.57 hours and a most likely value of X = 12 hours.
- A drilling rig will move to a new location to start drilling a new well in 5 days.
- At the beginning of any simulation, the probability that a drilling rig is currently working on a surface section, intermediate section or production section is equally likely.
- A treatment will not start unless all crew member are available at wellsite.

- An active member who exceeds the maximum duty hours is not allowed to leave wellsite unless a replacement arrives at the same wellsite.
- The selection of any crew member to start a new operation or replace another member on an ongoing operation is based on the total number of hours worked over a period of time. The member with least total hours is selected.
- If a member exceeds the maximum of 16 working hours on duty will be allowed to rest for exactly 8 hours.
- If a replacement member(s) arrive(s) at wellsite after treatment is complete, he will go directly to idle state waiting for a new service request.
- An equipment does not have a limit of working hours. Cement pump can operate as long as the treatment requires.
- Once the accumulated operating hours of an equipment reaches 400 hours, maintenance is required as per Schlumberger Well Service Standard 03: Maintenance
- Equipment maintenance is performed by 1 equipment operator and 1 helper.
- Equipment maintenance requires 8 hours
- An equipment remains unavailable until maintenance is complete.
- Priority is always given to operations over maintenance during the dispatching process of equipment operators and helpers.
- Transportation time for any member / equipment is neglected.
- All service crew members are at the origin point (Base) when at idle state.
- Drilling rigs are randomly positioned at the start of each simulation.

8.3. Simulation Model and AnyLogic Code

8.3.1. Drilling Rig Agent

Drilling rig module is created as a population of 6 identical agents that are randomly located in a space of a specific boundaries. A state chart the governs the behavior of the module is illustrated in figure 29.

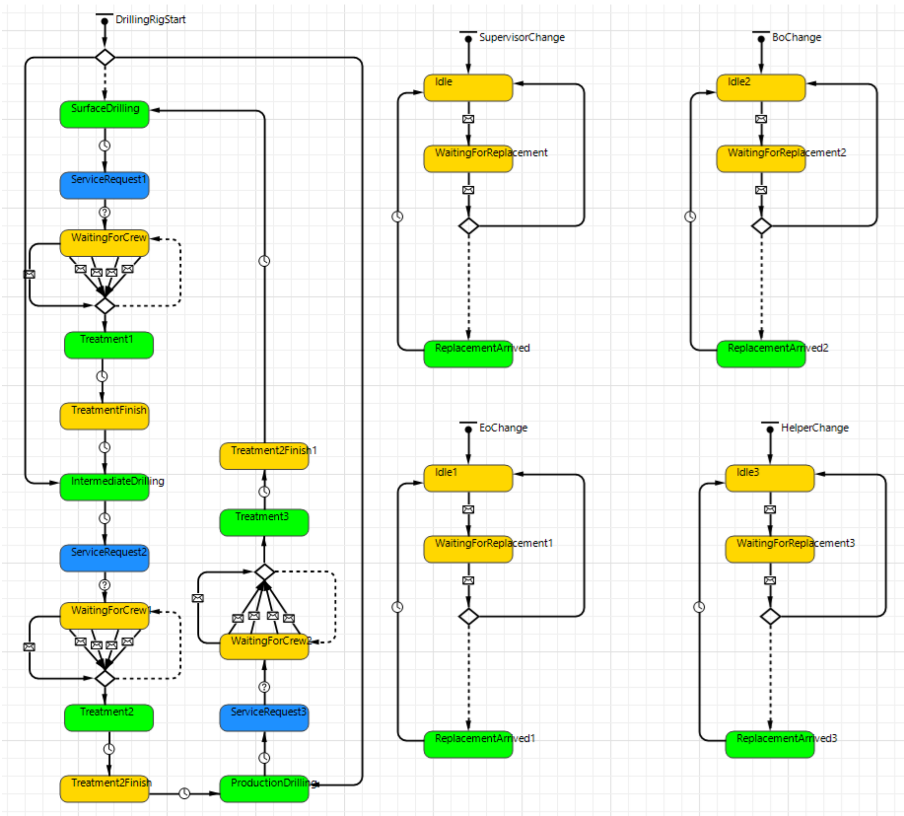

Figure 28: Drilling Rig Agent

At the start of every simulation, the "DrillingRigStart" state chart is activated. The first branch in the state chart selects randomly the current section being drilled. The probability to start in any of the 3 sections of an oil well is equally likely to happen for any section. Once drilling is complete, the state chart sends a service request to the dispatcher agent, where the drilling rigs moves to “WaitingForCrew” state until all members of the service crew arrive at wellsite to start the operation. Once all members are available, the treatment starts.

During the operation, each member for the crew is monitored and a replacement is sent by the dispatcher if required. The remaining 4 state charts are set to replace the currently active member with another member. These state charts also start at the beginning of each simulation. The transition to replace a member of a crew is triggered by a specific message received by the member agent after exceeding a certain number of hours on duty. An active member is not allowed to leave wellsite unless a replacement arrives.

Once the production section is complete, the rig mobilizes to another location to start a new well. This movement is set to take exactly 5 days, of which after that it will start with a new surface section.

8.3.2. Service Supervisor Agent

Supervisor agent is also created as population of identical agents containing 3 agents initially. The state chart for this agent is illustrated in figure 29 below.

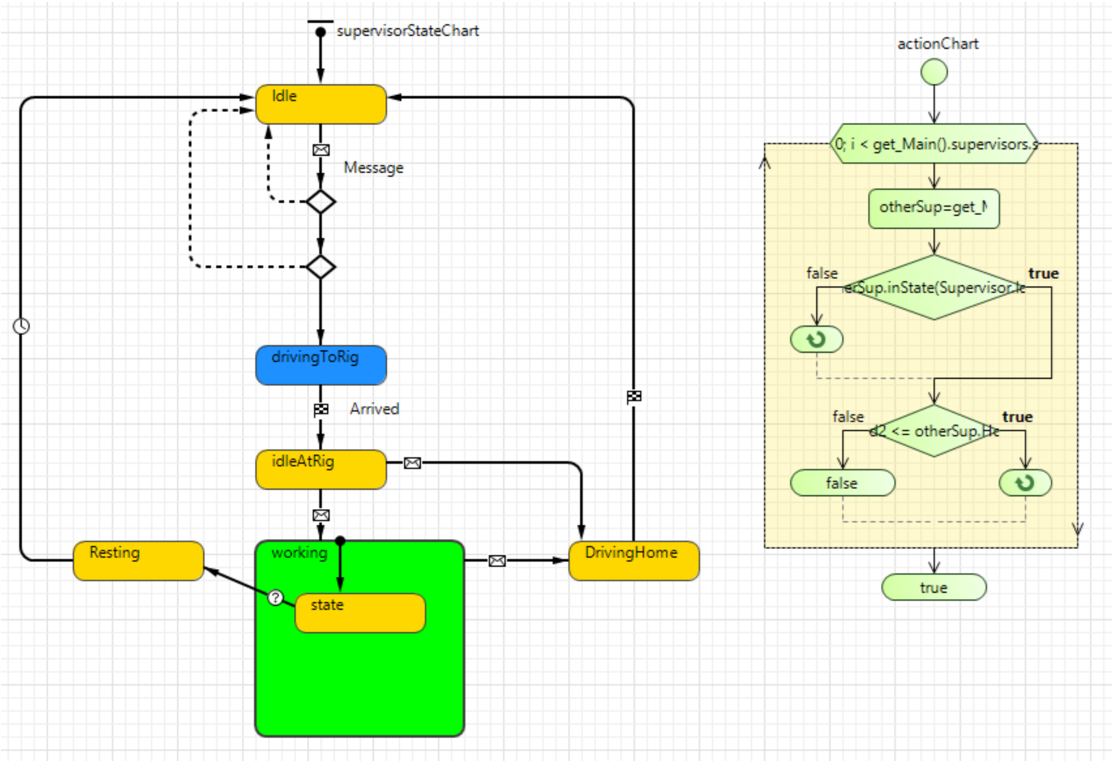

Figure 29: Service Supervisor Agent

As in the drilling rig agent, the supervisor state chart starts immediately at simulation start. All supervisors start as idle until a request for service is received from the dispatcher. This request is triggered by a specific message. Once a message is received, supervisor agents will execute the action chart show above. This action chart is created to regulate the selection of supervisors based on the total number of hours worked over the simulation. The supervisor with least hours will be able to collect the current service request. Once a supervisor collects a request, it is removed from the collection of pending requests. The prevents other supervisors in the population from collecting the same request.

An assigned supervisor will move to wellsite, where he remains idle until all other members of the crew arrive at the same wellsite. The start of operation is triggered by another specific message from the drilling rig state chart once all members are available on site. While executing service, the combined state "working" monitors the current active supervisor and sends a request for a replacement supervisor. The currently active supervisor will go to "resting" state for 8 hours once a replacement arrives at well site.

If the treatment is finished without exceeding the maximum duty hours a supervisor, the state chart receives a specific message indicating the completion of the job, where the supervisor returns back to base. Supervisor returns back to idle state upon arrival at the base origin point (0,0).

8.3.3. Batch Mixer Operator Agent

Batch mixer operator state chart is identical to the supervisor state chart. The agent is initially created as population of 3 agents, following the state chart in figure 30.

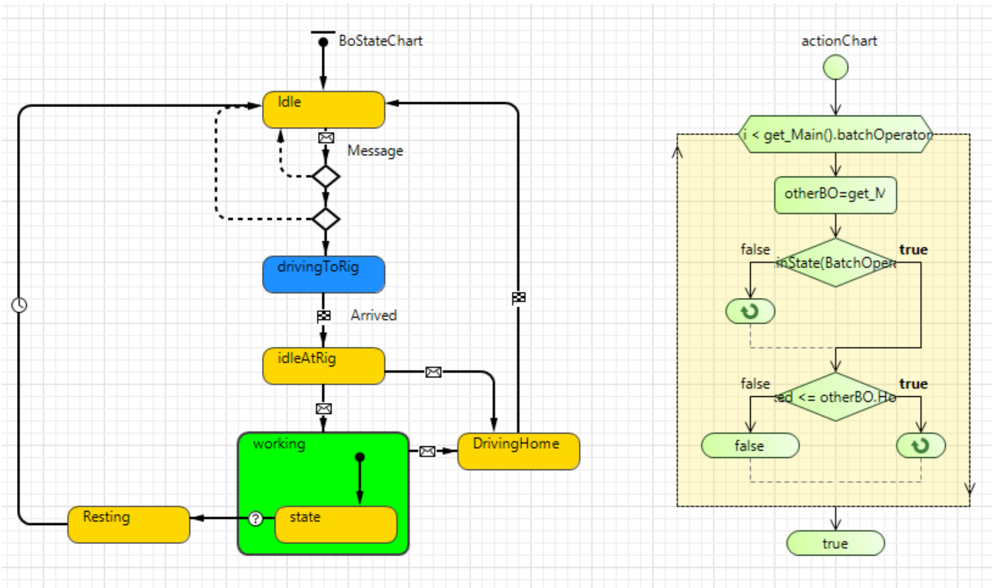

Figure 30: Batch Mixer Operator Agent

8.3.4. Equipment Operator Agent

This agent is similar to both the supervisor and batch mixer operator agents. However, the state chart is slightly modified to account for maintenance requests. This agent is of 3 identical members as well. The state chart is in figure 31.

