# Master's degree thesis

**LOG953 Petroleum Logistics**

**Risk Management Perspective on Employee Scheduling for Maintenance of Automated Safety Systems for Remotely Located Oil & Gas Facilities**

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It is my utmost pleasure to dedicate this work to my dear mother, father, and family, who granted me the gift of their unwavering belief in my abilities to accomplish this goal; thank you for your support and patience.

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**Ali Akbar**

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# Abstract

Information technology tools has reshaped modern business activities which has proved to be one of key facets for smooth running of businesses including oil and gas industry. The continuous support from humans have produced growth in all sectors of life which has created demand for chemical, food, energy, and commodities. In addition, the oil and gas industry faces dramatic challenges such as rise in demand, inconsistent prices, and lack of skilled workers in the field, which has derived the industry for exploration and production of oil into less developed and remote locations of the world.

The risk is integral part of oil and gas facilities and it is operated in hazardous process. While these processes pose high threat to the environment, personnel and facilities. The situation gets more complex given that the exploration and production processes are nowadays shifting into remote, offshore and Arctic locations and these locations require proper and timely maintenance by skilled workers.

In the thesis, a mixed integer linear programming model is developed to find the best employee schedules and maintenance decisions for remotely located facilities. The model explores tradeoffs between capital expenditures (CAPEX) and operational expenditures (OPEX) and potential consequences of incidents in the form of risk costs. The objective is minimization of the automated safety system's life cycle cost expressed as the present value of the cash flows of expenses.

The results of the model run allow to make conclusions and reveal the patterns for various issues relevant to maintenance decisions and workforce organization.

These results are relevant to the engineering departments developing and maintaining the automated safety systems.

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# List of Abbreviations

| | |
|---|---|
| ALARP | As Low As Reasonably Practicable |
| BP | British Petroleum |
| CBM | Condition-based Maintenance |
| CCF | Common Cause Failure |
| DC | Diagnostic Coverage |
| DD | Dangerous Detected |
| DU | Dangerous Undetected |
| E & P | Exploration and Production |
| ESD | Emergency Shutdown System |
| EUC | Equipment Under Control |
| F & G | Fire and Gas detection system |
| FC | Final Control element |
| FT | Fault Tolerance |
| FTA | Fault Tree Analysis |
| GA | Genetic Algorithm |
| HSE | Health and Safety Executive |
| IEC | International Electro technical Commission |
| ISA | The Instrumentation, Systems and Automation Society |
| IT | Information technology |
| KooN | K-out-of-N |
| LCC | Lifecycle cost |
| MA | Markov Analysis |
| MATLAB/Matlab | MATrix LABoratory (programming language) |

| | |
|---|---|
| MooN | M-out-of-N redundant arrangement |
| MRT | Mean Repair Time |
| O&G | Oil and Gas |
| PFD | Probability of Failure on Demand |
| PDFavg | Average Probability of Failure on Demand |
| PLC | Programmable Logic Controller |
| RAMS | Reliability, Availability Maintainability and Safety |
| RBD | Reliability Block Diagram |
| RCM | Reliability Centered Maintenance |
| RRF | Risk Reduction Factor |
| SDLC | Systems Development Life Cycle |
| SFF | Safe Failure Fraction |
| SIL | Safety Integrity Level |
| SINTEF | The Foundation for Scientific and Industrial Research (in Norwegian) |
| SD | Safe Detected |
| SIS | Safety Instrumented System |
| TBM | Time-based Maintenance |
| TI | Test Interval |

# 1 INTRODUCTION

## 1.1 Background

The operational procedures of oil and gas production are risk oriented and the process is mainly operated in hazardous industrial facilities typically in remote areas. According to Redutskiy (2017), such facilities are always at high risk and ignorance could forward to major losses that might be economical, personal, and may cause significant damage to the environment. In addition, oil and gas industry risks are associated with many factors which are related to a volatile commodity as well as to global socioeconomic, increased health issues, personal safety, and environmental which are results from past to recent accidents that portrait the negative image of the industry (Bigliani, 2013).

Modern business, especially in oil and gas industry, relies on information technology tools which has reshaped the industry from past practices to recent developments to protect and smooth running of day to day operations. The efficiency of dangerous and expensive operations mainly uses information technology applications and tools in order to reduce the chances of damages (Redutskiy, 2017b). While these services are beneficial for the industry, however, the human factor is also considered as an effective hand for maintaining and operating IT tools. The massive amount of investment has proved the need for technology in oil and gas industry for safer and risk reduced and efficient process. In addition, artificial intelligence AI is already changing the business around the world and these technology innovations are already employed in various sectors including oil and gas industry.

Risk management in today's world not only focus on human and computers, also for optimal risk management. This could lead to better and efficient control of risk factors associated with oil and gas industry. However, information technology developments have been significantly effective in all fields along with oil and gas and witnessed these developments in the form of algorithms, equipment's and now drones to monitor the offshore oil and gas industry (Drage-Arianson, 2018).

The continuous developments humans have produced in social and technology industries has created demand for chemical, energy, food, and commodities. This has increased the size and complexity of processing industries and stepped into new hazards and increased risk (Khan, Rathnayaka and Ahmed, 2015). In design approach, safety measures are combined at the end of the process, which enables add-on control measures. Thus, it requires continuous consideration of staffing, training, and maintenance throughout the operational process of the plant (Khan and Amyotte, 2002). Oil industries could address the risks associated with staff, workforce salaries, equipment availability, compliance issues, safety, environmental concerns. However, oil and gas industry lack of trained staff resources and it is becoming worse day by day and many companies are facing a shortfall in the hiring of skilled workers. According to (ILO, 2016) report the world's oil and gas industry is facing talent crises among united states alone might lose up to 80% of skilled workers who will retire in next five years. In addition, the survey highlighted key areas that lack in skilled workers such as, subsea specialists, health and safety specialists, operating engineers, project managers, operating engineers. Most of the companies around the world have declared the shortage of skilled workers and mentioned the problems in recruiting qualified and arctic experienced staff.

The staff sizing is associated with the size of the company. A large size company might have a greater number of workers in all fields as related to medium and small size company. Common issues that have a prominent effect on construction projects especially in offshore environment are: community impacts, safety and environmental standards, site staffing plan, contracting strategies, contract type, potential synergies with an existing project, geography, key execution principles, and scope of work (Wood, Lamberson and Mokhatab, 2011).

## 1.2 Safety Issues of Oil & Gas Facilities

The risk is an integral part of offshore installations and cannot be ignored and it has a significant effect on finances, environment and personal safety. Risk related issues may be appearing at the time of developing and installing an offshore facility, such accidents are reported in various documents such as personnel fatalities, facility and operational failure, and environmental issues. The reasons could be different at levels but the scale, causes, and severity of such undesirable incidents are variable in offshore facilities. Among these incidents some are small, and few are harsh and unacceptable.

High-reliability production industries put significant amount consideration in managing the safety of personals and infrastructure of the industry and such industries as oil and gas where potential hazards are present (Flin et al., 2000). Table 1 summarize few accidents happened in the past which caused human deaths.

*Table 1: Accidents in past with fatalities Source: (Christou and Konstantinidou, 2012)*

| **Description of Accident** | **Location** | **Year** | **Fatalities** |
|---|---|---|---|
| Alexander L. Kielland capsize | North Sea | 1980 | 123 |
| Piper Alpha Explosion | North Sea | 1988 | 167 |
| Macondo Blowout | Gulf of Mexico | 2010 | 11 |

The risk management chain comprises of prevention, early warnings, mitigation, preparedness, emergency response, and aftermath recovery. For every failure the recommendations are directed to operators and regulators to maintain the international standard and practices for remote facilities.

## 1.3 Remote Locations

A significant part of oil and gas resources in the world are now being developed in unconventional and remote or Arctic environments. For example, in Russia most of the hydrocarbon reserves are found and produced in the remote areas in the Arctic region in Western Siberia and also, in Eastern Siberia. The Bovanenkovo gas field is one of the largest gas fields of Russia, located on the central Yamal Peninsula in northwest Siberia (YNAO) (708200 N, 68800E), another oil field is located on the Varandei peninsula (688660 N, 58833E) in NAO is called Toravei oil field (Timo Kumpula, 2011). A similar issue is relevant for Norway, i.e. the development of the Arctic region because, Norway has the third largest share in Arctic oil and gas resources after Russia and the USA. The estimated distribution of Arctic oil and gas resources among five artic counties are as follows, Russia (216 billion barrels of oil equivalent) 52%, USA (83 bboe) 20%, Norway (47 bboe) 12%, Denmark/Greenland (44 bboe) 11% and Canada (22 bboe) 5% (Keil, 2014). Location of gas fields are based on remote sites and operated in different industrial conditions comparatively to other fields closure to populated areas.

## 1.4 Automated Systems for Industrial Processes. Automated Safety Systems Life Cycle Approach

The oil and gas industrial facilities operate hazardous processes. These processes pose threat to the environment, personnel and facilities. The impurified oil and gas is extracted from the reservoir through the wellheads for processing, where oil and gas is separated and transported to storage facilities, refineries and final customers. The hydrocarbons are very dangerous, where any incident may lead to greater social and economic losses. The contribution of proper design and technology plays a vital role to avoid such dangers and make sure for safety on such hazardous facilities. (Redutskiy, 2017).

***Utility Systems Planning:*** The problems of planning the information and communication networks, at the plant the process control system is used to control equipment and monitor data. This system processes data through censors and control the valves and switches etc. The process control system consists of the following major elements (Devold, 2013).

***Field Instrumentation:*** sensors and switches that check the conditions such as temperature and pressure or flow which are connected with electrical cables or communication bus systems called fieldbus.

***Control Devices:*** Such as valves actuators, electrical switchgear and drives connected to fieldbus.

***Controllers:*** Controllers run algorithms for decision-making and generate events; alarms depend on these changing and situations.

***Servers:*** Servers process and store data of engineering changes.

***Clients:*** such as operator and engineering stations are provided human interfaces to control the system.

The remote communication system can be connected to facilities to support operations and connection to such environments. (Devold, 2013).

***Instrumentation (and communication) Network Design and Maintenance Planning***

**Problem setting:** we are planning a facility with its industrial instrumentation network. The network consists of components, performing different function. Each of those components is chosen by the company out of a list of analogous alternatives of devices the components are organized into a network with the use of one or several options of industrial data network solutions.

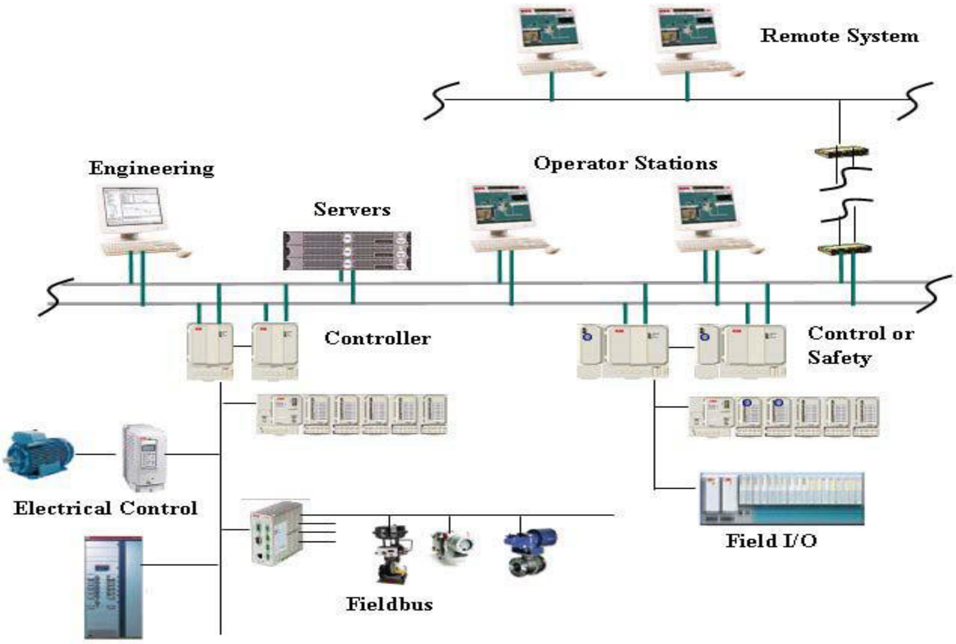


*Figure 1: Typical IT based process control system Source: (Devold, 2013)*

The planning problem on a strategic level is to establish the facility and determine the facility control, operations, maintenance, overhauls, etc. This is done in the form of an engineering project. The purpose of this research is to facilitate the planning phase of the course of the industrial project. Figure 2 demonstrates various stage of project. Whereas Figure 3 shows the automated system's control loop and structure of every subsystem.

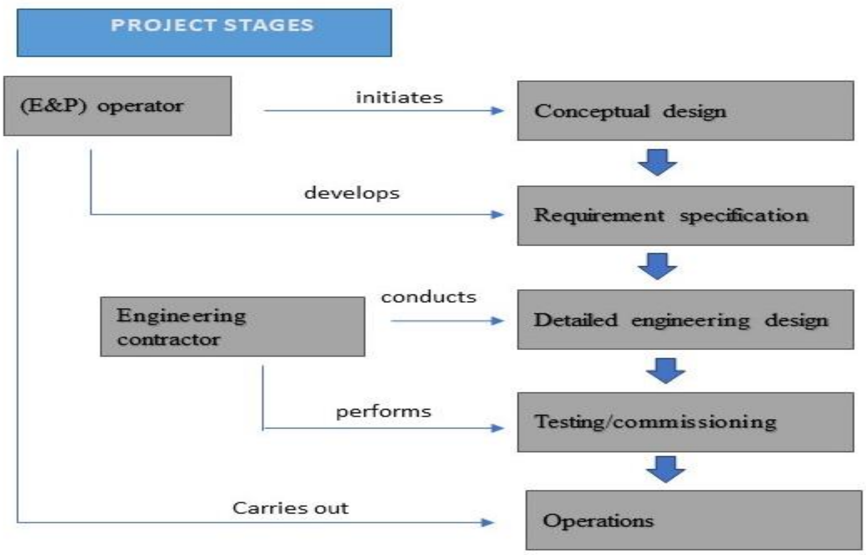


*Figure 2: Project phases and main stakeholders Source: (David Yoset, 2017; Redutskiy, 2017a)*

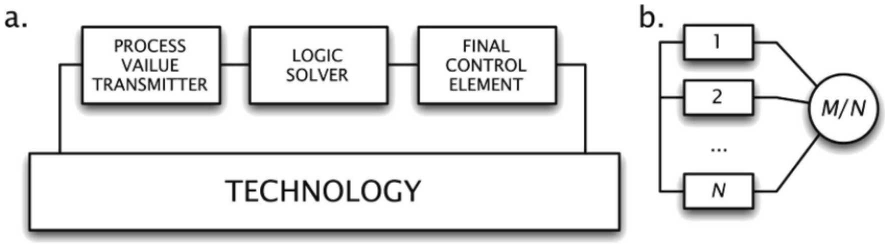


Figure 3: *a) Automated system's control loop b) Structure of every subsystem*

*Source: (Redutskiy, 2017)*

The IT-based solutions in the petroleum industry are carried in the form of engineering projects which consists of required design processes that define the actual and appropriate technology necessities in order to control the overall processes and ensures the operational activities are performed according to Standard Operating Procedures (SOPs). (Devold, 2013). As shown in Figure 1, the IT solutions which include:

- IT system devices i.e. personal computers (PCs) for staff including IT engineers and operators, communication networks, and servers.
- Process automation tools i.e. switches, valves, drives, sensors, and industrial computers such as programmable logic controllers (PLCs).