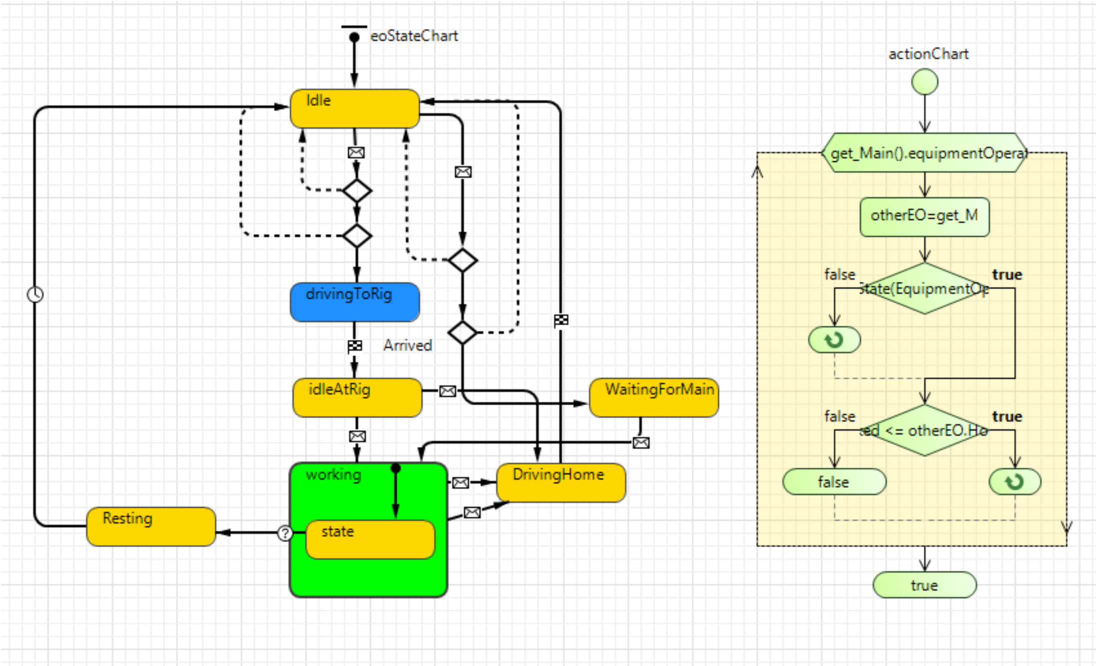

Figure 31: Equipment Operator Agent

This state chart enables the equipment operator to receive equipment maintenance request. This request is received from the dispatcher agent. The state chart is triggered by a specific message for equipment maintenance. Once message is received, the operator becomes dedicated for the specific equipment that requires maintenance. An operator will remain idle until the other member of the maintenance crew “Helper” is available becomes available to start the maintenance. Maintenance is required every 400 operational hours and requires 8 hours of continuous work to complete.

8.3.5. Service Helper Agent

This agent is exactly identical to the equipment operator agent, with 3 members initially inside the population.

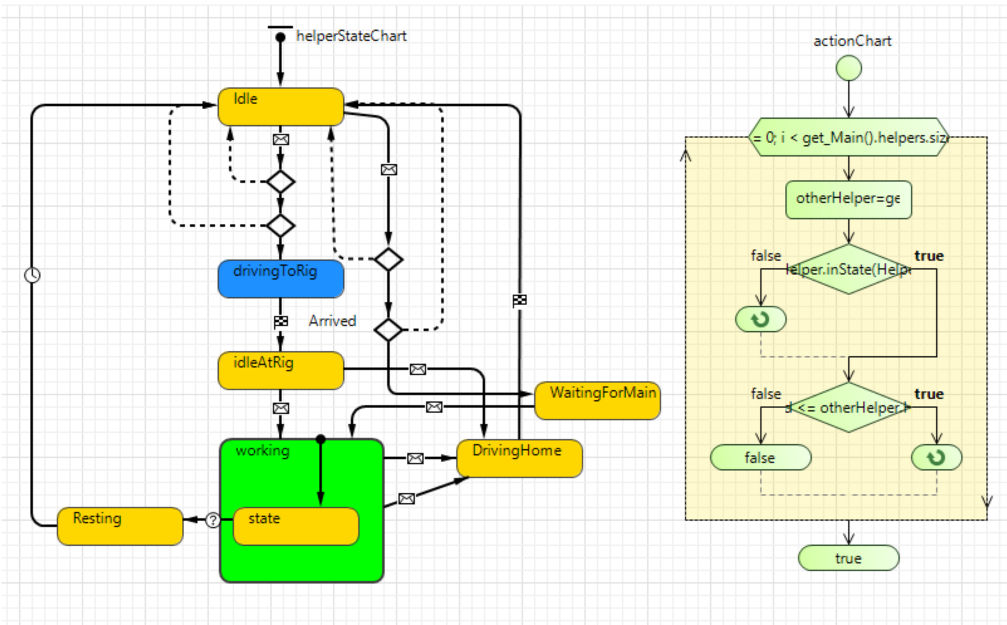

Figure 32: Service Helper Agent

8.3.6. Equipment Agent

The main difference in the equipment agent state chart is that it doesn’t require replacement during operations. Another difference is the requirement for maintenance after operating for 400 hours.

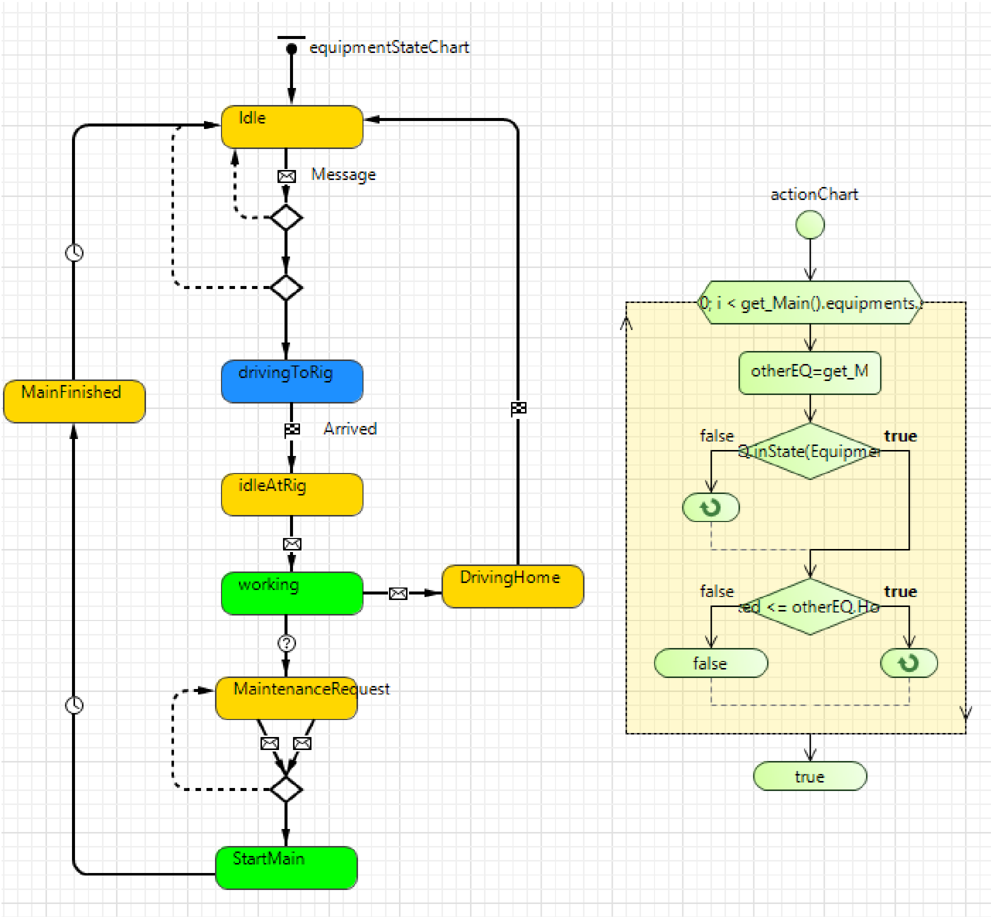

Figure 33: Equipment Agent

Straight after completing an operation, the equipment will send a message requesting for maintenance if the total number of operational hours exceeds 400 hours. The message will be processes by the dispatcher and requests will forwarded to equipment operators and helpers. Only 1 equipment operator and 1 helper will be allowed to work on this specific equipment. Maintenance will not start unless both members are available and will take 8 hours to complete the maintenance before it goes back to idle state waiting for another service request.

8.3.7. Service Dispatcher Agent

The dispatcher agent is the core of the proposed assignment policy. Basically the agent receives a service or maintenance request and stores them as a queue to be processed based on first come first served.

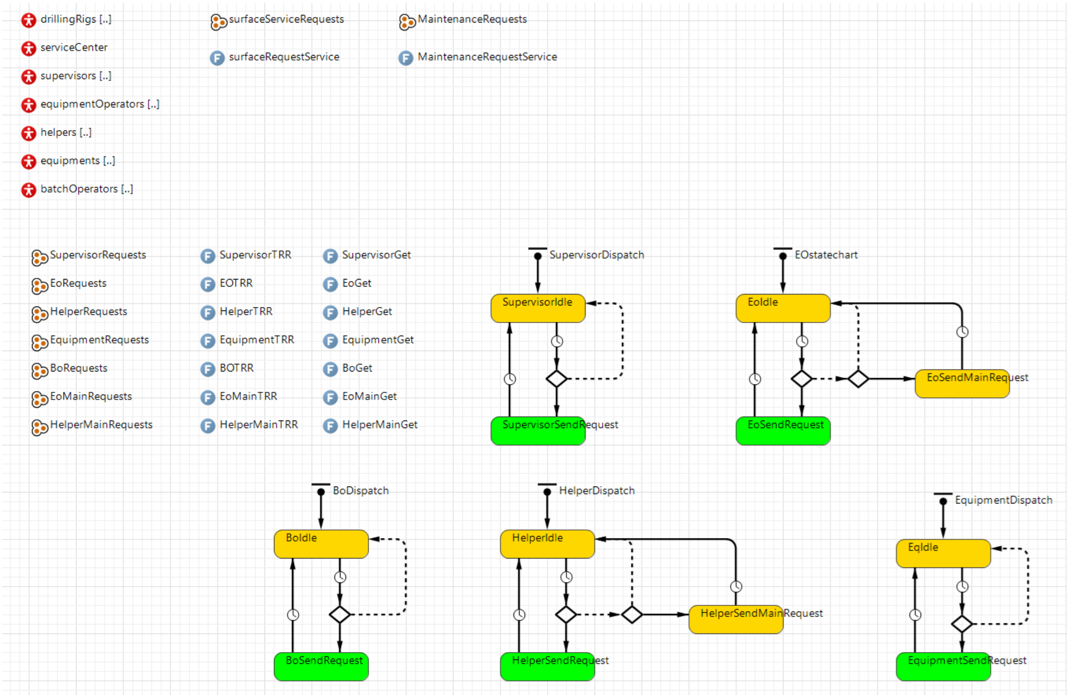

Figure 34: Dispatcher Agent

A service request is generated by calling the function “surfaceRequestService” which received the drilling rig index number and distributes it to the collection vector of each crew member. Similarly, a maintenance request is also generated by calling the function “MaintenanceRequestService” which also distributes the equipment index number on all collection vectors of the maintenance organization.