As shown in Figure 1, IT-based process control solutions include elements such as distributed control systems also known as (process control system), fire and gas detection system, firefighting systems, interlocks system, and emergency shutdown systems (Devold, 2013). Avison & Fitzgerald (2003) argue that the systems which are complex and multifunctional are designed and developed through the system development life cycle (SDLC), which emphasis on methods and techniques which are adopted during developing and implementing any system which is based on computer technology and such that the first step involves a project initiation which includes studying the existing system and preparing feasibility report. The next phase involves identifying the requirements i.e. system requirement specification for the new system and design is carried on the basis of requirements. After the design phase is completed, the testing of the system is initiated once it is tested and proved to be reliable, the next phase involves implementing the system and once the system is implemented, the continuous handling phase involves including operations and maintenance.

Moreover, the following few steps are employed during life SDLC within oil and gas industry. First, the starting of any project is considered as conceptual design of the system, as this stage addresses the selection of appropriate technology according to the purpose and requirement of the project. Process control solutions and IT related options are evaluated in this phase and such options include valves, sensors, controllers, system networking, hardware, and software. The design phase is usually initiated by large firms either national or multinational such as Shell, BP, Statoil, ExxonMobil, Rosneft, PetroChina (Exploration and Production Operators, as shown in Figure 2), etc. due to the fact of huge risk involved and such companies are also referred as Exploration and Production (E&P) operators or operating companies.

While structuring a new facility, most of the operating companies hire a contractor to complete the engineering workload. The selection of a contractor is completed through the bidding process and each of the contractors proposes a conceptual design process. During the bidding process, each of the company must fulfil pre-defined design requirements so that everyone has the equal right to participate. Once the contractor company is chosen, the engineering workload is assigned to the contractor, however, the operating company and contractor must approve an agreement based on 'requirement specification'. This document contains a complete set of requirements that a contractor has to fulfil during the development of the facility.

The requirements specification is one of the key phases of the project lifecycle. As shown in Figure 2, every module has its importance within the oil and gas industry and such that the specification has to cover all the aspects of the system including functional safety requirements. The threat and danger associated with functional safety are due to oil and gas industry high-risk environment, and in case of any mishap, it can lead to unwanted and severe consequences[1]. According to the report by (UK HSE, 2003), the requirement specification is in reference to the safety systems development process and inappropriateness within this phase can lead to harsh incidents. In addition, this report highlighted that the major share of incidents occurred in past due to deficiencies in the requirement specification of the control system which is associated with safety-related operations. Figure 4 demonstrates the incidents occurred due to deficiencies in various phases of the lifecycle.

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[1] Offshore World Trends and Technology for Offshore Oil and Gas Operations. June 2014. Available at: https://vdocuments.site/documents/offshore-561d348b877a4.html (accessed 17th of October 2018).

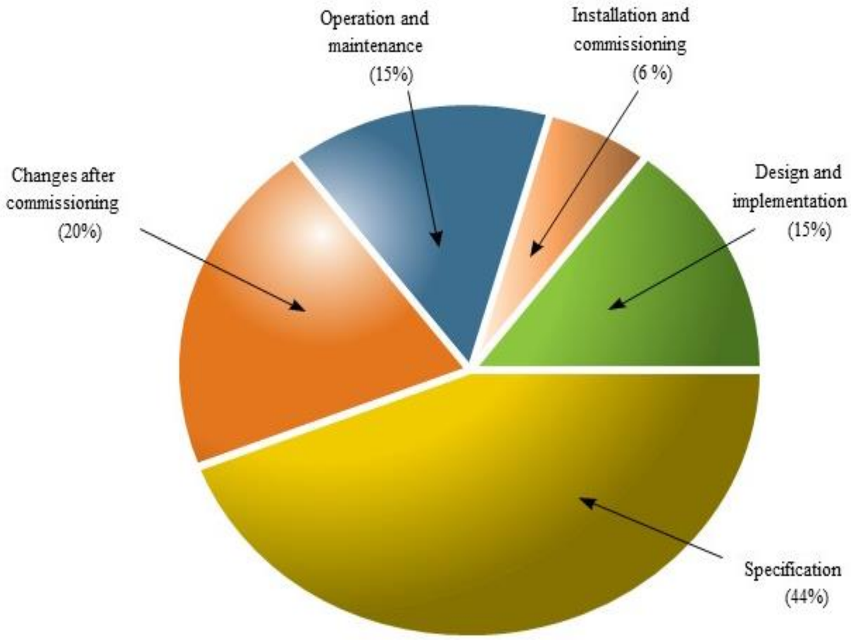


*Figure 4: Primary causes of incidents by phase  Source: (UK HSE, 2003)*

There are two main categories of safety requirements i.e. functional safety and safety integrity. Functional safety is related to the requirements for facility or equipment. For example, facility or equipment is according to industry requirements. While safety integrity refers to the overall performance of the proposed system which is also expressed in the form of numbers from 1 to 4 and known as the safety integrity level (SIL). According to the report by (UK HSE, 2003), these numbers represent the probability of occurrence of the safety system failures. There are various reasons for the failure of automated systems including safety systems such as inconsideration or exclusion of mistakes during the design process, fault-tolerant architecture development, selection of instrumentation with high-reliability indicator.

The design process must be according to the standards established by IEC 61508 and IEC 61511 and requirement specification related to safety requirements are clearly defined in these standards. These standards not only addressed the technical characteristics, but also, procedures, necessary tools, work process to develop, specify, operate, and maintain SIS software and hardware. The IEC 61508 is a type of standard which is generic in SIS design and development. Whereas, IEC 61511 is associated with process industry safety standards which define the safety requirements for SIS (Sintef, 2010; Hauge et al., 2009). Moreover, a clear and careful analysis of safety measures should be conducted for under progress projects in order to define and document SIL requirements.

The safety measures i.e. risk analysis of the technology and processes in oil and gas industry is performed in order to identify potential hazards, the probability of occurrences, consequences, and also indicates the possible protection layers for the projects. This process assists in identifying and specifying the required performance of the systems (McNeil et al., 2015). Whereas, UK HSE (2003) recommends that the critical review of all possible situations should be conducted while designing a safety system. This fact highlights that it is necessary for all safety systems that are operational or under development should be reviewed frequently. In addition, all stakeholders involved in oil and gas projects should be approached and inquired about their perception regards to requirement specification for safety systems. These stakeholders include a) national regulating authorities associated with natural resources; b) E&P operating companies who capitalize the project into developing hydrocarbon, processing, transporting, and distribution facilities; c) engineering contractors who are responsible for developing the facilities, units, IT and process control solutions for the projects. Figure 2 highlights the key stakeholders within the project for oil and gas facilities.

To summarize Figure 2, Exploration and Production operator initiates Conceptual design, and this be done by some project institution or a design operator. Engineering contractor builds the engineering solution and delegated to engineering contractor, also provides service according to the warranty. In this work, the engineering contractor’s perspective is considered (because they provide the service to the remotely located facilities). In addition, the government regulation perspective is implicitly considered, i.e. the designed systems must have the SIL3 level of safety.

The contractor initiates and provides a detailed engineering design in order to fulfil the requirements. In the next step, the commissioning and testing of technological solutions are carried out at the facilities in order to prepare for the operations. The contract specifies the responsibilities of the contractor in which the contractors still needs to provide and design service and maintenance. Once the process is completed, the testing part confirms about the reliability of the system i.e. safe and complies according to set standards; in case of failure, the whole process is carried out again to meet the safety system standards (David Yoset, 2017). Additionally, Redutskiy (2017) argue that the contractors have their own perception and designing context for engineering solutions including safety systems. As stated earlier, the contractors are hired through the bidding process and such that the competitors propose an inexpensive solution for the project which leads to redesigning the project in later stages especially safety system.

The documents related with requirement specifications detail the basis for design especially concerning with the safety requirements in order to develop an automated safety system. Therefore, the subcontractors and vendors should verify the expectations specified in the documents are in accordance with the agreement of the specified products, and any operational, functional, and environmental products which do not meet with the standards should be identified in earlier stages and brought to the attention of operators and engineering contractors (NPI, 2004). The overall purpose of the safety system design is to ensure that the system is reliable and envisioned to the safety functions. The design of safety system is related with the selection of devices among the available choices such as selection of certain instrumentation architectures, additional safety measures decisions, instrumentation system as well planning the maintenance of the facility (Redutskiy, 2017d, 2017c). Markest & Kumar (2001) argue that due to technical limitations, it is impossible to design a maintenance free industrial system. However, this can be obtained by balancing between maintenance expenses and investment into the complexity of safety system through adopting lifecycle recommendations at the time of safety system design under development (Moss, 1985; Markeset and Kumar, 2003).

The safety system installed at oil and gas facility is dependent on its design, operations, and maintenance, and its costs are carried until the entire life cycle of the system. The costs associated with the overall life cycle of the system are: the purchasing (procurement), system operations (i.e. system maintenance and energy consumption), and risk cost; and the maintenance of SIS is performed into two methods i.e.; during the operations on continuous basis, and interval tests (i.e. periodical in the form of tests), which can be done by shutting down the processes for specific period in order to fix the problems that cannot be performed while system is in running condition. In addition, Redutskiy (2017c) argue that the maintenance cost is related with staff, spare parts, maintenance tools, and facility downtime which has a major effect on the production and leads to massive losses. While, the preplanned maintenance helps in reducing the total costs associated with inspection, repairs, system downtime. Preplanned maintenance within oil and gas industry has huge importance due to the concerns of stakeholders who want to generate maximum profit from the operational facility.

Finally, a poorly designed safety system might increase the costs as well unable to prevent the system failure incidents which will have serious consequences such as harm to personnel and demolition of assets and operations. Also, the improper design creates problems such as spurious activation of the safety instrumentation (Chang et al., 2015; Wang et al., 2016). The stress on affected components and production losses within oil and gas industry are caused due to spurious activation of SIS, also it reduces the overall performance of SIS and leads to unwanted incidents due to increase in shutdown and start-ups. Therefore, it is important to design an appropriate system which must be capable to avoid unwanted failures and spurious activation, and also ensures the overall safety of process and operations.

## 1.5 Research Objectives

The objective of this study is to address the employee scheduling problem for remote for remote facilities maintenance from the risk management viewpoint.

In order to follow the set goals, the following steps were taken:

1. To explore the risk management issues in the oil and gas industry, specifically the systems relevant to hazards prevention.
2. To study the importance of design and maintenance of the safety system.
3. To review the area of employee scheduling and identify the issues which are relevant to organizing the maintenance for remotely located facilities.
4. To develop a linear programming model that would incorporate the issues of safety system design, maintenance and workforce scheduling relevant to ensuring the safety of operations in remotely located areas. The model should also be based on lifecycle.
5. To make conclusions upon the results of the model's run, and to provide the suggestions for future research in the area of safety systems design and workforce scheduling for its maintenance for remotely located oil and gas industrial facilities.
6. Staff training and developments will be investigated according to the oil and gas standards.
7. Finally, suggestions and recommendation will be drawn based on findings for improving the safety and staffing in the organization.

## 1.6 Research Methodology

This research is conducted in the field of risk management for remote facilities, staff size requirements and scheduling to execute onsite operations. The approaches within the risk assessment field are divided into two subgroups i.e. risk assessment techniques and risk reduction measures. Thus, characterized by hazard prevention measures and justification of consequences with staff sizing, health and safety standards.  It is aimed to analyze the operational process of risk associated with the process that might lead to serious damages for personals, infrastructure and environment. The precautious measures that take into consideration before and after hazardous event incidence that are aimed to reduce the possible damages for such conditions.

In this research, we will address the issues of risk management and staff size in small and large-scale organizations. The design of operational element of the facilitates will be taken into consideration and staff associated with operational process and risks will be discussed in detail. Furthermore, in this study evaluation of offshore facilities systems safety with and without the approved safety system will be addressed and this will be done measures of international safety standards.

This research will analyze the application of staff sizing and preventions in hazardous conditions for offshore facilities. In addition, safety system and its interaction with technology as a hypothetical process. The operational process we will discuss in this research is part of oil and gas remotely located production infrastructure. In this research will we will use primary data infrastructure project document, risk assessment and secondary data include governmental regulations and industry standards.

Finally, the research involves quantitative methods and applications, and will result in suggestions and recommendations.

# 2 THEORY OVERVIEW

## 2.1 Risk Reduction

Strategic planning of the remotely located hazardous facilities such as scheduling of well and facility operations and safety is a very relevant issue in offshore oil field development. Its planning horizon may be more than a decade and it comprises of number of platforms, oil fields and pipelines. (R. R. Iyer and I. E. Grossmann, 1998). One of the major safety elements is the dedication of organization's management towards safety culture. It depends on the coordination between subordinates and the role of site managers in relation to risks (A. O'Dea, 2001). Moreover, an IT-based Safety Management System checks the safety standards and checklists to assign different tasks. Safety standards and work procedures are communicated to the lower staff once they are finalized by the higher authority and make sure that it is understood correctly by the personnel (ThomasWold, 2015). Emergency procedures are unavoidable features of safety as there are laws, rules and regulations but there remains chance of negligence, in hazardous industries like nuclear power industry the operating procedures are strictly followed, and high level of safety system is guaranteed to avoid mass destruction. Yet in the past we have seen such accidents in USA, former Soviet Union and currently in Japan that alone rules and procedures does not guarantee of safety. As for as these procedures are concerned, there may be other factors that could change the security situation, such as design, location or following same procedures in a different way. Designers are confident about their safety application and guarantee to avoid accidents which may occur due to human error, but operators are still considered as potential generators of errors due to working conditions and emotional strain (Dien, 1998). The Three Mile Island and Chernobyl accident made it clear that future of nuclear power depends on safety and safety is dependent on the plant equipment and competent workforce. (Y. DIEN, 1992)

**Staffing size:** Personnel scheduling is the process of assigning staff to different tasks according to their abilities in an organization to satisfy the demands and services. Firstly, it is necessary to decide the number of staff with specific skills needed for the job. To meet the requirements of different shifts each worker is allocated to different working times and then each worker is assigned to different jobs according to their skills. Each workplace has its own rules and regulations which must be followed (A.T Ernst, 2004). Creating international HR system is a real challenge, as more and more companies extend their business internationally, the companies face many problems to hire a skilled person. (Darin Wiechmann, 2003). An organization's core activities are affected if it lacks any resource. The shortage of manpower can have serious impacts on the company's performance at this point this issue will be critical than any other problem. E&P performance will be affected and results in the inability of achieving goals (Segio Sama, 2012).

**Standards –** The international standard IEC 61511 "Functional safety: safety instrumented systems for the process industry sector" and IEC61508 "Functional Safety of Electrical / Electronic / Programmable Electronic Safety Related System" (Marcantonio Catelani, 2013) introduces the term safety instrumented system (SIS) which consists of sensors, logic solvers and controlling elements and implement safety functions to protect personnel, facility and environment. Many systems are put, and they make a layer or barriers to reduce the risk of hazardous facility (Redutskiy, 2017). Figure 5 demonstrates the responsibilities of various automated systems.

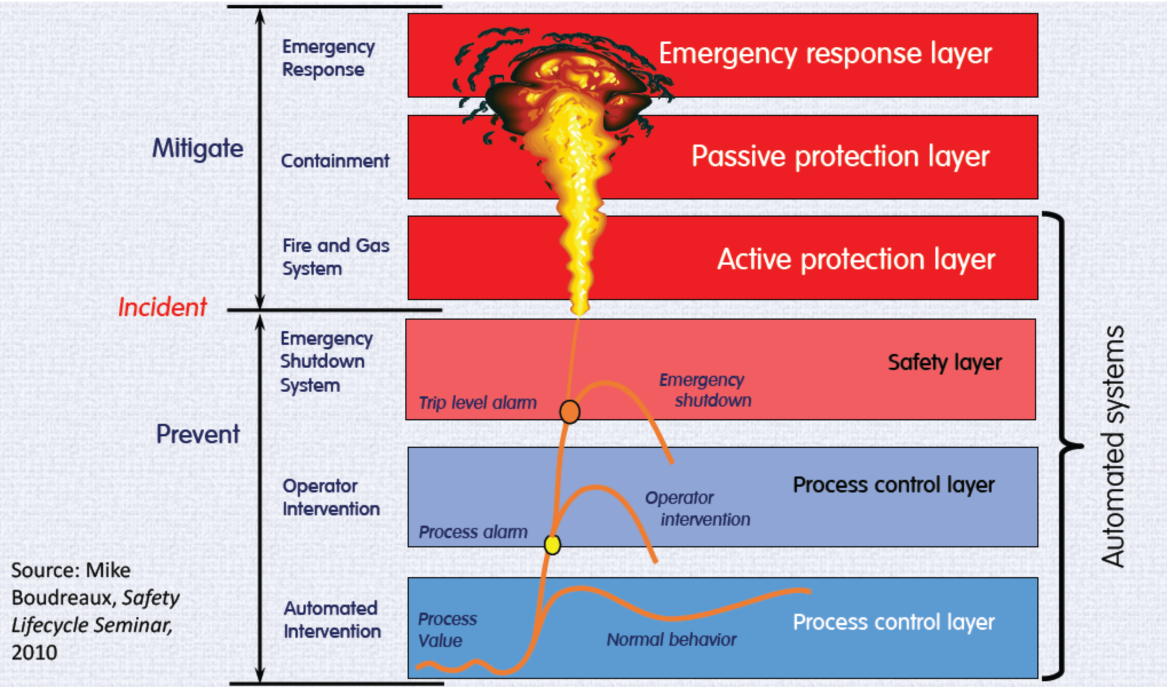


*Figure 5: Ranges of responsibilities of various automated systems Source: (Boudreaux, 2010)*

Risk reduction model is provided below (i.e. Figure 6), and oil and gas industry process control system is taken into consideration. DCS implements control of the whole technology. It keeps data and production operation mode and processing units at low range, alarms engineers and operators of any situation. The other risk reduction layer presents (Emergency shutdown system) ESD system, in any case it fully stops the facility in case of an emergency to avoid incident. On the other hand, there should be more SIS, such as fire extinguishing and Fire and gas detection (F&G) system. If DCS and ESD does not recognize any problem, we can put extra layers and consider emergency response of the facility staff and emergency response of local people in case of dangerous facility location.

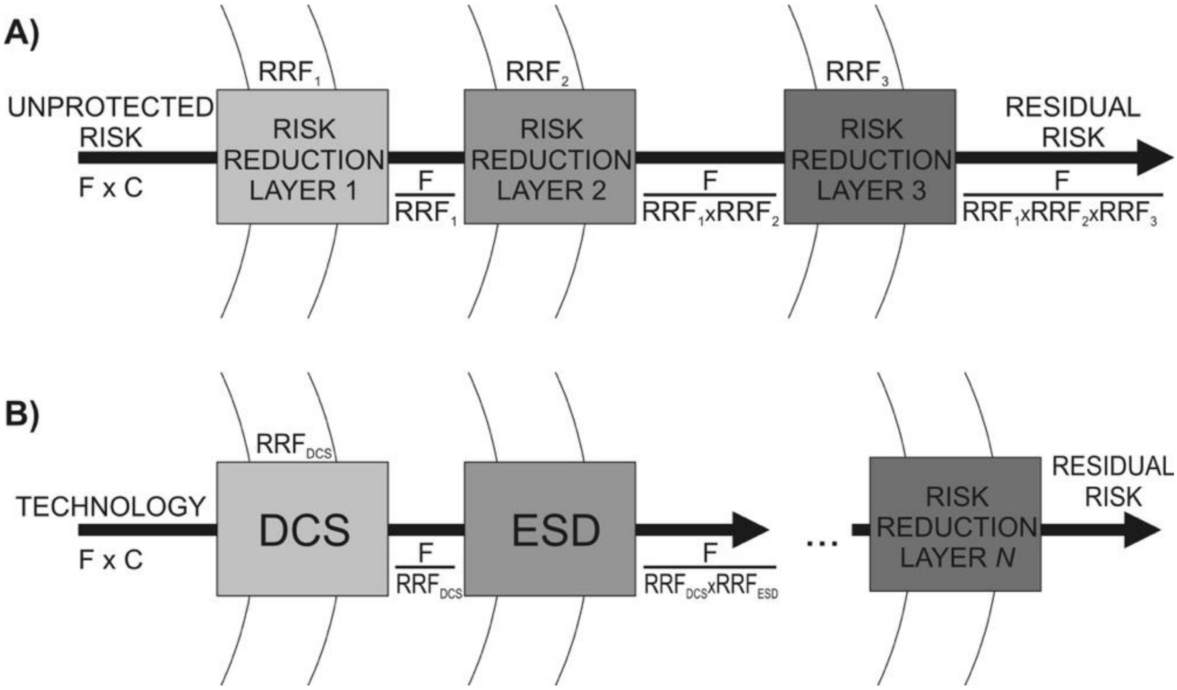


*Figure 6: Model of Risk Reduction Layers. A) General view. B) SIS, typical for petroleum industry (based on MacDonald 2003)*

The above mention IEC standards incorporate the risk reduction called ALARP i-e (as low as reasonably practicable) which determines three basic risk categories such as, negligible, tolerable and unacceptable risk. In taking measures the decision-maker will need to stop at tolerable risk level and it is center of economic loss where the decision-maker chooses one thing whether it can be costs of reducing risk or taking benefits of hazardous process by continuing the activities. Pipeline protection system has costs for installing and maintaining it and this needs investment in hardware and software. At some extent it depends on the company authorities to have costly and reliable safety systems to mitigate all potential risks or install cheaper systems to decrease costs and increase the level of threat to some extent.

In order to formulate a model, we may decompose the safety system to the simplest chain of control signal transmission.

Sensors collect data from valves and logic solver receives measurement information and pass signals to the actuator to turn on or off the equipment or make adjustments. The process control system uses discreet (interlock subsystem, ESD system) and continuous (proportional integral derivative or PID) control system.

As shown in Figure 6, the parameter falls into one of the ranges, if the value is in the dangerous zone then DCS starts using control algorithms to return the parameter to the nominal value. If the DCS fails to control the system, then ESD system will stop the technological process. If ESD fails, then parameter enters prohibited areas and further risk reduction layers are activated.

## 2.2 Reliability Theory

Generally, the reliability is defined the functionality of a system or thing to perform according to its predefined capability. Although, the term reliability has several meanings in different contexts which highlights the uncertainty of the term. Whilst in engineering field it is branch of engineering, an attribute or measure, a section of statistics and probability.

According to Kuo & Zuo, (2004) reliability is defined as the probability of a system to perform its required functions for specific period of time used under defined conditions. Additionally, reliability theory helps to identify the key problems associated with complex systems (Natvig, 2011). Reliability study has included many different aspects with the passage of time such as modelling, analysis, risk, and safety etc. Accordingly, its involvement also covered the reliability theory which is derived from combination of probability and statistics (Jardine and Tsang, 2013). Additionally, another aspect is system reliability, which emphasis on reliability of systems made of different components, which relies on time-based probability distribution system function to failure of connected systems.

Additionally, Rausand & Høyland, (2004) argued that basic definitions of these terms such as availability, quality, safety, dependability, and security are interconnected, however, these concepts have made confusion regarding their general and broadest understanding. However, system reliability is connected with various metrics, and out of these metrics only one is actual reliability, and this is also additional source of misunderstanding and confusion. Laprie, (1992) suggested a precise definition of the term i.e. dependability in terms of system application which consists of availability, reliability, safety, and security.

Whereas, safety and reliability share the same theory and methods, however, they are not the same, as foundation of reliability theory is before the safety engineering which holds many features of reliability theory. According to Leveson (1995) mostly the terms reliability and safety are considered as identical, but this is not the actual case in many situations. For example, an accident occurs without failure of any component and failure of component resulting without major accident. Additionally, firm reliability can increase the system safety, however, in some cases this is not the accurate assumption, but it can guide to conditions where safety is limited.

However, reliability indicates the probability of an item will perform its intended function under specific period and conditions. Thus, it is known as the probability of survival and non-failure. Hence, unreliability represents the opposite conditions. Frequently, the reliability term is used for non-repairable systems and availability refers to systems which are repairable (Rausand and Høyland, 2004). In addition, overall reliability of any system is made of various components can be measured based on the structure. The fundamental structure is parallel and series. Additionally, k-out-of-n is also commonly used structure.

According to (Goble, 2010) the process of numerically examine the control system design parameters have high importance in reliability and safety in order to balance the cost, maintenance, and performance. It does not limit this process only for economic perspective, but it also leads to protection of personnel and environment as well (Goble, 2010). In addition, to address such quantification methods various international organizations have provided standards such as ISA-84.01 standards provides quantification for performance level of safety instrumented systems (SIS). IEC standards IEC 61598 and 61511 recommend methods of system quantification by using simplified equations based on Fault Tree Analysis (FTA) and Reliability Block Diagram (RBD) (Redutskiy, 2017).

The international standard IEC 61511 Functional Safety-Safety instrumented systems for the process industry (IEC, 2003) to achieve the necessary safety integrity level there are number of methods and selection of such methods might depend upon many factors such as application complexity, regularity authorities' guidelines, risk nature and risk reduction requirements, personal experience and skills, availability of information (IEC, 2003). Furthermore, IEC-61511 standard introduced the SIS and defined the concept as a system consists of sensors, logic solvers, and final control elements (Redutskiy, 2017d).

Whereas, international standard IEC 61508 Functional safety of electrical/electronic/programmable electronic safety-related systems (IEC, 1997) was formulated to provide guidelines for ensuring safety based on the functionality of electrical, electronic and/or programable systems. The document is not limited any specific industry;

however, these generic guidelines are relevant with process, aircraft, nuclear, marine, automotive etc industries. Overall IEC 61508 document consists of seven parts. Whereas, first three parts address the requirements related with management (non-technical) requirements, technical (hardware and software) requirements. In addition, this standard established the safety lifecycle and defined the Safety Integrity levels (SIL). The requirement of this standard is based on achievement SIL for every safety function.

According to Redutskiy, (2017) various studies have been conducted in modelling and optimizing the SIS. System modelling is based on reliability theory, standards such as IEC 61511 and 61508 propose the safety quantification methods on Reliability Block Diagram (RBD) and Fault Tree Analysis (FTA). Next section will discuss the various system modelling techniques.

### 2.2.1 IEC 61511 and IEC 61508 Standards

IEC 61511 and IEC 61508 provides frame and guidelines for the industry requirements, methods, and principles for reliability and safety assessments and highlights the timely assessment actions should be undertaken within the industry.

The prime objective of these standards is to define a comprehensive approach for reliable and safe SIS design, operation, and implementation. Although some of the concepts and principals were already addressed in previous standards, but these standards addressed and defined the time-based changes and developments in the industry. These standards not only addressed the technical characteristics, but also, procedures, necessary tools, work process to develop, specify, operate, and maintain SIS software and hardware.

Additionally, required safety and reliability performance is defined through two concepts i.e. the safety integrity requirements, stating how well the SIS is required to perform, and the functional safety requirements, what the SIS is required to do. IEC 61511 and IEC 61508 differentiate between four level of SIL where SIL-1 represents the least level and SIL-4 represents the most reliable level. Therefore, SIL is selected for every single SIF in order to achieve the required risk reduction level. In addition, safety integrity is divided into three different parts: software integrity, hardware integrity, and systematic safety integrity. It is mandatory to demonstrate that all parts achieve the required SIL in order to meet the SIL requirements. For example, if the SIF achieve the SIL level 2 in terms of software integrity, the claim does not satisfy the required performance level until the same level is achieved in hardware and systematic integrity of SIL.

There is two-step process for verification of adequate hardware safety integrity. First, it is mandatory to specify the architectural constraints. Second, it is obligatory to calculate the reliability of SIF and results should be compared with the SIL requirements.

The main purpose of SIL is to provide guidelines and boundaries for the selection of necessary tools, software, hardware, work process, and procedures involved. Such case where a SIS applies several SIFs which have separate SIL requirements, thus, the application of strict SIL will be implemented for each shared component, for example, a logic solver.

IEC 61508 applies the probability of PFD for SIS that operates on demand, and dangerous failure per hour (PFH) for SIS that operates continuously. The IEC standards emphasis on the use of beta factor model for including CCFs in the measures, and ISA TR84.0.02, IEC 61508, and PDS methods provides some practical examples for modelling application of different hardware settings and configurations. Whereas, the standards also promote validation and verification in different stages of the SIS lifecycle including, commission, design, auditing, and testing in order to make sure that the standards compliance with software and hardware integrity. In addition, the important phase of auditing is functional safety assessment (FSA), which is an extended review of the IEC 61508 and 61511 where compliance with all requirements is investigated.