Each state chart in the above figure continuously checks for requests every 1 minute of time. Taking an example, the “SupervisorDispatch” state chart, the state chart checks for requests by calling the function “SupervisorTRR” of type Boolean. The function returns a value True if there is any request pending to be processed, and returns False otherwise. Once the value returned is True, the state chart calls another function “SupervisorGet” which returns and removes the first drilling index number stored in the collection vector “SupervisorRequests”. This method enables the system to serve on first come first serve bases.

The “EOStatechart” works similar to the supervisor state chart. However, this state chart also checks for maintenance requests. It first checks for service requests from the drilling rigs and moves to check maintenance only if there are no pending requests from any rig.

9. Results

Both policies simulated with the same number of human resources available and the drilling rig parameters. Each policy is simulated 10 number of times. Ten runs were taken for each case with a run length of 12 months. Results are provided in Appendix B.

9.1. Current Policy Results

The below figure demonstrates the average positive deviation from the 16 hours maximum duty.

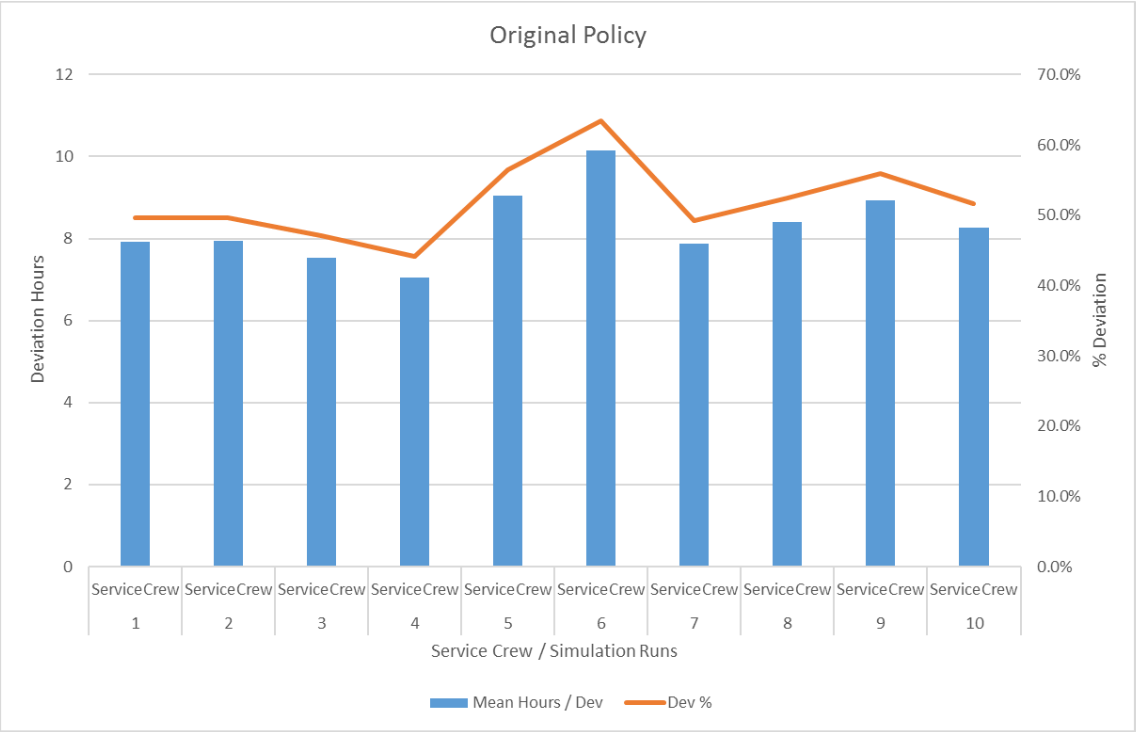

Figure 35: Original Policy Hours Deviation

The average positive deviation hours in the original assignment policy is 8.3 hours over all simulation runs, giving and average of 51.9% deviation from 16 hours. This is simply computed by dividing the average positive deviation computed by 16 hours.

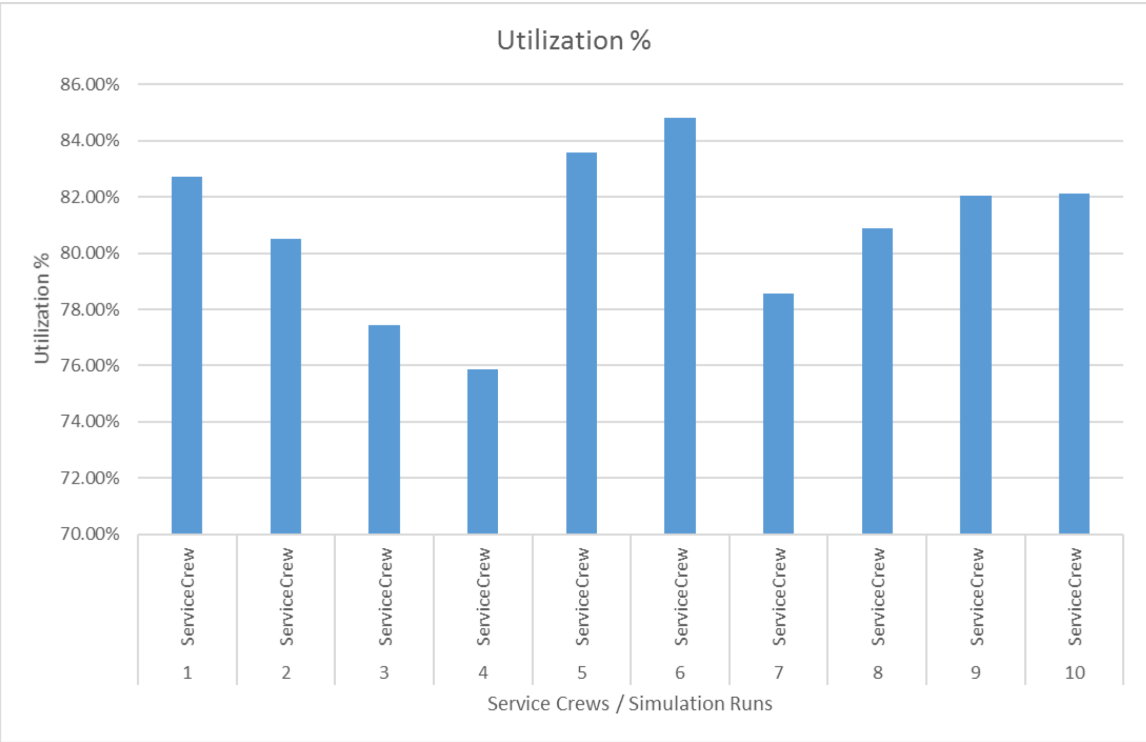

Figure 36: Service Crews Utilization

The average utilization of all service crews over all simulation runs is approximately 80.85%. This is based on having 4,224 hours of work available over the period of 12 months. This is calculated by allocating 16 hours of work per day and excluding 2 days from each week.

The maximum waiting time a drilling rig spends waiting for a crew to arrive over all simulation runs is 5 hours, which is still under the maximum pre-assigned waiting time of 24 hours.

9.2. Proposed Policy Results

The proposed policy is superior to the original assignment policy in term of positive deviation hours. Although the same number of resources is available, the average positive deviation hours over all simulation runs is calculated to be 3.89 hours.

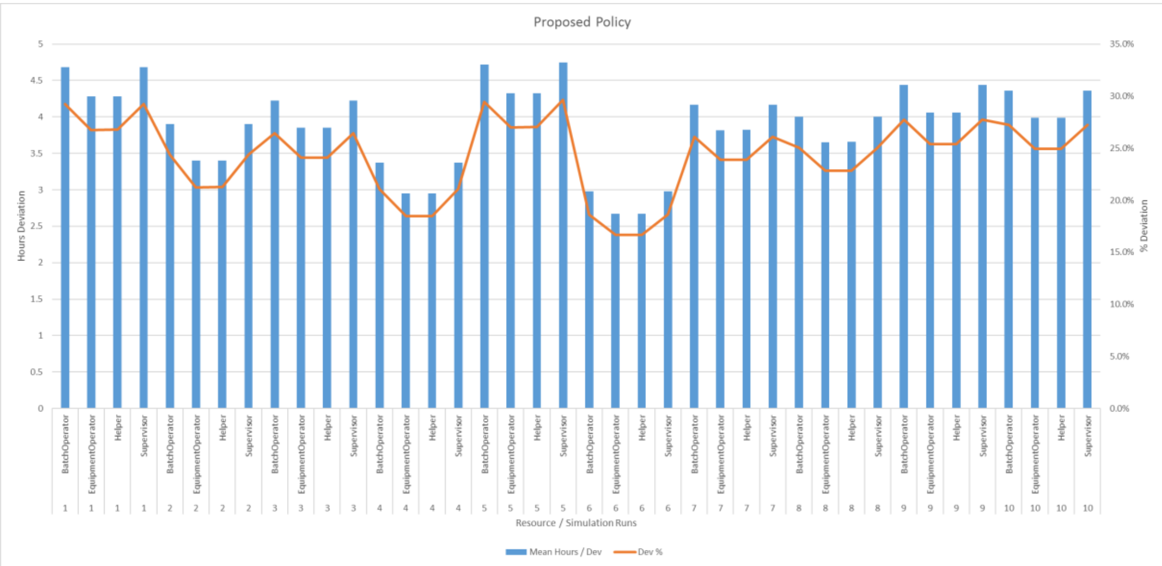

Figure 37: Proposed Policy Hours Deviation

The percentage deviation over all runs is computed to be 24.3% from the 16 hours maximum duty. The average utilization of personnel is simulated to be 78.17% over all simulation runs.