Finally, the application of IEC standards has directed the industry to unified levels of SIS design, construction, operation, and maintenance. Whereas, the standards have also opened new challenges and era for the industry, as they must apply new practices, concepts, requirements, and principals. However, the past literature has clearly discussed these standards, but more clarifications and understanding are required in order to fulfil the requirements of IEC.

### 2.2.2 Modelling Methods

There are various system modelling techniques, for example, analytical models are used for quantification, and these techniques are helpful for time dependencies analysis. However, their application can be applied only for fewer components. When modelling details are increased and approaching towards more complex models, these analytical models does not fulfil the required objectives and become difficult to get and handle the features such maintenance and diagnosing the systems. Hence, for handling the complex model's other probabilistic methods are used. RBD and FTA are among most popular modelling techniques. The application of RBD is generally applied for non-repairable systems, whereas, FTA is capable to handle repairable systems, also other modelling methods are available to handle sophisticated systems with time dependencies and repair policies such modelling techniques are Markov Analysis (MA), Bayesian Networks, and Petri Nets. The main modelling methods used for safety system analysis are:

- Reliability Block Diagram (RBD). System structure is represented through functional blocks and graphs are used to demonstrate the successful operation of the system (IEC, 1991; Rouvroye and van den Bliek, 2002).
- Fault Tree Analysis (FTA). The representation of top-down events of the system with graphics. The combination between top event leading to system failure and basic event such as faults (Vesely et al., 1981).
- Simplified equations (SE). this method is combination of set of equations acquired from other available methods and used for specific architecture and with simplified combination and used for larger set of systems (Hauge et al., 2006; IEC, 1997; ISA, 1999).
- Markov Analysis (MA). This method is used to demonstrate various possible states of the system components with details related among states transition (IEC, 1995).
- Petri Nets (Dutuit et al., 2008). This method is composed of two types of nodes i.e. transitions and states and such conditions are represented by graphs. The functionality of this method involves tokens to show the actual active states and they are stimulated one state to other in order to simulate the transitions (Dutuit et al., 2008).
- Hybrid methods. This method consists of combination of various methods such as FTA, RBD, and MA for solving various complex systems (Knegtering and Brombacher, 1999; Jean-Pierre, 2007; Dutuit et al., 2008).

Various researchers have provided a detailed analysis of these methods by defining as well as providing comparative analytical studies of various modelling methods. Such as Goble, (2010) applied MA and FTA techniques for several MooN architectures modelling which consists of diagnostic coverage and Common Cause Failure (CCF) quantification. These techniques were validated, and similar results were reported, whilst the MA method showed additional advantage over FTA by including interaction of multiple failure modes and time dependency.

ISA TR84.0.02 (1999) the application of MA, FTA, and SE specifically applied to treat the SIS and implies a comparison of these methods for modelling techniques. In case FTA is resulting with solution of Boolean algebra the usage of it can result for modelling more complex relationships inside the systems and its capability can be enhanced to handle diverse redundancy and repair times. Whereas, SE is capable to handle very simple systems. In addition, MA resulting with solution of matrix algebra can perform just like FTA with additional capabilities such as handling sequence dependent failures and modelling the time dependent requirements. In such scenario FTA keeps an immense advantage over MA which is visualization of failure paths with graphical representation that is easy to understand.

Goble & Cheddie, (2005) studied FTA and RBD such techniques are capable to provide graphical explanation of probability combinations. Their observation came with the major difference between these techniques i.e. FTA emphases on failure of systems, whereas, RBD focuses on success of system. Their preference was motivated towards FTA for SIS modelling due to reason of representation of multiple failure modes propagation mechanism.

Furthermore, Rouvroye & Brombacher, (1999) examined FTA, MA, hybrid, and RBD modelling methods and compared them for advantageous and disadvantageous exposure. The inclusion of hybrid method was based on the first edition of PDS and IEC-61508-6. The authors concluded that RBD performance is relatively less satisfactory and resulted least comprehensive method. Whereas, hybrid and FTA have same kind of capabilities such as inclusion of CCF, effect of test, effect of repair, effect of diagnostics, and only time-averaged, instead the FTA does not include systematic failure i.e. it does not indicate system failure also IEC method is not able to do so and show the same results in the experiment. According to them MA is holds advantage and among these methods holds the best position. In addition, they proposed a new method called Enhanced Markov Analysis (EMA) which was introduced with the combination of sensitivity analysis and uncertainty analysis through Monte Carlo simulation. The obtained results were lower for average Probability of Failure on Demand (PFDavg). However, they added the probability of system being in safe state, which was concluded by authors unsatisfactory calculation for PFDavg.

IEC 61508-6 suggests quantification method simplified equations taken from RBD. It shows the drawbacks of SE as mentioned above by various authors and its effects are unsatisfactory and oversimplified for large and complex systems. In addition, Hauge et al., (2006) presented more refined method of calculation formulas which was based on PDS method. The presentation included with an example of simple RBD. The formulation of this method was motivated to include failure categories and causes which were excluded by various methods. Additionally, Guo & Yang, (2007) proposed an approach based on RBD, which consists of equal mathematical characteristics as FTA that improves and addresses the approach proposed by IEC 61508-6 which was on simplified equations taken from RBD for SIL verification.

Andrews & Ericson, (2000) compared and examined the MA and FTA for various design complexities. According to them FTA provides best approximations and same results as MA. However, MA is more accurate, and it is required to exclude several contributing events to simplify the model which turns it into an approximation. Additionally, the authors highlighted that in order to create Markov models for systems which are not simple is a difficult task and leads to errors, whereas, for complex systems this can be achieved through by obtaining and using numerical methods. While comparing the model’s FTA is significantly powerful for modelling large and complex system and results are satisfactory when small probabilities are involved usually in safety systems. In addition, Bukowski, (2005) argued that SE might lead to significant errors, whereas, expert knowledge is required for MA applications.

Overall, it indicates that only one method that might surpass the FTA is MA, as it is capable to handle time-dependencies apart from sequential failures. Hence, MA has drawbacks as well because of growing complexities which increases with the exceeding number of system components. Also, it is possible that modelling components which are more than two become unmanageable where several failure modes exist. Also, it is important to mention that FTA is capable to provide graphical representation of failure mechanism and much easier to construct compared to MA. Furthermore, Petri nets method holds such capability to handle time-dependencies but in order to construct analyze it is more complex method. Also, dynamic fault trees are applied to handle sequential failure (Schneeweiss, 2001).

Additionally, RBD is less preferred compared to FTA due to capability of FTA to provide clear graphically presentation of failure process which is easy to understand, and its main focus is on failure probability rather than success (Andrews & Ericsson, 2000). Moreover, FTA is studied again and again and progressed at various stages. However, due to oversimplification hybrid, SE and simplified equation methods possess disadvantage as well inflexible in order to accommodate and manage the rapidly changing conditions of system design.

## 2.3 Maintenance in Remote Oil & Gas Industry Operations

The operational process of offshore facilities consists of a series of activates in order to produce commodities. The complete process involved is depicted in Figure 7.

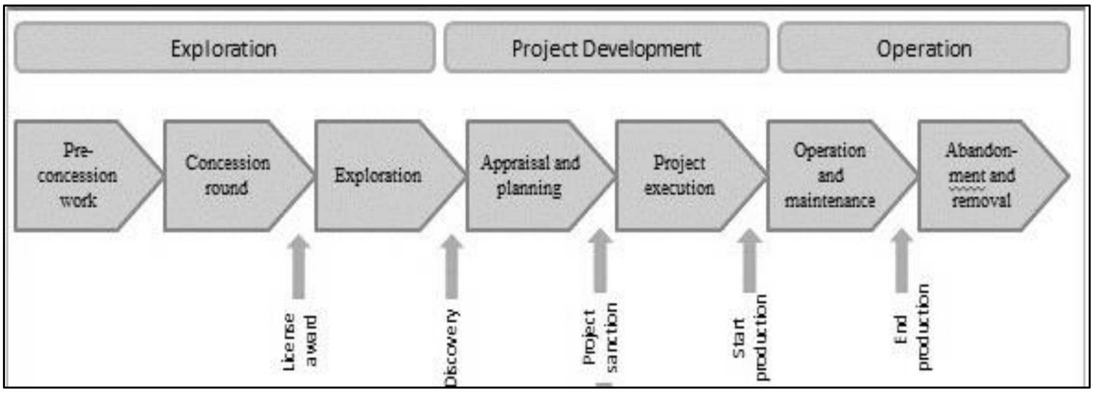


*Figure 7: Process of Offshore Facilitates Source: (Odland, 2014; Elisabeth, 2016)*

The offshore facilities involve in three key stages in the production of the commodity. Which are explained below.

- **Exploration**
  Offshore exploration refers to the process of probing for the hydrocarbons and how much oil the source contains. This process is performed through appraisal and geophysical techniques such as gravimetric and magnetic surveys, Ocean Bottom Cable (OBC) surveys, seismic surveys, rock cuttings, core samples and data is gathered through well surveys by drilling. Whereas, geophysical surveys are used for information about the source for determining the oil reserves, the positioning of drilling a whole and recoverable volume, also for property information.
- **Development and Installation**
  This stage involves the process of construction of the site whether it is onshore or offshore and installation of equipment. Offshore development process relates to the installation of structures such as subsea templates, platforms, and pipelines in an aquatic environment. The construction of the offshore facility is a quite difficult, costly and risky process due to the huge dimensions and complex structure. The

offshore environment is highly vulnerable due to weather conditions, waves, and winds on a continuous basis.

- **Drilling, Production and Transportation**

  Drilling activities follow the stages after exploration and installation. The key purpose of drilling is to produce the oil and gas from the source. Whereas, offshore drilling is a complex and high-risk process for engineers and such process consists of sub-contractors and subsystems. Particularly offshore drilling involves well design, mud design, downhole drilling strings, cementing and casing, completion, and well testing of the process. The facilities and services are complex in nature, such facilities are mud pump, solid control system, top driven system, and logging and monitoring system. The drilling units are classified into three types in offshore settings. Which include mobile drilling rigs such as jack-up and semisubmersible, self-contained fixed platforms, and fixed platforms through floating drilling tenders.

After the completion of substructure and fabrication of topside, the production of commodity begins. Pipelines are used to transfer the oil and formula the risk level at low through separation of gas and water produced from crude oil is carried out. Finally, the transportation of treated oil will be carried out through oil tank or pipeline to the onshore terminal.

### 2.3.1 Offshore Maintenance Management

Maintenance management is a term with many definitions and it is used for defining the activities to ensure that the assets are well operational, and that required maintenance is performed when required, to ensure that the assets are functioning properly it is a continuous improvement process in reliability, availability, and maintainability. According to (EN13306, 2010) British Standard document the fundamental maintenance term is defined as:

> *"Combination of all technical, administrative, and managerial actions during the lifecycle of an item intended to retain it in, or restore it to, a state it can perform the required function"*

Whereas, maintenance management is defined as *"All activities of the management that determine the maintenance objectives, strategies, responsibilities, and implementation of them by such means as maintenance planning, maintenance control and the improvement of maintenance activities and economics".*

The maintenance process has a significant role in the overall success of any business (Deming, 2000). In addition, maintenance has become an important subject for oil and gas industry due to the high risk associated with operations. Norwegian Petroleum Directorate presented a common model for the maintenance management process as shown in Figure 8.

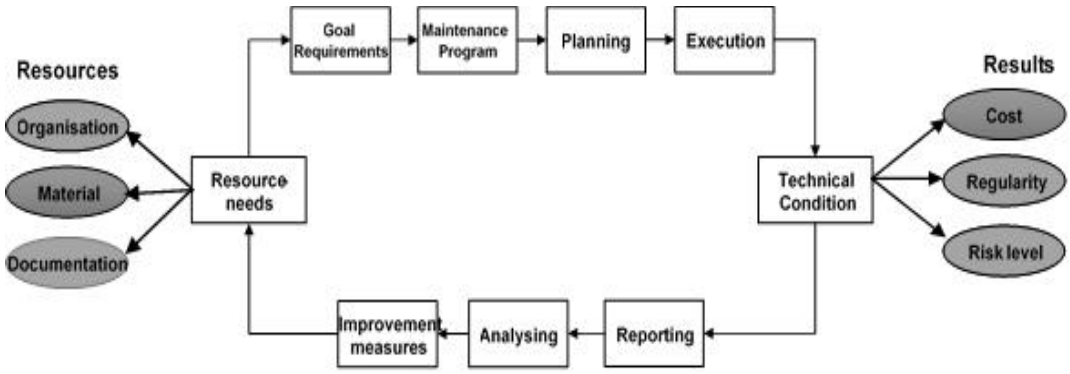


*Figure 8: Maintenance Model Source: (Norwegian and Directorate, 1998)*

The maintenance model covers the process of facilities from design to end of assets performance.

- ***Goal and Requirements:*** Goal and requirements are developed based on the organization and regularity demand.
- ***Maintenance Program:*** A maintenance program comprises of activities such as maintenance task, resources, intervals, spare parts, and documentation and formation of the maintenance program is to ensure that all the actions are performed the efficient, safe, and cost-effective procedure.
- ***Planning:*** Planning of maintenance program has significance in the overall process, which might consist of long and short-term plans for the execution of process and keep the equipment's maintenance cycle in process.
- ***Execution:*** The maintenance task should be prepared and executed accordingly, and the record should be kept for future reference.
- ***Reporting:*** The report for executed maintenance which might include the details of technical conditions of equipment's, regularity, cost, and risk associated should be reported and documented properly.
- ***Analyzing:*** generated reports should be analyzed for the working conditions and process and actions to be taken according to requirements.
- ***Improvement Measures***: Based on recommendation improvement measures should be taken in order to keep the process ongoing and well maintained.

As shown in Figure 8, three types of resources are required during the process which includes organizational, material and documentation. The outcomes from the maintenance process would be measured based on assets conditions, related cost, risk level and regularity requirements. In offshore facilities maintenance highlights the series of actions related to administrative, managerial, and engineering aspects. The complexity of equipment and system cannot be overlooked due to technological developments and to keep the process functioning most of the equipment performance is related to each other. Such integration of systems and equipment can be realized in the process of drilling where a lot of sophisticated equipment's and subsystems are integrated into offshore facility activities. The good maintenance results in overall efficient performance of working conditions and whereas bad maintenance might result in lower productivity, decreased life of assets, increased cost, poor safety, higher risk for personals and infrastructure, and long downtime. To some extent, proper maintenance contributes to asset maintainability, reliability, supportability of system and equipment, therefore, results of failure and loss could be avoided by prioritizing the maintenance process.

### 2.3.2 Cataloguing Offshore Facilities Operations and Maintenance Process

Offshore facilities are quite different from onshore oil and gas facilities. Offshore facilities are more complex in design, system, and operations compared to the onshore industry. The main difference could be categorized in the operational environment, equipment, installations, technology, cost, risk, and staff requirements. Offshore industry has some restriction based on space, a period of production, water depth, and the environment. The offshore facilities are exposed to the marine environment such as wind, typhoon, waves, solitons, salinity, and other extreme weather conditions (Devold, 2010; OCDK, 2010). Thus, the safety is considered as a top priority due to high risk and harshness of consequences. The offshore operation and maintenance process can categories as follows.

- ***Investment*****:** The offshore facilities require a huge investment in order to start the production. Immense work including construction of the site, installation, shipping, exploration, and drilling needs to be carried out before the oil is produced and transported.
- ***CAPEX OPEX (Capital Expenses/Operational Expenses)*****:** In order to manage and run the operations of the offshore facility. The capital expense, operational expenses,

maintenance cost, and performance are the factor which has high influence in offshore settings.

- ***Technology*****:** The offshore facilities are complex in design and technology developments have the made the offshore industries to manage the operations smoothly and to maximize the profit and minimize the risk and uncertainty in offshore enjoinments.
- ***High Risk*****:** A risk factor is associated with offshore operations and due to its high vulnerability to external factors and usually affected by management, personnel, environmental, and organizational and hazards related with the offshore facilities involve fire, explosives, the undesirable release of oil at the surface or subsea level.
- ***Complex Dynamic Settings*****:** The offshore process is exposed to complex marine settings and influenced by it. The influencing factors include water depth, waves, typhoon, temperature, fog, sea wind, as well human responses are also reflected in such climate. Such effects of the environment are analyzed in the safety of the environment and personnel, operational costs, and the duration of the project.
- ***Demand for Professionals and Workers*****:** There are different kinds of disciplines in offshore operations which include electrical engineering, instrument engineering, mechanical engineering, mud engineering, well surveys, logging services etc. thus, the demand for highly skilled workers has always remained a key concern in offshore facilities.
- ***Contractors and Sub-Contractors*****:** The offshore facilities include many contractors and sub-contractors with a different type of assignments. Managing contractor is challenging in offshore settings where for the single product there would be many suppliers and contractors.

### 2.3.3 Staffing in Remote and Offshore Installations

Remote and Offshore facility workers conditions require special kind of arrangements as mostly they face numerous challenges throughout the time they are employed on the facility. There working conditions are quite different such as shift work, long working hours, working in serious climate conditions or extraordinary warmth, and regularly performing exhausting and routine work (Khanthong, 2005). The industry has evidence that growing need of talented people to be appointed and trained. Thus, the offshore industry requires to bring and identify individuals who are fresh and willing to work in these conditions

(Greenwood and Ray, 2007). According to (Parkes, 2007), offshore installations working conditions evolve around hazardous production and the concentrated working patterns and two type of risks are always over the head of the workers such as operational risks i.e., fire, risk of explosion, shut-down, structural failure, and reduced productivity which might be results of human error, and another type of risk is physical and phycological well-being of workers such as illness, injuries, anxiety, and sleep disturbance. Such conditions are quite difficult for workers to handle.

Across all industries around the world have trends in employment such as permanent, contractual and part-time. Oil and gas industry has no omission to these trends. Upstream, contractors and employees are working for exploration, production, drilling, construction, catering, and transportation. Whereas at downstream they are engaged and have a huge presence in the refineries, which they are also involved in building, planning, equipping and maintaining and individuals are hired based on their qualification and expertise, and contract workers are hired through specialized employment agencies (Graham, 2010). According to Speight (2015), Offshore facilities presents logistics and HR challenges, and offshore platforms is a little group of individuals in itself with cafeteria, resting quarters, management and other support capacities. Most of the time staff workers are transported by helicopter for a 2-week shift, supplies and waste are transported by ships, the supply conveyances require to be precisely arranged in light of the fact that storage room on the platform is constrained.

### 2.3.4 Staffing in Oil and Gas Industry Overview

The workforce report by Oil and Gas UK UKCS (2009) provides overall employment statistics in the country where 0.45 M individuals were employed with 50 thousand were directly hired by contractors and companies. Whereas, the report also describes that 51,000 personnel travelled offshore in 2009. This trend further demonstrated that a 1% rise was recorded compared to 2008 figures. Additionally, the number of ‘core’ personnel who spent more than 100 nights at the site was recorded in increment of 13.6% compared to 2008. Also, the number of staff who spent more than 25 nights at offshore has also shown increment by 3.8%.

Whereas, the latest report by Oil & Gas UK (2017) related to workforce pattern in the industry indicates a decrease in employment. Table 2 provides a summary of employment trend changes for the five years.

*Table 2: Employment trend in UK upstream Oil and Gas Industry*

| Year | Direct | Indirect | Induced | Total |
|---|---|---|---|---|
| 2013 | 36000 | 198100 | 206200 | 440900 |
| 2014 | 41300 | 206100 | 216500 | 463900 |
| 2015 | 37300 | 163100 | 173400 | 373800 |
| 2016 | 29500 | 150600 | 135300 | 315400 |
| 2017 | 28300 | 141900 | 132000 | 302200 |

Additionally, worldwide workforce statistics of leading companies in the industry is demonstrated in Figure 9.

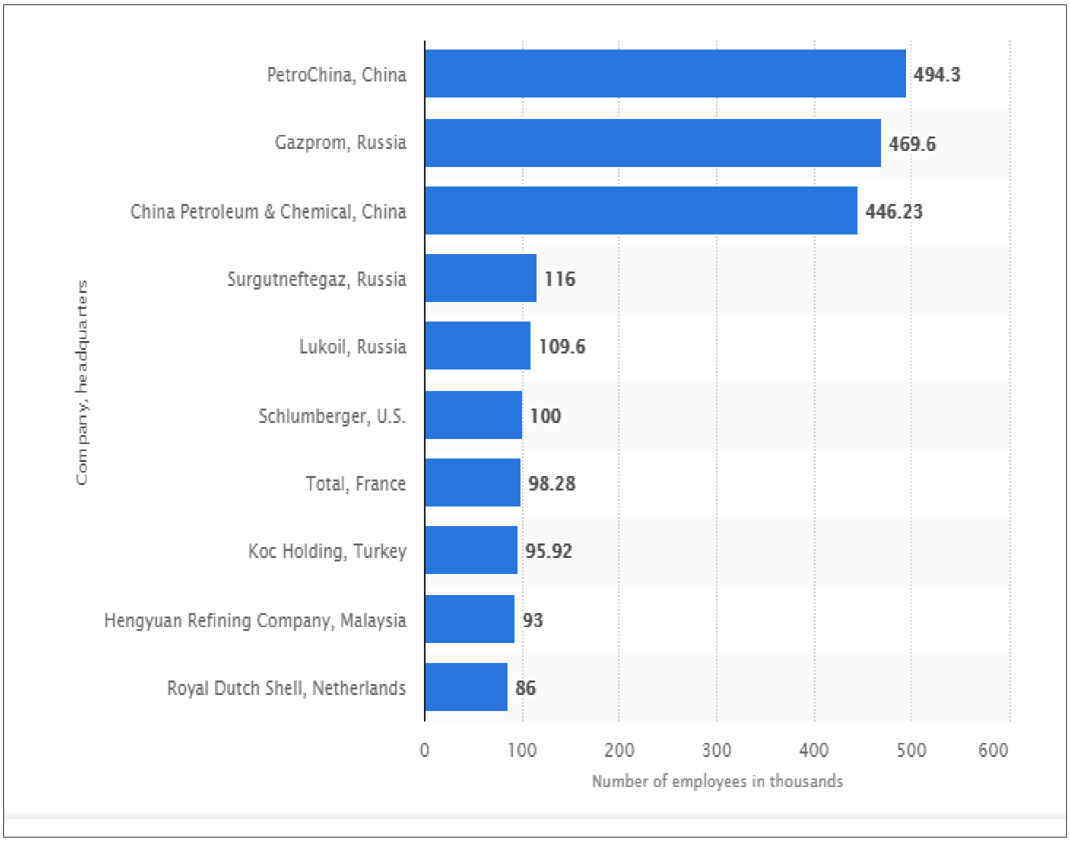


*Figure 9: Employment in Worldwide Leading Companies in the Oil and Gas Industry Source: (Statista, 2018)*

According to Ağralı et al., (2017) efficient size and management of the workforce is a most significant problem nowadays in many industries. The same kind of issue is being faced by the oil and gas industry where skilled and trained employees are in demand (Broadbent, 2008). Although, a robust kind of wages are being offered to skilled workers, but it does not activate the motivational aspects of individuals (Luke & Goswami, 2012. Accordingly, the offshore installations have been identified as “among the harshest and most stressful work environments in the world” (Deacon et al., 2010), and an average number of workforce required is 184 (Luke & Goswami, 2012). Barlow, (2017) stated that it can be between 100 to 200 employees on the offshore installations.

### 2.3.5 Staff Scheduling

Staffing term identifies the ideal size of the workforce and its composition. The planning perspective highlights the minimum duration and job description (function) of the staff and the period required to hire and train the newly appointed individual. Whilst, labour scheduling is associated with assigning the task to an individual which regularly involves staff performing the job in the field for a week or a day (Thompson, 1997). Nowadays, employees and employers need to be more flexible and required to make compromises to run the businesses and perform the required job. Additionally, in many industries workforce should perform the tasks at different geographical locations, e.g. technicians are required to do repairing task at different organizations, and healthcare individuals are required to visit patients at their house (Castillo-Salazar et al., 2016). According to Van Den Bergh et al., (2013) various research studies have addressed the issue of staff scheduling problem in past, but the research was motivated due to the economic perspective, such as many companies consider staff cost as a direct component, minimizing this cost could be achieved by implementing an efficient personnel scheduling mechanism. The time has separated the problems associated with staffing and personnel scheduling that were addressed in the 1950s by (Dantzig, 1954; Edie, 1954). The importance of satisfying the employee's requirements has grown significantly in staffing and scheduling decision. The companies offer and consider employees preferences in part-time contracts, working hours flexibility (e.g. employee working together with somebody, preferences for a particular shift, particular days on or off and etc.) while designing the work schedules (Van Den Bergh et al., 2013). Ernst et al., (2004) combined rostering and personal scheduling and presented staff restoring process with multiple modules.

**Module 1**: Demand Modelling

This module identifies staff planning requirements at different times horizons. Personnel's required to perform duties while incidents occur during the planning stage. Such case incident might happen i.e. enquiry at a call centre, per shift specification of staff, specified tasks assigned in sequence, and components of flight timetable. This modelling involves the process of predicting incidents into assigned personnel duties then applying task requirements to determine the need for staff. They further categorized incidents into three major demands for staff needs.

- ***Task-based demand*:** This category involves getting the list of personnel to perform a specific task. Generally, these tasks outline the pattern of starting and ending time, and the required skills in order to perform the task. In a few cases, these tasks might be location based. Rostering is the most common method in short or long-distance transportation applications where crew pairing optimization and crew pairing generation is related to the demand modeling.
- ***Flexible demand*:** In this category possibilities of future incident scenarios are less, and modelling should be carried out based on the forecasting method. The connection between staff levels and requested services is followed through the technique of queueing analysis. The results specify the required number of staff at a different time in daily routine into the restoring horizon. When the pattern for flexible demand is created it can be assigned to shift which are operational in order to fulfil the demand.
- ***Shift based demand*:** This category in the demand module is to allocate the number of personnel which are required to carry out services during different shifts. Shift based demand arise in services such as ambulance, nurse, call centers, offshore industries etc.

**Module 2:** Days off scheduling

This module applies the way of managing rest days. Such issues appear most often when rostering to shift or flexible demand compared to task-based demand.

**Module 3:** Shift Scheduling

Shift scheduling addresses the issue of selecting an individual (s) from a large pool of available employees or candidates. What shifts are required to be worked, combined task assignment of number of personnel to achieve the demand. The timings of meal break and rest within the workplace rules and industry requirements.

**Module 4:** Line of Work Construction

The module is dedicated to the generation of lines of work, sometimes known as roster line or work schedule for personnel involved. The process depends on initial building blocks, particular shifts, stints, duties, that are applied.

**Module 5:** Task Assignment

It might be required to assign one more than one tasks to be carried out during each shift. These tasks might demand seniority or skills and should relate to the line of work.

**Module 6:** Staff Assignment

This module addresses the issue of staff assignments related to the line of work.

According to Castillo-Salazar et al., (2016), the workforce scheduling and routing has remained a key research area. Such problem highlights the issues which refer to the mobilization of workers to perform their job assignments at different locations.

## 2.4 Organization of Activities in Remote Areas

The workforce has remained an important contributor to global and specifically for countries overall economy (Ross, 2009). According to Parkes, (2012), most of the onshore industries operates a roster of 12 hours shift sequence, usually working period of 7-14 days and with alternative extended leave days. Whereas, the offshore environment is considered as remotely operated work sites where movement/transportation is considered as 'fly-in, fly-out'. Such sites operate in extended work/leave rosters where accommodation for personnel is provided during work periods. This kind of work sites requires extended work pattern where workers spend 2 weeks at offshore installations followed by a short leave period (Parkes, 2007). In addition, Gibbs et al., (2002) stated that these remote sites operate in an extensive range of work schedules that also includes swing shifts of 7 days followed by seven nights, also 14 nights followed by 7 days and shifts of consecutive 14-21 days and nights. The personnel at offshore can adopt up to 14 days, 12-hour night shift (18:00-06:00) (Barnes et al., 1998). Parkes (2007) stated that the most common working period 2-2 which is 2-weeks of working and 2-weeks of leave before 2002 working period was followed as a 2-3-3-4 pattern. Also, another work pattern is followed such as 3-3 or 2-3 but this type of pattern is less frequent.

Only two crews can be accommodated at any time on board, therefore, the 12 h for day/night shift workers operating on a continuous basis which is standard shift duration is followed at the remote sites. Such shift during is of 168 hours maximum work, whereas, managers and supervisors might work more than these working hours. Whereas, there is an increase in providing long leave breaks for crew contractors and company personnel which can be 2-3, 2-2, and 2-4 has been in practice for recent years (Parkes, 2010; Ross, 2009).

Parkes, (2010) stated that the worldwide working timing arrangements depend upon several factors such as time of travel and distance between the shore and the installation, staff home locations (i.e. who come from long distance area work for longer period rotations compared to local employees), the travel mode, weather conditions, and national and local employment practices. Geographical, UK sector and Norwegian North-sea sector share the closest dissimilarity, leave and work schedules at Norwegian offshore installations offer extended shore breaks compared to UK installations. Norwegian offshore tours limit it to 2 weeks with a leave of four weeks compared to the UK where irregular work pattern is being observed. Additionally, Mikkelsen et al., (2004) stated that before 2002 offshore tour was 2-3-2-4 at Norwegian installations. Such duration at offshore locations seems to be longer tours in recent years (ILO, 2016).

However, the various countries operate in different work/leave arrangements such as Brazil, USA, Nigeria, China, Canada, Russia, Australia, and Azerbaijan. Whereas, due to cost and time involved in long-distance travel most of these countries operate at the equal pattern of scheduling such as 1-1 at East coast of Australia and 4-4 in south China sea (Parkes, 2010).