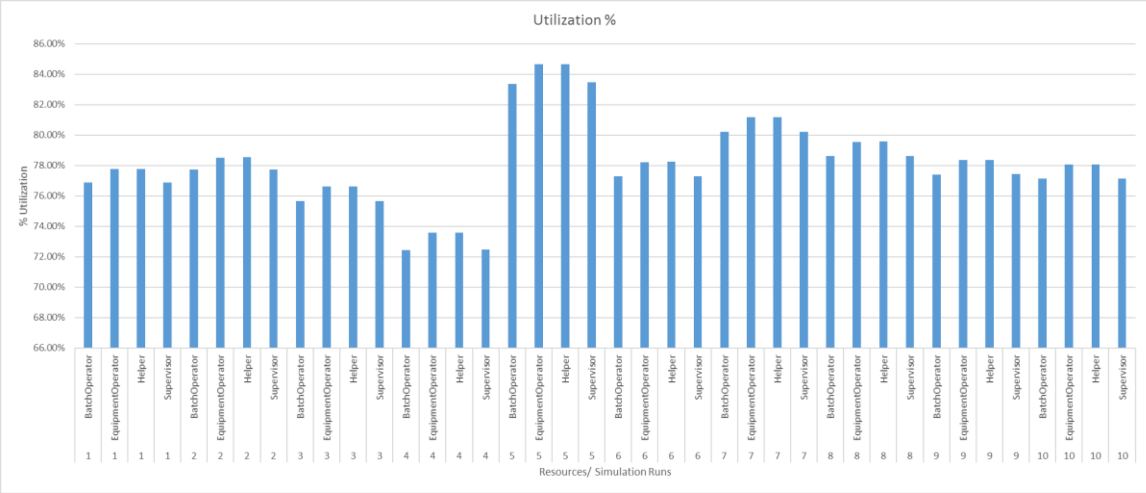

Figure 38: Personnel Utilization

The maximum waiting time a drilling rig spends until a crew arrives at wellsite is 6.7 hours, which is still under the 24 hours limit.

9.3. Results Analysis

Based in the data collected from operations in year 2014, the average number of hours worked by any crew is calculated to be 23.72 hours, where the simulation of the original policy gave an average working hours of 24.3. This validates the parameters of both original policy and proposed policy simulations models. Duration of processes also gives a validity indication for both simulation models.

Table 2: Duration of Processes

Process	13-3/8" Drilling	9-5/8" Drilling	7" Drilling	13-3/8" Treatment	9-5/8" Treatment	7" Treatment
Process Duration	Days	Days	Days	Hours	Hours	Hours
2014 Operational Data	14.72	9.72	11.80	17.95	25.86	27.70
Original Policy Simulation	14.61	9.58	11.50	19.43	25.70	27.69
Proposed Policy Simulation	14.57	9.48	11.41	18.10	24.23	27.80

On the other hand, the proposed policy simulation gave 20 hours of work on average.

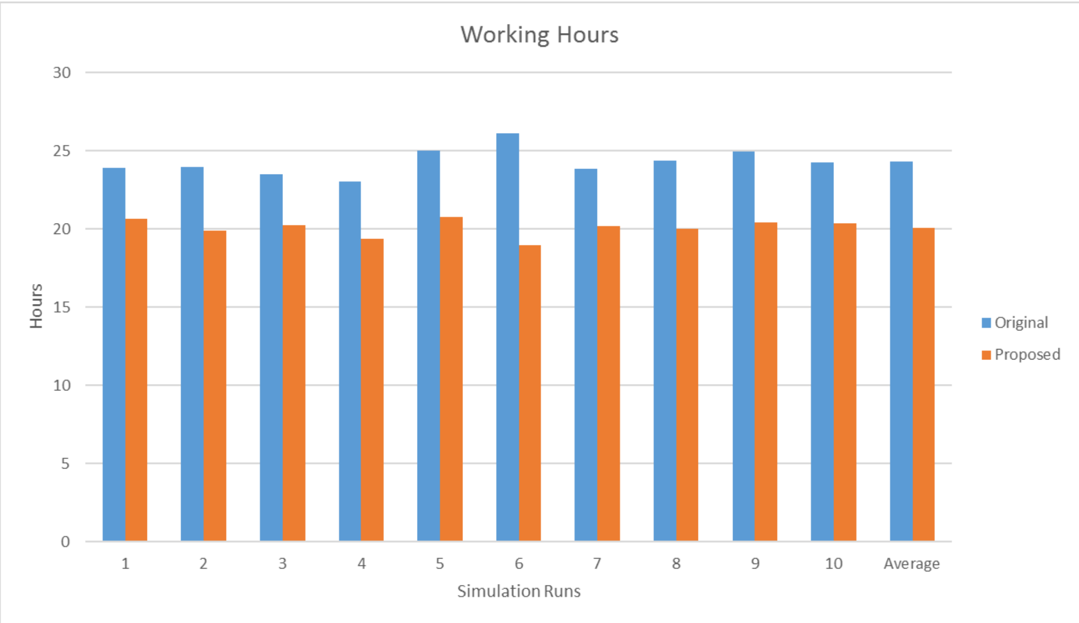

Figure 39: Original Vs. Proposed Policies Working Hours

The average deviation is reduced from 8.3 hours on average from the original policy to 3.89 hours from the proposed policy. Comparing these numbers to the data collected from 2014 operations, one can observe the actual deviation in 2014 is about 7.72 hours, which very close the simulated original policy.

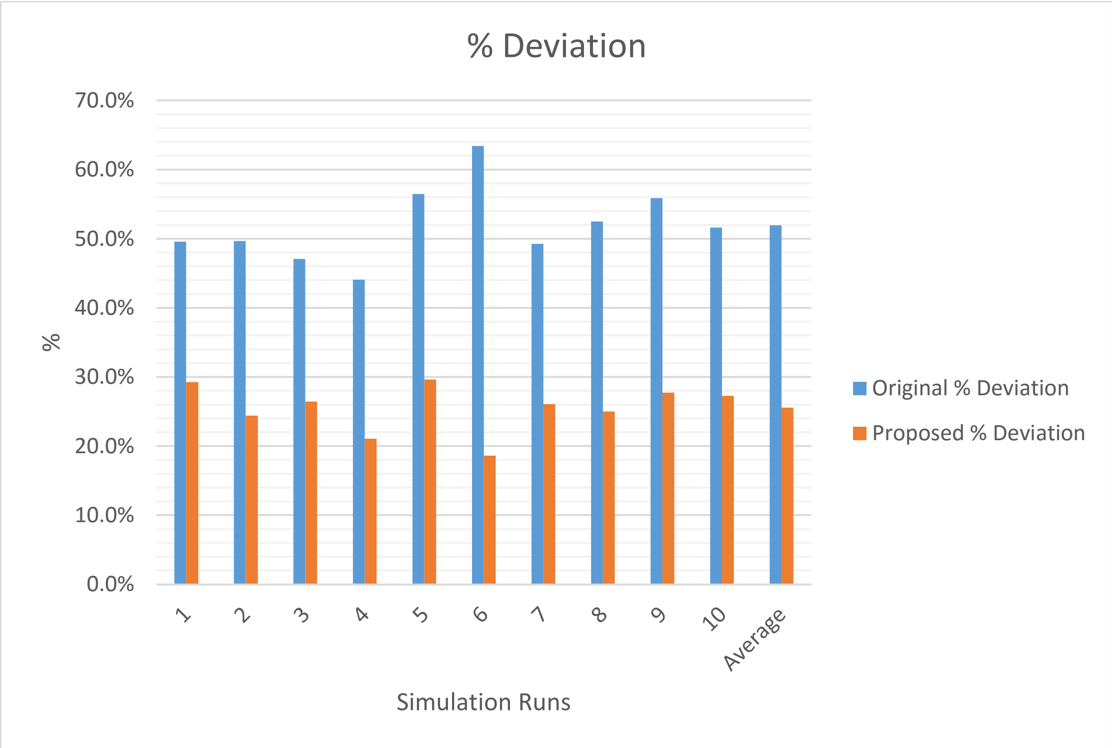

Figure 40: Original Vs. Proposed Assignment Policies % Deviation

Although equipment maintenance is captured in the proposed assignment policy model, one can see the average working hours remains lower compared to the original policy. This is due to the overall reduction in hours worked by all human resources, including the maintenance crew (Equipment Operator & Service Helper).

Rig waiting time remains below 24 hours for both policies. This indicates that we will not have any service delivery issue in either cases. Waiting time for both the Equipment Operator and Service Helper to perform maintenance is zero. This indicates that there are always resources available to perform equipment maintenance.

From a statistical point of view, the confidence interval for the generated data from both the original and proposed policies are computed. (Law & Kelton, 2000)

For the original policy, it has been found that:

- Average deviation from maximum allowed duty is μ= 8.31 hours
- Sample standard deviation S= 0.878 hours
- Number of simulation n=10

Since the sample is relatively small in size, confidence interval is estimated using t-distribution tables. Estimating the population standard deviation:

$$\sigma = \frac{0.878}{\sqrt{10}} = 0.277\ Hours$$

From t-distribution tables, $t_{n-1,0.95}$ = 2.262. This gives:

$$CI = 8.31 \pm 0.628\ Hours$$

In other words, we can say that we are 95% confident that the true mean of the population is between 7.681 and 8.938 hours.

Similarly, for the proposed policy:

- Average deviation from maximum allowed duty μ=4.087 hours
- Sample standard deviation S= 0.5571 hours
- Number of simulations n=10

Estimating the population standard deviation:

$$\sigma = \frac{0.5571}{\sqrt{10}} = 0.176\ Hours$$

From t-distribution tables, $t_{n-1,0.95} = 2.262$. This gives:

$$CI = 4.087 \pm 0.398\ Hours$$

We are 95% confident that the true population mean falls between 3.688 and 4.485 hours.

Performing the same statistical analysis on personnel utilization, it has been found that:

- For proposed assignment policy:

$$CI = 78.17\% \pm 0.020\%$$

We are 95% confident that personnel utilization falls between 78.15% and 78.19%.

- For current assignment policy:

$$CI = 80.85\% \pm 0.020\%$$

We are 95% confident that personnel utilization falls between 80.83% and 80.87%. Overall, personnel utilization was not expected to deviate significantly from the current assignment policy. Although equipment maintenance is accounted for, it barely adds additional 1% utilization for the equipment operator and service helper.

Calculating the confidence interval for rig waiting time, it has been found that:

- For proposed assignment policy:

$$CI = 1.087 \pm 0.815\ Hours$$

We are 95% confident that maximum rig waiting time falls between 0.271 and 1.902 hours.

- For current assignment policy:

$$CI = 0.199 \pm 0.181\ Hours$$

We are 95% confident that rig waiting time falls between 0.017 and 0.380 hours. Here one can see that both confidence intervals are overlapping and superiority of the new policy with respect to rig waiting time is not guaranteed. However, in both cases rig waiting time remains below 24 hours which achieves the objective.