Rotational work has been a key practice in remote areas of offshore installations in order to keep the workers stay longer. Such as Siberia (Russia) frequently tow forms of rotational work is applied. The first form is trans-regional rotations, which consist of specialist teams which are connected through shuttle shifts travel from various regions of the country at a distance of 2000-3000 KM or more. This method includes the personnel to fly from an actual residency location to the based point (North) then workers are moved to the working site by air or by ground. Whereas, the work management is followed in different shift systems such as 12-30 days and more. Once this working schedule is completed the workers return to their permanent residence. Whereas, in the second method rotation type, workers are transported through different types of transport at the working site and are accommodated in field towns.

Usually, in this method shift of 8 to 12 hours are used, and up to three months of rotation duration is practised.

### 2.4.1 Transportation

According to a report by ILO, (2016) addressed three modes of transportation by Air, Rail, supply ship and crane.

***Transportation by Air (Helicopters)***

The journey from and to work in the offshore installation is as dangerous as working itself. Personnel working either at onshore or offshore, most of the time round trip is made by helicopter (ILO, 2016). Whereas, Cooper, (1991) addresses helicopter travelling as 'fear and stress', and such flights are a high source of anxiety for personnel (Parkes, 1998). If the average time is 30-50 minutes of flight itself, but the time required to reach the helicopters, check-in, plus flight briefing are also cause of anxiety among workers of offshore installations. Additionally, poor weather conditions can also delay the flights, such time spending is not considered as working time, whereas, this consumption of time adds few extra hours to the last and first days of offshore sites (Parkes, 2010). In addition, workers at offshore travel longer distances compared to onshore staff. Such travelling can be the distance from the heliport, and drive instantly once they reach, but such immediate driving exposes them to road-accidents risks, particularly after night shift works the circadian adaptation disturbance is highly linked.

Additionally, Kirkcaldy.,(1997) compared work pattern of offshore and onshore personnel and found that personnel work a minimum of 84 hours are at a reduced risk level of road accidents compared to the onshore personnel who have worked for minimum 48 hours. Also, road accident risk factor is 6 hours heliport check-in time for some flight which may require personnel to drive in the morning early hours which is known the time for increased road accidents (Philip and Åkerstedt, 2006).

***Transportation by Rail***

The demand for rail cars increased by 1,300% between the period from 2010 to 2013 in North America due to the non-existence of pipeline in many parts of Canada and North America. The hydrocarbon shipments possess high risks to population and workers which may occur from rail lines, waterways, pipelines, and at rans-shipment sites (ILO, 2016).

***Transportation by Supply-Ship and by Crane***

The operating boats at offshore sites carry people, supplies, and equipment to and from offshore installations. This mode of transportation area produced more improvements in safety. The oil and gas industry has adopted the various type of crane-assisted devices to transfer personnel from crew supply boats. In 2009 the report indicated that these cranes offer seat and quick-release clips which have improved the safety measures, due to progressive initiatives such as training, preflight briefings, videos on operational procedures, and transfer device inspections (ILO, 2016).

### 2.4.2 Working-Time Arrangements

Offshore working hours arrangement is associated with the demands and constraints which are not applicable to the onshore installations. Globally 12 hours shift, and long rotation patterns are practised on offshore installations. (ILO, 2016). The accommodation facilitates are limited in offshore installations that cause the offshore workers to stay for longer period of time which makes the tour longer.

While in Australia, the workers' wages are based on 12 hours, 7 days a week in the offshore. Worldwide work time arrangements are based on the agreement, duty duration and period can be, 1-1,2-2,4-4,5-5, whereas, such timings do not make difference for permanent and contractual employees (Graham, 2010).

Whereas, in Russian Federation, both contractors and operators used to work for 40-hours per week. Such conditions are practised for more than a decade and this practice is not considered as excessive by the workers. In addition, the workers in Ecuador, work for 77-hrs per week both the contractor and operator with over time such practice far beyond the 40 hours working time. The situation of offshore workers depends on the oilfield production and these arrangements have not been altered for past decades (Graham, 2010).

According to the law at Norwegian weekly offshore working time average is 36 hours for the once who are covered through collective agreement, it averages 33.6hrs. According to the agreement, the working schedule is 14 day and 12 hours shift, then 28 days off. The law states that workers to should follow the one-third pattern for offshore before coming back at offshore. Whereas, all offshore workers have annual working hours limit of 1582 hours with 5-weeks off. Instead few companies are operating on rotation which limits it to 1460 hours which eventually result in a pay cut.

UK installations at North-Sea sector, follow the pattern of "the most common work pattern is two weeks offshore alternating with two weeks shore leave (2-2 pattern). Less frequently, 3-3 or2-3 patterns (or combination of 2-2 and 3-3 schedules) are worked". Whereas, specialist personnel, who frequently move between different installations, often have irregular and or/unpredictable work pattern in both the Norwegian and United Kingdom sectors" (Parkes, 2010). Workers at Canadian installations observe a work pattern of 12 hours with a schedule such as first week 7-am to 7-pm, second week 7-pm to 7-am, the third week off.

### 2.4.3 Employment Trends

The oil and gas industry has played a crucial role in the economy of any country, it has created jobs not only for men but also encouraged the women to hold the key positions, overall oil and gas industry creates the energy resources that support the economy (ILO SAD, 2012). Any companies' real asset is highly skilled staff with motivation to work in hard conditions. One of the oil and gas industries key needs is enhancing the work proficiency. The Rosneft one of the leading oil and gas company of Russia had total number 295.8 thousand employees as of the year 2016 and the company had employment increase of 13% as compared to 2015 (Rosneft, 2018). The industry will create 1.4 million jobs in the United States by 2020 and only Shale gas industry will provide 600,000 jobs, out of that 148,000 jobs will be based in the US and nearly 194,000 jobs in supplying countries, and more than 259,000 induced jobs. The trend shows that by 2035, the shale gas industry alone will support more than 1.6 million jobs in the US. The numbers for contract workers for oil and gas industry globally does not exists, however, there is a lot of space and job rotation in the industry, and given the demand, the contract workers remain in service (ILO SAD, 2012). As shown in Table 3, Utica formation employment analysis: Industries in Ohio with at least ten employees.

*Table 3: Utica Formation Employment Analysis: Industries in Ohio with at least Ten Employees Source: (Kleinhenz & Associates, 2011)*

| **Category** | **2011** | **2012** | **2013** | **2014** | **2015** |
|---|---|---|---|---|---|
| Support activities for mining | 2 473 | 13 521 | 63 118 | 105 709 | 117 204 |
| Retail trade | 166 | 1 007 | 4 948 | 8 990 | 10 743 |
| Professional and technical services | 149 | 885 | 4 299 | 7 675 | 8 988 |
| Administrative and support services | 107 | 625 | 3 023 | 5 365 | 6 236 |
| Ambulatory health care services | 106 | 634 | 3 215 | 5 911 | 7 060 |

| | | | | | |
|---|---|---|---|---|---|
| Construction | 98 | 660 | 3 235 | 6 673 | 9 077 |
| Food services and drinking places | 71 | 434 | 2 156 | 3 994 | 4 940 |
| Wholesale trade | 54 | 321 | 1 539 | 2 722 | 3 162 |
| Real estate | 43 | 259 | 1 287 | 2 307 | 2 670 |
| Personal and laundry services | 33 | 201 | 1 010 | 1 834 | 2 158 |
| Private households | 24 | 148 | 737 | 1 349 | 1 606 |
| Monetary authorities – central bank | 23 | 133 | 647 | 1 551 | 1 348 |
| Repair and maintenance | 22 | 128 | 616 | 1 084 | 1 247 |
| Rental and leasing services | 21 | 117 | 550 | 948 | 1 078 |
| Hospitals | 21 | 125 | 634 | 1 168 | 1 420 |
| Membership associations and organizations | 18 | 109 | 537 | 967 | 1 144 |
| Nursing and residential care facilities | 15 | 93 | 470 | 873 | 1 075 |
| Fabricated metal product manufacturing | 13 | 75 | 351 | 588 | 633 |
| Securities, commodity contracts, investments | 12 | 69 | 334 | 598 | 699 |
| Management of companies and enterprises | 11 | 65 | 309 | 526 | 575 |
| Educational services | 10 | 63 | 324 | 619 | 786 |
| Performing arts and spectator sports | 10 | 61 | 297 | 543 | 658 |
| **Total** | **3 500** | **19 733** | **93 636** | **161 994** | **184 507** |

### 2.4.4 Shortage of Skilled Workforces

The oil and gas industry is facing skilled workers shortage for a long time, especially in the offshore industry where the working conditions are quite different compared to onshore sites. The survey reports show a trend of skilled workforce shortage in different key areas and high growth companies to growth companies. (Rostand, 2011). Figure 10 shows a shortage of skilled workforce in different categories.

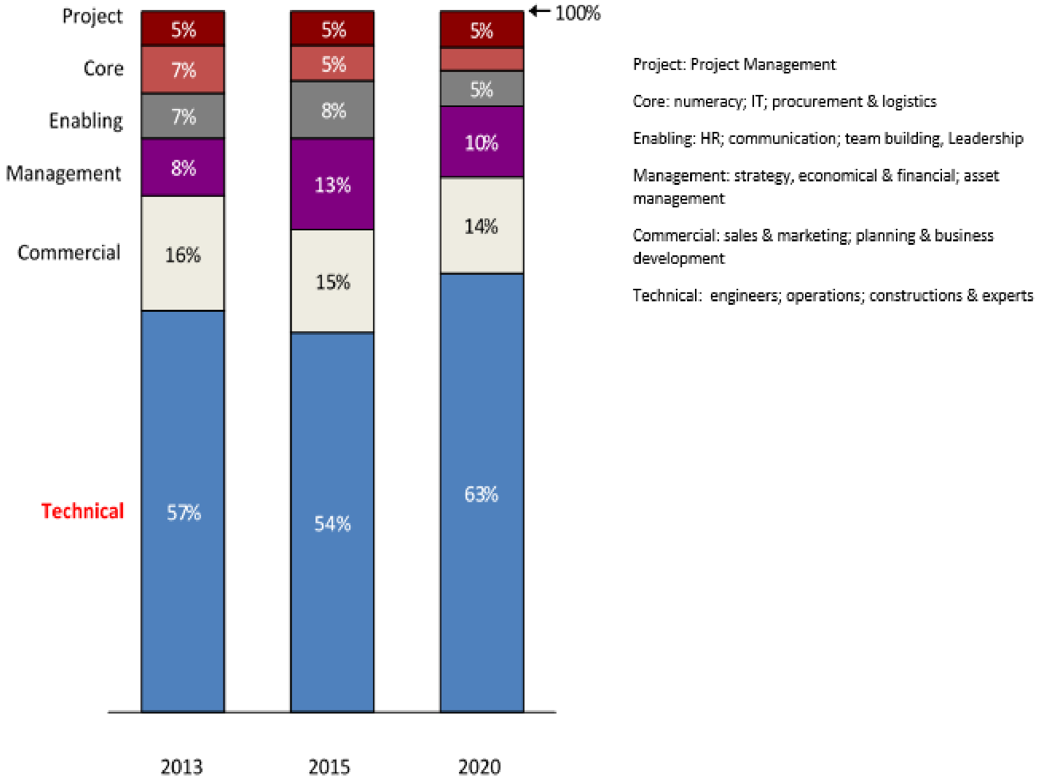


*Figure 10:Top Skill Shortage Faced by Companies Source: (Rostand, 2011)*

A survey conducted by Broadbent (2008), about the key skills shortage areas in oil and gas industry and the respondents were asked to provide their feedback about five skill areas which were technical, management, financial, marketing and leadership. Right around four out of five said that technical skills were a key deficiency area, against half expressing that management skills were a deficiency area. At the base of the rundown were financial skills which 40% recorded as a deficiency area. Strikingly, both marketing and leadership aptitudes were appraised similarly hard to find – simply under a portion of the respondents referring to this issue.

***Technical***

Engineers

Drilling, electrical power, chemical, operations, reservoir, petroleum, pipeline, production, structure, mechanical and those workers with practical expertise, consultancy skills and report writing.

General technical

Drilling and well-site supervisor, IT skilled, alternative energies, fire safety, metallurgist, pressure vessel designers, industrial energy efficiency, particularly research and development and problem-solving skills.

***Scientific***

Microbiologists, geologists/geophysicists, chemists.

***Management***

Project management

Risk management, experienced project managers for small and large projects, technical management skills, contract skills, additional practical compared to theoretical skills, experience engineers with management skills, enhanced industry awareness of grass root problems, and integration work and a global environment.

***People Skills***

Department managers, line management skills, managing managers skills, and a common trend was that these kind of management skills are low and most often best found internally.

***Financial/Commercial/Business Skills***

International finance, energy training, economist, overseas finance management, reporting skills.

***Marketing***

Selling the added value of the company, sales and marketing managers, marketing profile skills, understanding of world markets, closing sales, marketing of technical skills, dealing with clients, commercial skills to develop new markets, managers with broader skills of commercial technology.

***Leadership***

Industry engagement in key initiatives, people that can lead not follow skills, individuals' ability to work alone and lead the team, with all-around skills rather than specific, ability to develop technologists as leaders, business interaction understanding, engineering with MBA degree, self-confident and work in any conditions and levels, project managers.

## 2.5 Overview of Employee Scheduling Models

The term scheduling defines the time-sequence of jobs that need to be performed with allocating required resource i.e. personnel, tools, machinery etc. (Elmaghraby and Artriba, 1997). Koole and van der Sluis (2003) argue that the staff scheduling has gained huge importance in operational research area which emphasizes on efficiently managing the workforce. Also, the scheduling and shift design of employees is highly relevant due to legal issues concerned with employees working timings, employees' health, and most importantly cost associated with the overall process which is defined and promises a high level of services and performance (Urquhart, 2013). According to Castillo-Salazar, Landa-Silva and Qu (2016), the employers often make compromises to keep their best employees in the workplace, and employees also attempt to be flexible in the profession they are working. While, shift scheduling addresses the issue of demand and availability of resources, and there are two type of shift demands i.e. 'hard' and 'soft'. While hard constraints define a fixed number of employees need to be scheduled at a specific time. Whereas, soft constraints define a large number of employees can be assigned within one interval who can also compensate shortage in another interval (Koole and van der Sluis, 2003a). For example, machine operators scheduling relates to hard constraints where a machine should be operational at each point of time. Soft constraints relate with staff scheduling in call centres where a number of call agents are available at each time of interval and sometimes exceeds the required number of employees in order to meet the demand.