Another method of comparing both approaches is the paired-t confidence interval method. This method is constructed as follows:

$$Z_J = X_{1J} - X_{2J}$$

Where:

- X_{1J} is the performance matric computed from the current assignment policy simulation.
- X_{2J} is the performance matric computed from the proposed assignment policy simulation.
- Z_J is the difference between X_{1J} and X_{2J}

Estimating the mean of the difference between X1J and X2J:

$$\bar{Z} = \frac{\sum_{J=1}^{n} Z_J}{n}$$

Variance of the mean can be computed by:

$$\widehat{Var}[\bar{Z}(n)] = \frac{\sum_{J=1}^{n} \left[Z_j - \bar{Z}(n)\right]^2}{n(n-1)}$$

The confidence interval of the difference becomes:

$$\bar{Z}(n) \pm t_{n-1,1-\alpha/2}\sqrt{\widehat{Var}[\bar{Z}(n)]}$$

Since the average positive deviation from maximum work hours is the most important performance matrix, Z_J values are calculated for each simulation run to be:

Table 3: APD Hours

Average Positive Deviation Hours			
Run	**Original (X_{1J})**	**Proposed (X_{2J})**	**Z_J**
1	23.93152	20.68035	3.251171
2	23.94804	19.9031	4.044938
3	23.52988	20.2271	3.302784
4	23.05071	19.37126	3.679447
5	25.03498	20.74435	4.290632
6	26.14552	18.9777	7.167821
7	23.8783	20.17008	3.708224
8	24.39802	20.00423	4.393792
9	24.935	20.43899	4.496014
10	24.25577	20.36115	3.894624

The mean of the difference becomes $\bar{Z} = 4.222\ Hours$ and

$\widehat{Var}[\bar{Z}(n)] = 0.125\ Hours$. Thus, the 95% confidence interval becomes:

$$CI = 4.222\ Hours\ \pm 0.799\ Hours$$

With the above 95% confidence interval, we can observe that proposed assignment policy is superior to the current policy, since it reduces the average positive deviation anywhere between 3.423 and 5.021 hours.

9.4. Additional Simulation Run

An additional simulation run is performed using the same number of resources. However, the maximum duty is limited to 12 hours in this run. Figures 41 and 42 below illustrate the results.

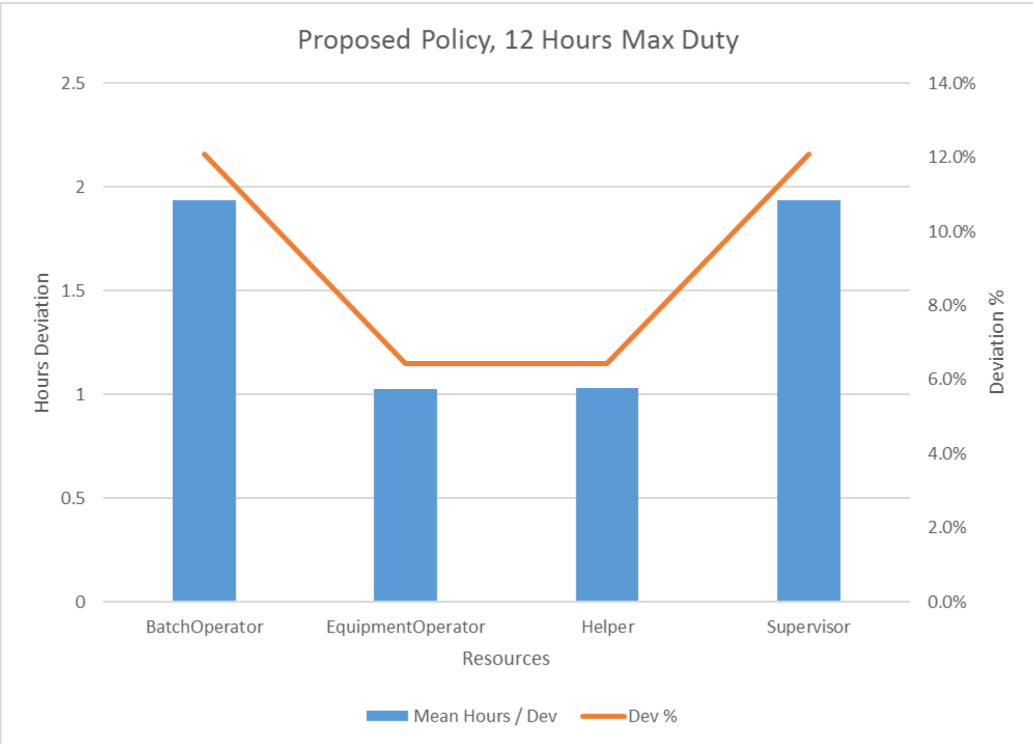

Figure 41: Deviation from Maximum Allowed Working Hours

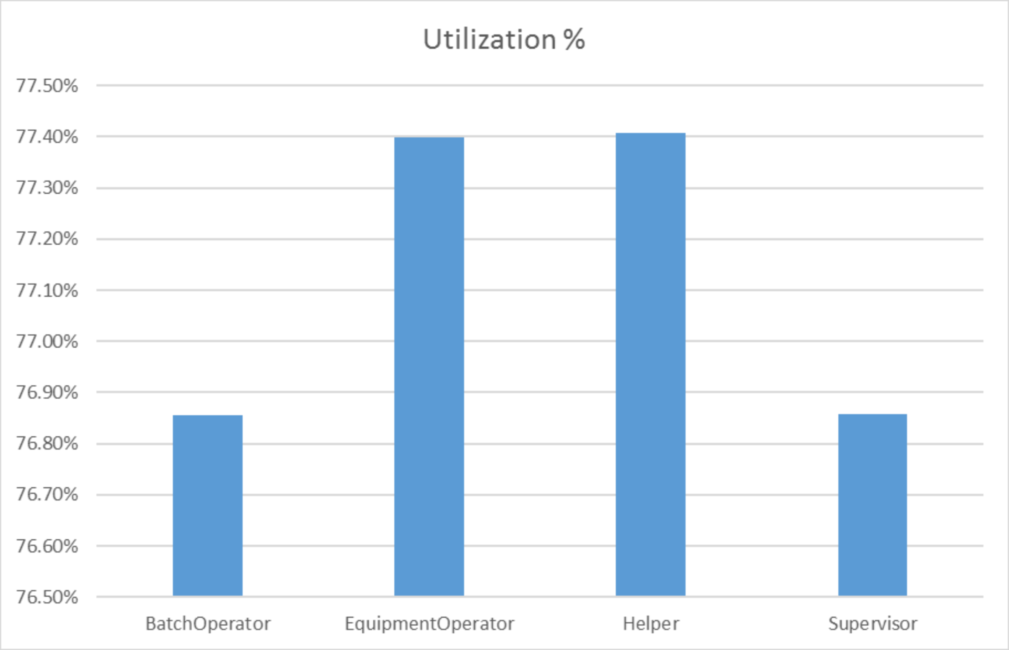

Figure 42: Utilization of Resources

Maximum rig waiting time recorded in this simulation run is 7.46 hours, which is still below the 24 hours limit. The deviation shown in figure 41 is from the maximum duty of 16 hours. In other words, simulating with a target of 12 hours max duty gave about 11% deviation from 16 hours, without compromising rig waiting time. Equipment maintenance was done on time without delays. Personnel utilization remains around 78%.

10. Conclusion and Recommendations

10.1. Conclusion

Personnel assignment and planning is a valuable aspect in service industries. Nowadays, additional focus is given to this part of the industry due to the increased demand of services rather than production, which is accompanied by the need to reduce the overall cost.

In this project, we have demonstrated that there's a better solution to schedule service personnel in the field of cementing services in Qatar. A proposed assignment policy based on adding a dispatcher function was demonstrated and simulated on AnyLogic Simulation software. The proposed policy results were compared with the current policy simulation results and 2014 operational data to confirm its superiority. Both simulation models were built based on the forecasted demand extracted from the operational data of the year 2014.

The proposed policy reduced the average deviation of personnel duty hours from above 50% to 25% on average. These results also captured the maintenance of equipment which is not accounted for in the current system. Furthermore, the new policy didn't compromise the rig waiting and didn't result in any additional delay charges from the operating company.

Finally, the same policy was simulated targeting a 12 hours maximum duty hours for personnel. A maximum of 12% deviation from 16 hours maximum duty is observed. Also, this case didn't compromise rig waiting time or equipment maintenance. Utilization figures remained approximate the same.

In such a harsh work environment, every single minute saved without compromising the integrity of the operations, is much valued by the personnel, the operating company and the service company.

10.2. Recommendations

One could easily notice that having such a method of running operations is severely exhausting the human resources. Another alternative that could be considered is to have fixed shifts for service crews, each shift is 12 hours for example. The assigned service crew during a particular shift will be idle until a service request or maintenance request is received. In situations where multiple requests are received, the next service crew in queue could process the request and start the shift earlier.

This particular approach is a possible alternative for the current assignment method. However, this approach needs to be studied thoroughly to evaluate its effectiveness relevant to previously mentioned performance metrics and the additional costs associated with such approach. Eventually, service provider might need to allocate more than 3 service crews to cover the current demand pattern.

As a further improvement to the model on hand, one can simulate the actual transportation time of personnel from the service center to wellsite. Although transportation times in the field of Dukhan is considered negligible, transportation in larger size fields may have considerable impact on simulation results.

Another improvement could also be including remedial cementing services. However, predicting the demand pattern for remedial operations could be very difficult due to the large number of contributing factors.

Annual vacation and weekly days off planning could also be another addition to the simulation model. Including both will further improve the integrity of the simulation model and the proposed assignment policy.

Finally, a professional version of AnyLogic software would provide a variety of simulation options for this model. One can choose to vary certain parameters within a specific range of values and record simulation results. Another way of simulating the model is by defining an objective and letting the software define the optimum parameters to achieve the objective.