Castillo-Salazar, Landa-Silva and Qu (2016) argue that there is the great importance of 'flexible' and 'mobility' in workforce scheduling arraignments. In terms of working timings and tasks, a personnel is considered as flexible, and mobility is concerned with travelling for the purpose of fulfilling the required task, and such type of scheduling issues referred as workforce scheduling and routing problem (WSRP). WSRP highlights the issues where employees should work more and spend less time travelling in scenarios where travelling is also counted as a working period (Fosgerau and Engelson, 2011). Cordeau et al., (2010) argue that in WSRP scenario employees having specific tasks have high importance and it requires an appropriate workforce scheduling and such that a lot of articles in literature admit that the workforce is homogenous with regards to their skills (Castillo-Salazar, Landa-Silva and Qu, 2016). WSRP characteristics that appear most in the literature are defined below:

- ***Time Windows:*** This type of characteristic defines a job that is performed at the client's premises. It is argued that the personnel may commence working once they arrive at the location/site. The schedule of time windows can be tight or flexible that would be according to the contract. Sometimes there is no time window and employees work is based on annualized hours. However, in a few cases, workers can take advantage of over-time wages which makes it comply with time window as a soft constraint (Castillo-Salazar, Landa-Silva and Qu, 2016).
- ***Start and End Location:*** The location of employees start of working is considered as important in various industries where employees start their working from the main office or home up to many locations (Eveborn, Flisberg and Rönnqvist, 2006). In some cases, employees are forced to start the work from the main office due to policies and can return to their home from the field without physically reporting back at the main office (Eveborn et al., 2009).
- ***Qualification and Skills:*** The skill and qualification filters employees job assignments and there are two main groups i.e., a) anyone can perform any task as all employees hold the same level of qualification and skills; b) diverse level of abilities among employees such as healthcare and consulting industries. The complex organization often consider employees skills should be according to the task assigned (Cordeau et al., 2010).
- ***Service Time:*** In the literature, most of the models consider a fixed duration approach, and service time indicates the duration of the task and varies according to employee and type of task. In case service timings are long enough it will limit each personnel to perform a single job, and hence it will decrease the effect on task allocation as every route treat and consider a single job per employee (Castillo-Salazar, Landa-Silva and Qu, 2016).
- ***Teaming:*** Sometimes due to nature of the job teaming is necessary in order to perform a task (Li, Lim and Rodrigues, 2005). In case there is no change in team members then it will be considered as a single unit and it will be assumed that they will start and end the task at the same time. On other hand, if team members are changed based on the task demand, then the synchronizing the arrival of each personnel at the location is required. Whereas, synchronizing within teaming refers to the arrival of employees, not the task they are assigned (Cordeau et al., 2010).

- ***Clusterisation:*** distribution of employees within clusters might be necessary due to various reasons such as employees may not or avoid travelling for more than a few miles. Second, when companies set a certain geographical area for the employees to perform a task. In addition, creating clusters might reduce the size of problems and converting it into clustered sub-problems in order to address the required issues and take actions with ease (Castillo-Salazar, Landa-Silva and Qu, 2016).

Castillo-Salazar, Landa-Silva and Qu (2016) argue that the routing part is also considered as an example of WSRP which is based on vehicle routing problem with time windows (VRPTW). It describes and addresses the issues for minimizing the distance covered by a number of vehicles while they are serving the customers who located at disbursed positions. Where each customer declares a specific time window for visiting and such that delivery vehicle must reach the location within the assigned period (Desrochers, Desrosiers and Solomon, 1992). Moreover, VRPTW is relevant with the employees scheduling and routing where employee’s transportation is considered from one location to another i.e. from the main office to working site (Desaulniers and Lavigne, 1998; Castillo-Salazar, Landa-Silva and Qu, 2016). Multiple trips are referred to as an extension of VRPTW which indicates the cases where employees are required to perform more than one visit to the site in order to complete a series of tasks at the same location. In addition to employee’s trips, vehicle synchronization is also important to WSRP. This is how two are more personnel are modelled in a same method as two or more vehicles are required to arrive simultaneously at the location of the same customer (Bredstrom and Rönnqvist, 2007).

The past literature has addressed WSRP issues in real-world scenarios within various industries. The following subsection presents an overview of the problems and methods used in order to solve the WSRP issue in the industry including scheduling of technicians, home health care, and manpower allocation.

**Home Health Care (HHC):** It is referred to as providing service such as visiting and nursing to the patients at their residence (Bertels and Fahle, 2006). In HHC, nursing staff have time limitations due to the number of working hours and patients’ preferences is also considered and respected within that limited period. When nurses have to visit more than one patient, therefore, transportation modality is presented due to travelling. In HHC, a set of diverse qualification and skills exists, and organizations cannot afford and consider the nurses to have skills in various procedures. Also, the start and end location of nurses may vary such as nurses might depart from their residence or from the main location. Services time also differs for nurses such as 45 minutes of physical therapy to 10 minutes of injection. In addition, activities that are interconnected and arise during job performance such as medication administration. For instance, medication is given in the morning and the second dose will follow after 3 hours schedule (Castillo-Salazar, Landa-Silva and Qu, 2016). According to Cheng and Rich (1998) nursing is not considered with special kind of skills or qualification, however, they propose and work under matching and collaboration method in which bonding between patient and nurse plays an important role where sometimes it is feasible and for some reason not. While their main aim is to reduce the overtime amount and employment as part-time.

Begur, Miller and Weaver (1997) argue that the main approach used in HHC is a hybrid approach in which a combination of mixed integer programming with heuristic either for the scheduling or routing component is applied. In addition, combining two approaches is required when the use of constraint programming is applied in order to get good feasible results and followed by next stage when a series of meta-heuristics including tab search and simulated annealing is applied for improving the quality of solution (Bertels and Fahle, 2006).

**Technician Scheduling:** Mostly companies who are related with telecommunication industry require their employees to perform tasks such as installation and maintenance (Cordeau et al., 2010). This type of problem in literature is referred to as technician and task scheduling problem (TTSP). Telecom sector follows strict time window procedures due to enforcement of jobs to be performed as per commitment. There is a high demand for vehicle routing since technicians have to carry equipment's from one customer to another. In this sector, technician work starts from the company office, however, in some cases, they can carry the equipment and company vehicle from the location close to the next assignment to be carried out. In addition, skills and qualification is of high consideration due to technical job requirements. Also, the level of seniority is also well defined in this sector (e.g. supervisor, senior technician, junior technician etc.). Personnel who are at the senior levels assists and define the service time for a specific task during fieldwork, and such that tasks are treated as independent from one another during the same day working, but in the broader working area sometimes they are asked to work collaboratively. Hence teams are also formed in order to complete the required job having a different set of skills, and such that it helps workers to learn from each other in order to improve their skills and expertise.

Additionally, most of the telecom companies adopt clusterisation approach due to many branches situated in the wider geographical area. Ropke and Pisinger (2006) argue that a heuristics approach is widely used in solving the scheduling issues of technicians, and then local heuristics-based repair and destroy moves are applied in order to improve the solutions. Also, the problems such as employee's allocations, routing, and skill matching are addressed with the use of different heuristics (Cordeau et al., 2010). However, evolutionary approaches such as swarm optimizations are also used to find suitable solutions for cases of up to 300 employees (Günther and Nissen, 2013).

**Manpower Allocation:** According to Li, Lim and Rodrigues (2005), the manpower allocation problem refers to the deployment of a serviceman for performing certain tasks at the customer locations. The key purpose of this is to minimize the usage of personnel, reduce the travel distance, reduce the waiting time, and maximize the tasks assigned and such issue also expresses the example of WSRP (Castillo-Salazar, Landa-Silva and Qu, 2016). The time window is relevant with the manpower issue due to an explicit requirement from customers when they need the manpower. While there is restriction related with working for the number of hours for each personnel. Whereas, the waiting time during the deployment of a serviceman is also included within service time at the customer location. Such issues have been raised and tackled at airports in the context of team scheduling (Dohn, Kolind and Clausen, 2007, 2009). Within manpower allocation, the literature defines three types of methods. Such as exact method uses integer programming (Dohn, Kolind and Clausen, 2009), metaheuristics including tabu search (Lim, Rodrigues and Song, 2004), and relaxed integer programming formulation (Li, Lim and Rodrigues, 2005).

**Security Personnel Routing and Resorting:** In this scenario, security personnel are required to visit customer premises within various location over a period of 24 hours. The common practice used by the various organization in order to hire security personnel when their premises are closed also some cases indicate that security is outsourced all the time (Misir et al., 2011). Most of the time vehicles are used in order to transport security personnel from one location another, and once they reach the facility are required to check the buildings. According to Misir et al., (2011), security companies record 16 types of skills a security guard should have and sometimes the company enforces the personnel to acquire those skills and expertise. While duration of working hour may vary but it should be within the contract. Also, clients are situated in various locations hence they are divided into clusters. This industry is flexible in terms of the contract which leads to various constraints in the problem. Also, it is not irrational in order to define the teams of two are more personnel are often used. Additionally, Chuin and Aldy (2012) used a mathematical approach for solving the problem of security teams for patrolling various underground subway stations within the network. Also, hyper-heuristics is another method which is used for solving the same type of problem, by using simple random and adaptive dynamic heuristics methods followed by an upgrading heuristic (Misir et al., 2011).

Whereas, WSRP refers to the scheduling of skilled workforce within distributed and different geographical locations in order to perform a series of tasks and it is defined within scheduling the tour of the workforce. Tour scheduling process refers to the methods of the workforce is converted into schedules which highlights the shifts that are needing to be staffed on each day by each personnel over the prescribed period. The standard model for tour scheduling is a two-stage scheduling approach (Robbins, 2011). In this approach first step defines the requirement of the staff, and staffing requirements are determined by using a queuing model i.e. an analytical model which measures the queue parameters. According to Koole and van der Sluis (2003), multimodularity was introduced for service priority rule assignment in the queue.  Where a queue is considered as a sequence of tasks that at a controller who is responsible to assign certain sections to a queue (Hajek, 1985). After defining staffing requirements, the next step involves tour scheduling in which the main purpose of tour scheduling is to assign a number of personnel to each possible schedule in order to minimize the staffing requirements at as low cost as possible.

Robbins (2011) argue that while integer programs are difficult to solve, however, change of assumptions in such formulated models can provide a much better and larger model and changes that can improve and increase the size of the model are may include:

***Hours of Operation:*** Expanding the hours of service operations.

***Shift Options:*** Adding more shifts with more flexible options which include part-time options and different shift lengths.

***Breaks:*** Factoring break time into the schedule including meal or rest breaks during the working schedule.

***Variable Shifts:*** Creation of tour based on different days and different shift schedules.

While the increase in staffing flexibility benefits, more cost control perspectives are desirable staffing options. Such an increase in the complexity of optimization issues, staffing scheduling is undesirable from computational outlook. The literature highlights various approach in order to find an appropriate solution for competing goals. All of them can be placed into two main categories:

**Implicit Scheduling Models:** This approach conceptually divides the scheduling problem into two components. Schedules are created without any break. The second component describes that the breaks are then scheduled and assigned to operation schedules. A schedule without breaks i.e., no breaks within a single day or between days at the site. Employees who are on break during any specific time, a separate set of decisional variables are established. breaks and shifts are basically settled independently, even though constraints are built up to guarantee that the breaks will fit into schedule break windows. After completing the optimization, a generally clear methodology can be utilized to allow breaks to singular shifts. In models where this detailing can be consolidated, the understood definition will measure considerably quicker than the explicit set covering approach; requiring somewhere in the range of 25% and half of the PC time required to explain the essential set covering model (Bechtold and Jacobs, 1990). Different models have been created that increase adaptability also, may provide solutions much quicker (Thompson, 1995; Aykin, 1996; Koole and van der Sluis, 2003b). According to Brusco and Jacobs (2000), implicit scheduling models were later stretched out to implicit tour scheduling models which can be used for 24 ×7 activities where workers are engaged over various days. This model settles the scheduling issue for seven days when the days worked are consistent, and all movements are a similar length. Under the conditions, the model significantly decreases the number of decision variables required and makes integer programs that are very appreciable (Robbins, 2011).

**Heuristic Solutions:** In this approach, heuristic algorithms are designed in order to provide a suitable and quick solution to the problem. According to Robbins (2011), a heuristic is a solution technique that is intended to rapidly discover an answer that is exceptional, however not really ideal. Heuristics have the favourable position that they can frequently tackle an issue substantially quicker than a method that is ensured to tackle the issue to optimality. A key weakness is that not just do they regularly not take care of the issue to optimality, yet they more often cannot give an important measure of the optimality gap. Staff scheduling problem and the issue of determination is of high importance when the size of staff is considered, heuristics are frequently utilized to understand the issue. Numerous sorts of heuristics can be used to this issue. With this approach of the planning issue is as yet figured as an integer program, however, heuristics are utilized to either decrease the extent of the issue or to accelerate the solution procedure. The second kind of heuristic plans the issue in an essentially distinct style and such for staff scheduling issue, this is the most regularly done by detailing the issue as a discrete event simulation model and solving it using simulation-based optimization.

***Integer Programming Heuristics:*** The use of heuristics is a common approach within the complex integer programs. One of the suitable approaches is to formulate an integer program model than to apply the heuristics algorithm. (e.g. simulated annealing or genetic algorithm). The second kind of heuristic for comprehending the scheduling IP looks to decrease the span of the problem by reducing with potential solutions. A sensible method is to decrease the number of schedules that can be chosen. A generally basic strategy is to keep away from unequivocal break scheduling, permitting supervisors to oversee breaks based on how conditions change during the process of the shift.

***Simulation-based Heuristics:*** This approach serves as an alternative in order to solve the shift scheduling problems by using a discrete event simulation model. the simulation model deals and process call individually and distribute it. In this method, supervisors can interactively evaluate policy or scheduling changes. Saltzman and Mehrotra (2001) launched an application of simulation modelling at IT support call centre in order to estimate and evaluate priority support services. Additionally, simulation modelling can be used through simulation-based optimization. In which, the use of simulation is to evaluate the schedule then look for an algorithm which provides better solutions. Whereas, the most frequently used technique for the simulation-based method is the application of the analytical method in order to create a casual schedule which is then evaluated on the basis of the simulation model (Robbins and Harrison, 2008).

**Joint Staffing Models:** All other basic models separate shift scheduling and staffing requirements into two distinct phases. Whereas, joint staffing model combines these two phases into one in order to determine the problem. The essential set covering model verifiably makes a few critical presumptions that are free in joint scheduling models. To begin with, by taking as an information the number of specialists required in every period, the model certainly accepts that service level prerequisites are strict in each interim. For example, in call centres focuses with the short interim busy schedule, staffing to fulfil the top entry rate may result in overabundance limit in different periods. In reaction to this issue, some call centres focus to look for to accomplish their service level focuses over a broadened period; maybe multi-day, week, or even multi-month. This is regularly alluded to as a global service constraint. A second issue is an implicit assumption that entry rates are known before the planning scheduling procedure. While the standard queueing model utilized when setting staffing necessities expect that the time between call arrival is random, the models accept the normal rate at which those calls arrive is known. As a rule, this isn't the case, and entries are viewed as doubly stochastic; customers arrive casually with an average rate that itself is random (Jongbloed and Koole, 2001; Brown et al., 2005).