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Appendix A: 2014 Operational Data

Job Duration (Hours)	Date	Job Type	Well	Job Type	Well Type	Drilling Days
12.00	30-Nov-13	13 3/8 in Casing	DK-738	P	Oil Well	11
12.00	29-Dec-13	13 3/8 in Casing	DK-748	P	Oil Well	5
16.00	1-Feb-14	13 3/8 in Casing	DK-779	P	Oil Well	11
11.00	17-Aug-14	13 3/8 in Casing	DK-750A	P	Oil Well	11
12.00	13-Oct-14	13 3/8 in Casing	DK-774	P	Oil Well	17
20.00	13-Nov-14	13 3/8 in Casing	DK-751	P	Oil Well	10
8.00	4-Dec-13	13 3/8 in Casing	DK-768	P	Oil Well	15
10.00	17-Jan-14	13 3/8 in Casing	DK-763	P	Oil Well	20
10.00	1-Mar-14	13 3/8 in Casing	DK-720	P	Oil Well	22
42.00	5-Apr-14	13 3/8 in Casing	DK-759	P	Oil Well	10
33.00	31-May-14	13 3/8 in Casing	DK-776	P	Oil Well	8
12.00	28-Aug-14	13 3/8 in Casing	DK-778	P	Oil Well	16
13.00	8-Oct-14	13 3/8 in Casing	DK-770A	P	Oil Well	17
21.00	28-Nov-14	13 3/8 in Casing	DK-772	P	Oil Well	13
12.00	25-Nov-13	13 3/8 in Casing	DK-764	P	Oil Well	17
12.00	12-Jan-14	13 3/8 in Casing	DK-762	P	Oil Well	18
16.00	24-Feb-14	13 3/8 in Casing	DK-767	P	Oil Well	16
29.00	8-Apr-14	13 3/8 in Casing	DK-773	P	Oil Well	16
40.00	28-May-14	13 3/8 in Casing	DK-771	P	Oil Well	9
15.00	19-Jul-14	13 3/8 in Casing	DK-769	P	Oil Well	14
12.00	13-Sep-14	13 3/8 in Casing	DK-765	P	Oil Well	21
27.00	25-Oct-14	13 3/8 in Casing	DK-775	P	Oil Well	27
12.00	11-Dec-13	9-5/8 in Casing	DK-738	P	Oil Well	11
20.00	7-Jan-14	9-5/8 in Casing	DK-748	P	Oil Well	9
22.00	15-Feb-14	9-5/8 in Casing	DK-779	P	Oil Well	14
20.00	30-Aug-14	9-5/8 in Casing	DK-750A	P	Oil Well	13
17.00	20-Oct-14	9-5/8 in Casing	DK-774	P	Oil Well	7
34.00	21-Nov-14	9-5/8 in Casing	DK-751	P	Oil Well	8
12.00	15-Dec-13	9-5/8 in Casing	DK-768	P	Oil Well	11
24.00	27-Jan-14	9-5/8 in Casing	DK-763	P	Oil Well	9
29.00	11-Mar-14	9-5/8 in Casing	DK-720	P	Oil Well	9
30.00	15-Apr-14	9-5/8 in Casing	DK-759	P	Oil Well	10
45.00	11-Jun-14	9-5/8 in Casing	DK-776	P	Oil Well	11
22.00	30-Jul-14	9-5/8 in Casing	DK-777	P	Oil Well	8
51.00	6-Sep-14	9-5/8 in Casing	DK-778	P	Oil Well	9
11.00	15-Oct-14	9-5/8 in Casing	DK-770A	P	Oil Well	7
12.00	3-Dec-13	9-5/8 in Casing	DK-764	P	Oil Well	8
22.00	20-Jan-14	9-5/8 in Casing	DK-762	P	Oil Well	8
24.00	10-Mar-14	9-5/8 in Casing	DK-767	P	Oil Well	14
42.00	18-Apr-14	9-5/8 in Casing	DK-773	P	Oil Well	6
35.00	13-Jun-14	9-5/8 in Casing	DK-771	P	Oil Well	15

22.00	27-Jul-14	9-5/8 in Casing	DK-769	P	Oil Well	8
22.00	23-Sep-14	9-5/8 in Casing	DK-765	P	Oil Well	9
41.00	5-Nov-14	9-5/8 in Casing	DK-775	P	Oil Well	10
12.00	19-Dec-13	7 in Casing	DK-738	P	Oil Well	8
20.00	16-Jan-14	7 in Casing	DK-748	P	Oil Well	9
24	25-Feb-14	7 in Casing	DK-779	P	Oil Well	10
16.00	21-Sep-14	7 in Casing	DK-750A	P	Oil Well	22
30.00	29-Oct-14	7 in Casing	DK-774	P	Oil Well	9
17.00	30-Nov-14	7 in Casing	DK-751	P	Oil Well	9
12.00	23-Dec-13	7 in Casing	DK-768	P	Oil Well	8
20.00	2-Feb-14	7 in Casing	DK-763	P	Oil Well	6
57.00	21-Mar-14	7 in Casing	DK-720	P	Oil Well	10
38.00	26-Apr-14	7 in Casing	DK-759	P	Oil Well	11
28.00	7-Aug-14	7 in Casing	DK-777	P	Oil Well	8
30.00	16-Sep-14	7 in Casing	DK-778	P	Oil Well	10
36.00	10-Nov-14	7 in Casing	DK-770A	P	Oil Well	11
12.00	20-Dec-13	7 in Casing	DK-764	P	Oil Well	17
30.00	3-Feb-14	7 in Casing	DK-762	P	Oil Well	14
53.00	18-Mar-14	7 in Casing	Dk-767	P	Oil Well	8
42.00	4-May-14	7 in Casing	DK-773	P	Oil Well	16
38.00	30-Jun-14	7 in Casing	DK-771	P	Oil Well	17
12.00	18-Aug-14	7 in Casing	DK-769	P	Oil Well	22
27.00	16-Nov-14	7 in Casing	DK-775	P	Oil Well	11

Appendix B: Simulation Results

Original Assignment Policy: Crew Working Hours, Mean Deviation and Utilization

Run	Agent type	Statechart	State	Mean Hours	Total Hours	Min Hours	Max Hours	Mean Hours / Dev	Dev %	Utilization %
1	ServiceCrew	ServiceStateChart	working	23.93152293	3494.002348	8.087208889	56.71318722	7.931522934	49.6%	82.72%
2	ServiceCrew	ServiceStateChart	working	23.94804178	3400.621933	9.635542222	67.27320472	7.948041782	49.7%	80.51%
3	ServiceCrew	ServiceStateChart	working	23.52988283	3270.653713	8.646045833	63.46617972	7.529882828	47.1%	77.43%
4	ServiceCrew	ServiceStateChart	working	23.0507114	3204.048885	8.096988056	60.28525222	7.050711405	44.1%	75.85%
5	ServiceCrew	ServiceStateChart	working	25.03498244	3529.932524	9.333142222	55.24262306	9.034982437	56.5%	83.57%
6	ServiceCrew	ServiceStateChart	working	26.14551761	3581.935913	8.918445556	76.02973639	10.14551761	63.4%	84.80%
7	ServiceCrew	ServiceStateChart	working	23.87830396	3319.08425	7.530629444	79.90298917	7.878303959	49.2%	78.58%
8	ServiceCrew	ServiceStateChart	working	24.3980234	3415.723276	8.229253056	69.53519667	8.398023401	52.5%	80.86%
9	ServiceCrew	ServiceStateChart	working	24.9350028	3465.965389	8.002635	75.44596139	8.9350028	55.8%	82.05%
10	ServiceCrew	ServiceStateChart	working	24.25577172	3468.575357	4.197560556	68.95689139	8.255771725	51.6%	82.12%

Original Assignment Policy: Rig Waiting Time

Run	Agent Type	Statechart	State	Max Hours
1	DrillingRig	DrillingRigStart	WaitingForCrew	0.017291667
1	DrillingRig	DrillingRigStart	WaitingForCrew1	0.017773889
1	DrillingRig	DrillingRigStart	WaitingForCrew2	0.018100556
2	DrillingRig	DrillingRigStart	WaitingForCrew	0.019241389
2	DrillingRig	DrillingRigStart	WaitingForCrew1	0.019551389
2	DrillingRig	DrillingRigStart	WaitingForCrew2	0.019151667
3	DrillingRig	DrillingRigStart	WaitingForCrew	0.019095556
3	DrillingRig	DrillingRigStart	WaitingForCrew1	0.018990833
3	DrillingRig	DrillingRigStart	WaitingForCrew2	0.018999444
4	DrillingRig	DrillingRigStart	WaitingForCrew	0.018214167
4	DrillingRig	DrillingRigStart	WaitingForCrew1	0.017809722
4	DrillingRig	DrillingRigStart	WaitingForCrew2	0.019133611
5	DrillingRig	DrillingRigStart	WaitingForCrew	0.018699444
5	DrillingRig	DrillingRigStart	WaitingForCrew1	0.018051111
5	DrillingRig	DrillingRigStart	WaitingForCrew2	0.018975278
6	DrillingRig	DrillingRigStart	WaitingForCrew	0.018467778
6	DrillingRig	DrillingRigStart	WaitingForCrew1	0.0192425
6	DrillingRig	DrillingRigStart	WaitingForCrew2	5.465555278
7	DrillingRig	DrillingRigStart	WaitingForCrew	0.019616111
7	DrillingRig	DrillingRigStart	WaitingForCrew1	0.019109444
7	DrillingRig	DrillingRigStart	WaitingForCrew2	0.019218611
8	DrillingRig	DrillingRigStart	WaitingForCrew	0.018405556
8	DrillingRig	DrillingRigStart	WaitingForCrew1	0.018715556
8	DrillingRig	DrillingRigStart	WaitingForCrew2	0.018124444
9	DrillingRig	DrillingRigStart	WaitingForCrew	0.018349722
9	DrillingRig	DrillingRigStart	WaitingForCrew1	0.019210278
9	DrillingRig	DrillingRigStart	WaitingForCrew2	0.01846
10	DrillingRig	DrillingRigStart	WaitingForCrew	0.018818056
10	DrillingRig	DrillingRigStart	WaitingForCrew1	0.018914444
10	DrillingRig	DrillingRigStart	WaitingForCrew2	0.019641944

Note:

- WaitingForCrew1: Waiting for service crew to perform surface treatment
- WaitingForCrew2: Waiting for service crew to perform intermediate treatment
- WaitinForCrew3: Waiting for service crew to perform production treatment

Original Assignment Policy: Section Drilling Simulated Durations

Run	Agent type	Statechart	State	Mean Days	Total Days	Min Days	Max Days
1	DrillingRig	DrillingRigStart	IntermediateDrilling	9.548483276	486.9726471	6.316271956	16.19896359
1	DrillingRig	DrillingRigStart	ProductionDrilling	11.12109021	567.1756007	6.179757558	27.4004306
1	DrillingRig	DrillingRigStart	SurfaceDrilling	13.82767033	663.7281756	5.0972425	24.59610993
2	DrillingRig	DrillingRigStart	IntermediateDrilling	9.461370847	463.6071715	1.110282419	15.56658941
2	DrillingRig	DrillingRigStart	ProductionDrilling	10.42696879	500.4945021	1.298823866	25.78960539
2	DrillingRig	DrillingRigStart	SurfaceDrilling	15.29781607	764.8908037	4.093660949	26.00109321
3	DrillingRig	DrillingRigStart	IntermediateDrilling	9.803382654	460.7589847	6.135684271	17.23336066
3	DrillingRig	DrillingRigStart	ProductionDrilling	10.68349706	512.8078588	0.018701505	17.65786823
3	DrillingRig	DrillingRigStart	SurfaceDrilling	15.70114285	769.3559997	5.140215347	26.35227771
4	DrillingRig	DrillingRigStart	IntermediateDrilling	9.38064344	450.2708851	6.383916551	15.97595715
4	DrillingRig	DrillingRigStart	ProductionDrilling	11.47745917	539.4405811	5.963960544	21.96384741
4	DrillingRig	DrillingRigStart	SurfaceDrilling	15.44801049	756.9525141	1.416428125	26.16952105
5	DrillingRig	DrillingRigStart	IntermediateDrilling	9.877653386	474.1273625	6.088157975	15.97270095
5	DrillingRig	DrillingRigStart	ProductionDrilling	10.82030981	519.3748708	1.562745428	20.15322948
5	DrillingRig	DrillingRigStart	SurfaceDrilling	14.84594878	727.4514904	0.74296772	26.53141554
6	DrillingRig	DrillingRigStart	IntermediateDrilling	9.149003843	430.0031806	1.679814433	15.27028861
6	DrillingRig	DrillingRigStart	ProductionDrilling	12.44476349	597.3486474	6.11098544	23.26792986
6	DrillingRig	DrillingRigStart	SurfaceDrilling	14.78066566	694.691286	5.233406215	27.32483512
7	DrillingRig	DrillingRigStart	IntermediateDrilling	9.682486129	455.0768481	3.900928542	14.63705512
7	DrillingRig	DrillingRigStart	ProductionDrilling	11.76973275	553.1774391	6.125412523	21.08493278
7	DrillingRig	DrillingRigStart	SurfaceDrilling	14.46771969	723.3859844	5.237108472	23.62179581
8	DrillingRig	DrillingRigStart	IntermediateDrilling	9.823374847	471.5219927	6.4011775	16.81643612
8	DrillingRig	DrillingRigStart	ProductionDrilling	11.64024963	570.3722317	6.27888088	27.32432017
8	DrillingRig	DrillingRigStart	SurfaceDrilling	14.26506544	684.7231411	5.279200475	27.63484716
9	DrillingRig	DrillingRigStart	IntermediateDrilling	9.098209399	436.7140512	1.399828935	14.67018441
9	DrillingRig	DrillingRigStart	ProductionDrilling	12.76708332	625.5870828	6.258737836	25.1888247
9	DrillingRig	DrillingRigStart	SurfaceDrilling	13.87959651	666.2206324	1.205681262	25.98583233
10	DrillingRig	DrillingRigStart	IntermediateDrilling	10.01489135	490.7296762	5.856670579	14.71784689
10	DrillingRig	DrillingRigStart	ProductionDrilling	11.89893334	583.0477336	1.847037743	28.32460459
10	DrillingRig	DrillingRigStart	SurfaceDrilling	13.6733671	656.3216209	5.218982396	22.72478314

Original Assignment Policy: Section Treatment Simulated Durations

Run	Agent type	Statechart	State	Mean Hours	Total Hours	Min Hours	Max Hours
1	DrillingRig	DrillingRigStart	Treatment1	18.06753441	867.2416517	8.087208889	40.91122361
1	DrillingRig	DrillingRigStart	Treatment2	25.40819476	1270.409738	11.014265	56.71318722
1	DrillingRig	DrillingRigStart	Treatment3	28.25731164	1356.350959	14.03884306	54.10846528
2	DrillingRig	DrillingRigStart	Treatment1	21.73131871	1064.834617	9.635542222	57.45687861
2	DrillingRig	DrillingRigStart	Treatment2	22.61883474	1063.085233	11.12876472	54.66533472
2	DrillingRig	DrillingRigStart	Treatment3	27.6674366	1272.702084	12.12903111	67.27320472
3	DrillingRig	DrillingRigStart	Treatment1	18.11001185	851.1705569	8.646045833	53.04521833
3	DrillingRig	DrillingRigStart	Treatment2	25.66392985	1206.204703	11.07324889	57.61029333
3	DrillingRig	DrillingRigStart	Treatment3	26.96174341	1213.278453	12.11746778	63.46617972
4	DrillingRig	DrillingRigStart	Treatment1	16.44168488	772.7591892	8.096988056	42.17218306
4	DrillingRig	DrillingRigStart	Treatment2	28.11519181	1321.414015	11.20713278	55.07377139
4	DrillingRig	DrillingRigStart	Treatment3	24.66390402	1109.875681	12.04603	60.28525222
5	DrillingRig	DrillingRigStart	Treatment1	20.76703883	955.2837864	9.535983889	46.18247306
5	DrillingRig	DrillingRigStart	Treatment2	25.46846018	1222.486089	9.333142222	49.70985167
5	DrillingRig	DrillingRigStart	Treatment3	28.76941806	1352.162649	12.65064333	55.24262306
6	DrillingRig	DrillingRigStart	Treatment1	21.43772451	943.2598783	8.918445556	42.26816778
6	DrillingRig	DrillingRigStart	Treatment2	26.36149597	1212.628815	11.07420694	55.55607528
6	DrillingRig	DrillingRigStart	Treatment3	30.34143021	1426.04722	12.60890306	76.02973639
7	DrillingRig	DrillingRigStart	Treatment1	17.97482828	826.8421008	7.530629444	45.81221694
7	DrillingRig	DrillingRigStart	Treatment2	27.59785028	1269.501113	11.03740056	79.90298917
7	DrillingRig	DrillingRigStart	Treatment3	26.01576674	1222.741037	12.25465972	62.0178425
8	DrillingRig	DrillingRigStart	Treatment1	20.68357635	930.7609356	8.229253056	45.07334917
8	DrillingRig	DrillingRigStart	Treatment2	24.48107048	1150.610313	11.51774611	60.89729722
8	DrillingRig	DrillingRigStart	Treatment3	27.79900058	1334.352028	8.281448056	69.53519667
9	DrillingRig	DrillingRigStart	Treatment1	19.79489727	930.3601717	8.002635	43.77306056
9	DrillingRig	DrillingRigStart	Treatment2	23.83164275	1096.255566	11.30426778	66.72289944
9	DrillingRig	DrillingRigStart	Treatment3	31.29020981	1439.349651	12.53289389	75.44596139
10	DrillingRig	DrillingRigStart	Treatment1	19.29190746	906.7196508	8.540670833	43.30169389
10	DrillingRig	DrillingRigStart	Treatment2	28.16217757	1379.946701	6.847338333	68.27475778
10	DrillingRig	DrillingRigStart	Treatment3	25.14700011	1181.909005	4.197560556	68.95689139

Note:

- Treatment 1: Surface Casing Cementing
- Treatment2: Intermediate Casing Cementing
- Treatment3: Production Casing Cementing

Proposed Assignment Policy: Crew Working Hours, Mean Deviation and Utilization

Run	Agent type	Statechart	State	Mean Hours	Total Hours	Min Hours	Max Hours	Mean Hours / Dev	Dev %	Utilization %
1	BatchOperator	BoStateChart	working	20.68014	3246.78198	0.1885114	68.293464	4.68013997	29.3%	76.87%
1	EquipmentOperator	eoStateChart	working	20.2810622	3285.53208	0.1551781	68.293464	4.281062239	26.8%	77.78%
1	Helper	helperStateChart	working	20.2822968	3285.73208	0.1885114	68.293464	4.282296807	26.8%	77.79%
1	Supervisor	supervisorStateChart	working	20.6803523	3246.81531	0.1885114	68.293464	4.680352284	29.3%	76.87%
2	BatchOperator	BoStateChart	working	19.9031038	3284.01213	0.0338856	60.936492	3.90310379	24.4%	77.75%
2	EquipmentOperator	eoStateChart	working	19.398301	3317.10948	0.0338856	60.936492	3.398301043	21.2%	78.53%
2	Helper	helperStateChart	working	19.4004453	3317.47615	0.0672189	60.936492	3.400445292	21.3%	78.54%
2	Supervisor	supervisorStateChart	working	19.9031038	3284.01213	0.0338856	60.936492	3.90310379	24.4%	77.75%
3	BatchOperator	BoStateChart	working	20.2270993	3195.88169	0.5070706	72.946643	4.227099283	26.4%	75.66%
3	EquipmentOperator	eoStateChart	working	19.8517176	3235.82997	0.5070706	72.946643	3.851717589	24.1%	76.61%
3	Helper	helperStateChart	working	19.8533536	3236.09663	0.5070706	72.946643	3.85335358	24.1%	76.61%
3	Supervisor	supervisorStateChart	working	20.2270993	3195.88169	0.5070706	72.946643	4.227099283	26.4%	75.66%
4	BatchOperator	BoStateChart	working	19.370842	3060.59304	0.8914572	56.704269	3.370841997	21.1%	72.46%
4	EquipmentOperator	eoStateChart	working	18.9522569	3108.17014	0.9247906	56.704269	2.952256922	18.5%	73.58%
4	Helper	helperStateChart	working	18.9532732	3108.3368	0.9247906	56.704269	2.953273183	18.5%	73.59%
4	Supervisor	supervisorStateChart	working	19.3712639	3060.6597	0.8914572	56.704269	3.371263938	21.1%	72.46%
5	BatchOperator	BoStateChart	working	20.7145461	3521.47284	0.0237511	60.075625	4.714546137	29.5%	83.37%
5	EquipmentOperator	eoStateChart	working	20.3212392	3576.5381	0.5905706	60.075625	4.321239206	27.0%	84.67%
5	Helper	helperStateChart	working	20.3227544	3576.80477	0.6239039	60.075625	4.322754358	27.0%	84.68%
5	Supervisor	supervisorStateChart	working	20.7443501	3526.53951	0.0237511	60.075625	4.744350059	29.7%	83.49%
6	BatchOperator	BoStateChart	working	18.977697	3264.16389	0.1037675	48.165159	2.977697024	18.6%	77.28%
6	EquipmentOperator	eoStateChart	working	18.6674043	3304.13055	0.1037675	48.165159	2.667404264	16.7%	78.22%
6	Helper	helperStateChart	working	18.6706058	3304.69722	0.1371008	48.165159	2.670605771	16.7%	78.24%
6	Supervisor	supervisorStateChart	working	18.977697	3264.16389	0.1037675	48.165159	2.977697024	18.6%	77.28%
7	BatchOperator	BoStateChart	working	20.1698817	3388.54013	0.2303639	70.794296	4.1698817	26.1%	80.22%
7	EquipmentOperator	eoStateChart	working	19.8179583	3428.50679	0.1970306	70.794296	3.817958337	23.9%	81.17%
7	Helper	helperStateChart	working	19.8198851	3428.84013	0.2303639	70.794296	3.819885119	23.9%	81.18%

7	Supervisor	supervisorStateChart	working	20.1700801	3388.57346	0.2303639	70.794296	4.170080112	26.1%	80.22%
8	BatchOperator	BoStateChart	working	20.0040303	3320.66903	0.7153639	69.41581	4.004030321	25.0%	78.61%
8	EquipmentOperator	eoStateChart	working	19.653815	3360.80237	0.7486972	69.41581	3.65381501	22.8%	79.56%
8	Helper	helperStateChart	working	19.6555694	3361.10237	0.7486972	69.41581	3.655569396	22.8%	79.57%
8	Supervisor	supervisorStateChart	working	20.0042311	3320.70237	0.7153639	69.41581	4.004231124	25.0%	78.62%
9	BatchOperator	BoStateChart	working	20.4385722	3270.17155	0.2239664	56.323092	4.43857216	27.7%	77.42%
9	EquipmentOperator	eoStateChart	working	20.0612417	3310.10488	0.2239664	56.323092	4.06124169	25.4%	78.36%
9	Helper	helperStateChart	working	20.0628579	3310.37155	0.2572997	56.323092	4.062857852	25.4%	78.37%
9	Supervisor	supervisorStateChart	working	20.4389888	3270.23821	0.2239664	56.323092	4.438988826	27.7%	77.42%
10	BatchOperator	BoStateChart	working	20.3609391	3257.75025	1.1314503	56.133946	4.360939054	27.3%	77.12%
10	EquipmentOperator	eoStateChart	working	19.9859611	3297.68358	1.1314503	56.133946	3.985961103	24.9%	78.07%
10	Helper	helperStateChart	working	19.9875773	3297.95025	1.1314503	56.133946	3.987577264	24.9%	78.08%
10	Supervisor	supervisorStateChart	working	20.3611474	3257.78358	1.1314503	56.133946	4.361147387	27.3%	77.13%

Proposed Assignment Policy: Rig Waiting Time

Run	Agent type	Statechart	State	Max Hours
1	DrillingRig	DrillingRigStart	WaitingForCrew	3.5
1	DrillingRig	DrillingRigStart	WaitingForCrew1	0.0193461
1	DrillingRig	DrillingRigStart	WaitingForCrew2	3.5
2	DrillingRig	DrillingRigStart	WaitingForCrew	0.0190575
2	DrillingRig	DrillingRigStart	WaitingForCrew1	0.0186417
2	DrillingRig	DrillingRigStart	WaitingForCrew2	0.3
3	DrillingRig	DrillingRigStart	WaitingForCrew	0.0192189
3	DrillingRig	DrillingRigStart	WaitingForCrew1	0.0197392
3	DrillingRig	DrillingRigStart	WaitingForCrew2	0.0187208
4	DrillingRig	DrillingRigStart	WaitingForCrew	0.0196103
4	DrillingRig	DrillingRigStart	WaitingForCrew1	5.8666667
4	DrillingRig	DrillingRigStart	WaitingForCrew2	0.0182506
5	DrillingRig	DrillingRigStart	WaitingForCrew	6.7
5	DrillingRig	DrillingRigStart	WaitingForCrew1	0.0184306
5	DrillingRig	DrillingRigStart	WaitingForCrew2	2.3162969
6	DrillingRig	DrillingRigStart	WaitingForCrew	4.3333333
6	DrillingRig	DrillingRigStart	WaitingForCrew1	0.0188486
6	DrillingRig	DrillingRigStart	WaitingForCrew2	0.0187986
7	DrillingRig	DrillingRigStart	WaitingForCrew	0.0666667
7	DrillingRig	DrillingRigStart	WaitingForCrew1	0.0195303
7	DrillingRig	DrillingRigStart	WaitingForCrew2	0.0185489
8	DrillingRig	DrillingRigStart	WaitingForCrew	0.5666667
8	DrillingRig	DrillingRigStart	WaitingForCrew1	0.0188894
8	DrillingRig	DrillingRigStart	WaitingForCrew2	0.0191494
9	DrillingRig	DrillingRigStart	WaitingForCrew	0.0196656
9	DrillingRig	DrillingRigStart	WaitingForCrew1	0.0193175
9	DrillingRig	DrillingRigStart	WaitingForCrew2	0.0198172
10	DrillingRig	DrillingRigStart	WaitingForCrew	5.1
10	DrillingRig	DrillingRigStart	WaitingForCrew1	0.0178989
10	DrillingRig	DrillingRigStart	WaitingForCrew2	0.01867

Note:

- WaitingForCrew1: Waiting for service crew to perform surface treatment
- WaitingForCrew2: Waiting for service crew to perform intermediate treatment
- WaitinForCrew3: Waiting for service crew to perform production treatment

Proposed Assignment Policy: Section Drilling Simulated Durations

Run	Agent type	Statechart	State	Mean Days	Total Days	Min Days	Max Days
1	DrillingRig	DrillingRigStart	IntermediateDrilling	9.1265325	456.32663	4.865427	13.54387
1	DrillingRig	DrillingRigStart	ProductionDrilling	11.204524	560.22618	6.087726	21.98553
1	DrillingRig	DrillingRigStart	SurfaceDrilling	14.836517	712.1528	4.993259	23.31832
2	DrillingRig	DrillingRigStart	IntermediateDrilling	9.0007309	423.03435	6.100501	15.39627
2	DrillingRig	DrillingRigStart	ProductionDrilling	11.486953	562.86072	6.042348	24.65971
2	DrillingRig	DrillingRigStart	SurfaceDrilling	14.568214	742.97892	0.29653	25.72896
3	DrillingRig	DrillingRigStart	IntermediateDrilling	9.9557636	467.92089	6.59265	15.42353
3	DrillingRig	DrillingRigStart	ProductionDrilling	11.411053	547.73053	6.278039	24.0517
3	DrillingRig	DrillingRigStart	SurfaceDrilling	14.998401	719.92323	1.015748	26.77452
4	DrillingRig	DrillingRigStart	IntermediateDrilling	9.5866016	440.98367	6.133794	15.17397
4	DrillingRig	DrillingRigStart	ProductionDrilling	11.712658	562.20758	0.885913	25.23329
4	DrillingRig	DrillingRigStart	SurfaceDrilling	15.141597	741.93827	2.913906	29.99303
5	DrillingRig	DrillingRigStart	IntermediateDrilling	9.2538601	453.43915	6.249829	14.45003
5	DrillingRig	DrillingRigStart	ProductionDrilling	10.67054	512.18592	0.8658	22.43491
5	DrillingRig	DrillingRigStart	SurfaceDrilling	15.142287	757.11436	5.062644	24.86163
6	DrillingRig	DrillingRigStart	IntermediateDrilling	9.2846238	445.66194	5.954322	14.68798
6	DrillingRig	DrillingRigStart	ProductionDrilling	11.23882	550.70218	0.619943	26.69486
6	DrillingRig	DrillingRigStart	SurfaceDrilling	14.766982	738.34912	2.773468	26.97803
7	DrillingRig	DrillingRigStart	IntermediateDrilling	9.5569265	487.40325	4.039304	16.23235
7	DrillingRig	DrillingRigStart	ProductionDrilling	11.503671	575.18353	2.785826	28.90142
7	DrillingRig	DrillingRigStart	SurfaceDrilling	12.818718	653.75459	0.61536	23.51606
8	DrillingRig	DrillingRigStart	IntermediateDrilling	9.394571	450.93941	6.041216	14.75949
8	DrillingRig	DrillingRigStart	ProductionDrilling	11.4169	536.59432	6.12732	25.71987
8	DrillingRig	DrillingRigStart	SurfaceDrilling	14.530977	741.07983	0.837975	25.23763
9	DrillingRig	DrillingRigStart	IntermediateDrilling	9.6402977	482.01489	0.989019	15.12784
9	DrillingRig	DrillingRigStart	ProductionDrilling	11.832193	544.28089	6.580601	21.09807
9	DrillingRig	DrillingRigStart	SurfaceDrilling	14.163561	708.17805	5.267725	28.15884
10	DrillingRig	DrillingRigStart	IntermediateDrilling	10.038063	491.86508	1.700449	15.15365
10	DrillingRig	DrillingRigStart	ProductionDrilling	11.677863	548.85957	6.465389	27.96064
10	DrillingRig	DrillingRigStart	SurfaceDrilling	14.752634	708.12644	4.814448	28.89737

Proposed Assignment Policy: Section Treatment Simulated Durations

Run	Agent type	Statechart	State	Mean Hours	Total Hours	Min Hours	Max Hours
1	DrillingRig	DrillingRigStart	Treatment1	16.0737689	739.393372	8.0912444	33.398059
1	DrillingRig	DrillingRigStart	Treatment2	23.4936497	1151.18883	11.35735	52.879491
1	DrillingRig	DrillingRigStart	Treatment3	28.5820736	1371.93953	12.383543	71.220722
2	DrillingRig	DrillingRigStart	Treatment1	17.1631334	806.667271	8.2597903	42.463703
2	DrillingRig	DrillingRigStart	Treatment2	26.4366193	1242.52111	11.330062	77.269826
2	DrillingRig	DrillingRigStart	Treatment3	26.8962204	1264.12236	12.185034	51.569067
3	DrillingRig	DrillingRigStart	Treatment1	17.3403013	762.973255	8.21099	37.537919
3	DrillingRig	DrillingRigStart	Treatment2	24.9397069	1172.16623	11.91601	57.812392
3	DrillingRig	DrillingRigStart	Treatment3	26.4773921	1270.91482	12.024092	72.946643
4	DrillingRig	DrillingRigStart	Treatment1	17.2881344	795.254183	8.1698925	44.648446
4	DrillingRig	DrillingRigStart	Treatment2	22.4933082	1034.69218	11.018596	67.192606
4	DrillingRig	DrillingRigStart	Treatment3	27.8179452	1279.62548	12.592779	62.405334
5	DrillingRig	DrillingRigStart	Treatment1	20.1523883	967.314638	8.2970892	44.068886
5	DrillingRig	DrillingRigStart	Treatment2	25.0155317	1200.74552	11.184345	60.075625
5	DrillingRig	DrillingRigStart	Treatment3	30.5398123	1404.83137	12.236985	67.303779
6	DrillingRig	DrillingRigStart	Treatment1	18.9135691	907.851318	8.0560072	44.832448
6	DrillingRig	DrillingRigStart	Treatment2	22.6114611	1085.35013	11.490654	62.952073
6	DrillingRig	DrillingRigStart	Treatment3	27.6491559	1271.86117	12.079198	50.884551
7	DrillingRig	DrillingRigStart	Treatment1	17.1853609	824.897324	8.56067	55.712305
7	DrillingRig	DrillingRigStart	Treatment2	23.9554681	1197.77341	11.171959	57.888716
7	DrillingRig	DrillingRigStart	Treatment3	28.6576739	1375.56835	13.000415	70.794296
8	DrillingRig	DrillingRigStart	Treatment1	18.5190751	870.39653	8.3702572	52.145268
8	DrillingRig	DrillingRigStart	Treatment2	23.8707175	1145.79444	11.270768	69.41581
8	DrillingRig	DrillingRigStart	Treatment3	28.2341892	1327.00689	12.145872	74.315732
9	DrillingRig	DrillingRigStart	Treatment1	19.813723	970.872426	8.08732	56.074023
9	DrillingRig	DrillingRigStart	Treatment2	23.5707301	1107.82432	11.024321	48.608854
9	DrillingRig	DrillingRigStart	Treatment3	26.5264484	1220.21663	12.613823	56.323092
10	DrillingRig	DrillingRigStart	Treatment1	18.5642968	891.086245	8.145955	41.882811
10	DrillingRig	DrillingRigStart	Treatment2	25.9541989	1219.84735	11.051145	56.133946
10	DrillingRig	DrillingRigStart	Treatment3	26.6844129	1174.11417	1.1314503	74.23148