## 2.6 Research Strategy

(a) Determining the risk assessment for staffing size estimation to remote location facilities might not be enough beside the theoretical risk analysis and management. There may be rules and regulations to the particular industry, these factors must be considered in risk assessment and estimation of staff sizing.

The research will examine the case of a Russian company and statistical data. The safety norms and regulations will be analyzed, and solutions will be compared. Generally, it means primary data – infrastructure documentation, risk assessment, reliability calculations. Besides secondary data includes consideration of industrial standards, rules and regulations for staff sizing and operations.

The value of this research study is making conclusions and formulating improvement guidelines on what kind of risk management strategies and practices are done in Russia.

(b) The documentation of a real engineering project is provided by Rosneft. The technology of oil and gas preliminary processing that the facility run will be studied in detail. The number of critical parameters will be determined to be included in the ESD system.

(c) The number of employees providing the service for the ESD system will be chosen according to the size of the system (i.e., the amount of determined critical parameters).

(d) A mixed integer problem will be composed to determine the number of staff (labour force) needed to provide the necessary service to the system and choose the optimal service policy (sequential and parallel service).

# 3 EMPLOYEE SCHEDULING MODEL

## 3.1 Model Description

In this section, a mathematical model for the aggregated decision-making on (a) structure of the safety system, (b) maintenance organization, and (c) workforce organization, is introduced. The model is a mixed integer linear programming model with binary decision variables used for certain maintenance and workforce organization decisions, and integer variables used for workforce scheduling decisions (planning the travelling of employees to and from the facility).

The model's objective function is the cost of the system's life cycle. The cost structure represented in the objective function includes capital expenditures (CAPEX) associated with initial organizational decisions, operational expenditures (OPEX), and evaluation of potential losses associated with the consequences of hazardous events.

The initial organizational decisions include the safety system's architecture, and in addition, the decision on recruiting the workforce. The engineering companies have to provide the necessary maintenance of their solutions throughout the solution's life cycle according to the warranty. In order to provide the necessary service, the company may send their employees from the main offices (headquarters) to the facilities to conduct the necessary tests and maintenance. However, in reality, the engineering companies are usually located in large cities or industrial centers, whereas the oil and gas production sites and the facilities are located in quite remote areas such as, for example, in Russia: in Arctics, North Siberia and West Siberia. This has been discussed in the previous chapters of this thesis.

Travelling from large cities to these remote areas usually include several transportation links (e.g., first travelling from the city where the company's main offices are located to a smaller city closer to the production site, and then travelling with a helicopter from that smaller place to the actual production site). Of course, these trips are quite long and expensive. This is why it has become a common practice to open a subdivision of an engineering company closer to the remote facility or production site location. At this local company's subdivision, local engineers may be hired. Opening the local offices require some initial investments, as well as training the personnel for the specifics of operating and maintaining the hazardous oil and gas industrial facilities. In addition to the savings ensured by avoiding long-distance flights, an advantage of opening the local engineering offices is cheaper labor costs: in many countries, especially in the developing countries, there is a significant difference between the salaries of workers in the big industrial centers and smaller provincial towns.

In the decision-making model below, we are evaluating both options: the possibility of employees travelling from the head offices, and also, opening the local offices, and hiring, and training new employees.

To evaluate the operational expenses associates with the system's functioning (consuming electricity, requiring maintenance tools and spare parts) and organizing the labor force for conducting the maintenance and organizing the travels to the remote facilities and back, a time horizon is introduced in the model. The life cycle of the technological solution may be 10-15 years, however, for the purposes of planning the maintenance, we are considering one-year split into a set of 52 weeks. All the years of the system's life cycle are considered identical.

Due to the life cycle spanning over many years, all the costs need to be adjusted with the consideration of time value of money, thus the life cycle cost evaluated in the model includes the present value of the costs associated with every year of the solution's operations. Therefore, the objective of the decision-making model is minimization of the present values of the costs.

The issues relevant to opening the local offices include the cost of establishing a subdivision of the company and evaluating the staffing size, i.e. the number of engineers to be hired to work at these offices. All of these engineers have to undergo a specialized training, which leads to the costs dependent on the staffing size. All of these engineers receive a certain monthly salary, which is another element in the overall cost structure. Additionally, an important factor that needs to be addressed while determining the staffing size of the local offices, is the limitation on time spent in trips. This limitation is usually determined by the company's management policy, and it may be expressed as a rule that each employee should not spend more than, for example, six months away from his/her home, i.e. the place where the local offices are situated.

The representation of the employee scheduling is based on the set-covering constraint formulation proposed by Dantzig (1954). The formulation is modified for the purposes of the modelling context for oil and gas industrial facilities maintenance. The modification implies extending the meaning of Dantzig's decision variable (how many employees are sent on a particular trip to satisfy the requirement for the number of employees at a particular period of the planning horizon) to specifying the location the employees travel from, and the shift choice the employees are going to work. The shift choice is made between the 8-hour daily work shifts and 12-hours of working daily. Each of these options is associated with particular pay rate (a cost modifier is introduced to reward for the longer working hours). Also, to ensure the continuity of the service, each of these options is associated with the number of people in the crew that travels on a particular trip. For example, if the requirement states that one person should be available at a facility at any time for the purpose of conducting maintenance and repairs, and the daily shift choice is 8 hours, then we need three people working these 8-hour shifts to provide the service for the continuous industrial processes. If the 12-hour shift is chosen, then the crew should consist of two people. Therefore, it is obvious that the choice of the daily shifts influences the staffing size.

Modeling the staffing requirements for the maintenance at a remotely located facility is done for the two kinds of maintenance that are organized at the facility: continuous maintenance and periodic maintenance. The former kind implied repairing or replacing the devices which fail during the normal course of operations. The requirement to the number of people needed for this sort of jobs is based on the policy specified in the engineering solution's warranty. An example of such a requirement may be given as a statement that during the course of operations, all the device failures in the automated safety system while the whole system is still in the good state, should be fixed within a pre-defined amount of time (let's say, within 8 hours).

Modeling the staffing requirements during the proof tests (when the technology is shut down and all the devices are tested) is done with consideration of the number of devices in each subsystem (the system's architecture), the amount of time needed to test, repair, and/or replace each type of device, and the choice of maintenance policy: parallel or sequential tests. Parallel tests imply that all the devices are tested simultaneously, each by an individual worker. Sequential tests imply that the devices in each subsystem are tested one by one, and therefore it may be done by the same worker. As a result, the choice of maintenance policy influences the downtime of the facility: the parallel tests result in shorter downtime periods, while sequential tests take longer to run, resulting in longer downtime, which in turn is associated with greater production losses.

Another aspect influencing the technology downtime is the test interval (TI) or the period of time between two consecutive shutdowns for the system's overhaul. The shorter the TI is, the more time is devoted to proof tests, and the greater the production losses are. However, another aspect of the TI choice is its impact of the system's reliability: the more seldom the proof tests are run, the bigger the chances are for the unwanted consequences in case of hazardous events. The latter is represented in the model as an evaluation of the possible cost of incident, or risk cost.

Representing the overall reliability that the safety system provides is done by evaluation of the average probability of failure on demand ($PFD_{avg}$) in the model. This indicator is the key safety measure specified in the international standards IEC61508 and IEC61511. The factors in our model that influence the value of this indicator are the system's architecture (the greater the redundancy, the less the $PFD_{avg}$ is), and the test interval (the greater the TI, the greater the $PFD_{avg}$ is). To model the changes in $PFD_{avg}$ we are using a linear evaluation of how adding a device into a particular subsystem of the safety system's architecture improves the system's reliability, and thereby decreases the $PFD_{avg}$. The evaluations of the $PFD_{avg}$ for the base configuration and the improvements are done with the help of a Markov model explained in (Redutskiy, 2017d).

To conclude, the mathematical model developed in this thesis intends to facilitate making the following decisions:

- Architecture for each subsystem (number of identical components in each subsystem)
- Opening (or not opening) a location office and train the new workers
- Number of crews going on particular trips from particular locations to work particular daily schedules
- Maintenance policy (parallel or sequential proof testing)
- Test interval (TI) the time between two consecutive shutdowns for the complete system's overhaul

The last-mentioned decision (TI) is represented as a model's parameter in the mathematical formulation provided in the next subsection. We are running the model for several options of the test interval, and the results of the model runs will be analyzed and compared to gain insight into how the choice of TI influences the model's outcome.

## 3.2 Mathematical Model Formulation

*Table 4: Notations for the model*

| Indices and sets | |
|---|---|
| $\tau$ | index for years of the technological solution's life cycle $\tau \in \{1..LC\}$ |
| $w$ | index for weeks in a year, $w \in \{1..52\}$ |
| $t$ | index for trips, $t \in \{1..N^{trips}\}$ |
| $s$ | index for daily shift options, $s \in \{1..N^{shifts}\}$ |
| $p$ | index for maintenance policies, $p \in \{Par, Seq\}$ |
| $q$ | index for subsystems of the safety instrumented system, $q \in \{1..N^{subsystems}\}$ |
| $r$ | index for redundancy options for each subsystem $r \in \{1..N_q^{redundancy}\}$ |
| $l$ | index for the company locations, $l \in \{HQ, LC\}$ |
| **Parameters** | |
| $f$ | frequency of technological incidents |
| $C^{risk}$ | cost of risk, i.e. losses estimation due to the incident taking place |
| $T^{startup}$ | time required to start the facilities after a shutdown |
| $C^{prod.loss}$ | production losses due to facility shutdown (per hour) |
| $C_{t,l}^{trip}$ | cost of trip *t* from location *l* |
| $S_s^{crew}$ | crew size corresponding to the daily shift choice *s* |
| $\beta_s$ | cost modifier corresponding to the shift choice *s* |

| | |
|---|---|
| $C_l^{comp}$ | cost of establishing a company at location *l* |
| $C^{train}$ | training cost per worker (for the new local company/department) |
| $C_l^{wage}$ | monthly wage for employee of a company / department at location *l* |
| $T_l^{max}$ | upper bound on travel time (number of weeks per year) for the employees working at location *l* |
| $\sigma_{t,w}$ | binary covering parameter showing if week *w* is covered by trip *t* or not |
| $C_q^{device}$ | purchase cost of one device for subsystem *q* of the safety system |
| $C_q^{el}$ | yearly electricity consumption by one device in subsystem *q* of the safety system |
| $T_q^{repair}$ | repair time for one device for subsystem *q* of the safety system |
| $T^{repair.max}$ | upper bound on the repair time for the safety system |
| $N_{q,r}^{devices}$ | number of devices in subsystem *q* corresponding to the redundancy option *r* |
| $\gamma^{parts}$ | share/percentage of the safety system cost intended for spare parts |
| $PFD_{avg}^{base}$ | average probability of failure on demand for the base configuration of the safety system (minimal redundancy) |
| $PFD_{q,r}^{improve}$ | improvement of the $PFD_{avg}$ given the redundancy choices for the corresponding subsystems |
| $TI$ | test interval: number of weeks between two consecutive proof tests |
| $\delta$ | discount factor (to reflect the changes in the time value of cashflows) |
| $B$ | large number |
| **Decision variables** | |

| | |
|---|---|
| $x_{q,r}^{arch}$ | architecture choice r for particular subsystem *q* (binary) |
| $x_{l}^{company}$ | if a company is established at location *l* (binary) |
| $x_{p}^{maint}$ | maintenance policy choice (binary) |
| $y_{t,s,l}^{travel}$ | number of crews travelling from location *l* on trip *t* to work with daily schedule *s* (binary) |
| $y_{w}^{required}$ | number of crews required to be present at the facility in week *w* |

The objective function is minimizing the total cost of the safely system's life cycle. Lifecycle costs include capital expenditures (CAPEX), i.e. initial investments, and also yearly operational expenditures and risk costs. The two latter terms are relevant for every year of the system's operations; therefore, their present value should be calculated.

$$\mathbf{min}\, C^{lifecycle} = CAPEX + \sum_{\tau=1}^{LC} \frac{1}{(1+\delta)^{\tau-1}} \cdot (OPEX_{\tau} + RISK\_COST_{\tau}) \tag{1}$$

Capital expenditures will include the costs associated with opening a local division of a company (the first term in the summation), the cost of training the newly hired local employees expressed as the cost of training one employee multiplied by the evaluation of the necessary staffing size for the local company (LC) subdivision (the second term in the summation), and the cost of purchasing the necessary number of devices for the safety system's architecture (the third term in the summation).

$$\begin{aligned} CAPEX = &\sum_{l \in \{HQ, LC\}} C_{l}^{comp} \cdot x_{l}^{company} \\ &+ C^{train} \cdot \sum_{w=1}^{52} \sum_{t=1}^{N^{trips}} \sum_{s=1}^{N^{shifts}} \frac{S_{s}^{crew} \cdot \sigma_{t,w}}{T_{LC}^{max}} \cdot y_{t,s,l}^{travel} \\ &+ \sum_{q=1}^{N^{subsystems}} \sum_{r=1}^{N_{q}^{redundancy}} C_{q}^{device} \cdot N_{q,r}^{devices} \cdot x_{q,r}^{arch} \end{aligned} \tag{2}$$

Operational expenditures for one year of running the technological process with the safety system includes the following four elements: salaries for the employees dedicated to the safety system maintenance from both company headquarters and local subdivision (the first term in the summation); travel costs for all the employees from both company headquarters and local subdivision with consideration of each trip cost and duration and the daily shift work (the second term in the summation); electricity consumption by the devices included in the safety system's architecture (the third term in the summation); the cost of spare parts required for maintenance, which is calculated as a given percentage of the overall purchase cost of the devices (the fourth term in the summation); and finally, the production losses due to the technology downtime for the planned maintenance (the fifth term in the summation).

$$
\begin{aligned}
OPEX = 12 \cdot \sum_{l \in \{HQ,LC\}} C_l^{wage} \cdot \sum_{w=1}^{52} \sum_{t=1}^{N^{trips}} \sum_{s=1}^{N^{shifts}} \frac{S_s^{crew} \cdot \sigma_{t,w}}{T_{LC}^{max}} \cdot y_{t,s,l}^{travel} \\
+ \sum_{l \in \{HQ,LC\}} \sum_{t=1}^{N^{trips}} \sum_{s=1}^{N^{shifts}} C_{t,l}^{trip} \cdot \beta_s \cdot S_s^{crew} \cdot y_{t,s,l}^{travel} \\
+ \sum_{q=1}^{N^{subsystems}} \sum_{r=1}^{N_q^{redundancy}} C_q^{el} \cdot N_{q,r}^{devices} \cdot x_{q,r}^{arch} + \gamma^{parts} \\
\cdot \sum_{q=1}^{N^{subsystems}} \sum_{r=1}^{N_q^{redundancy}} C_q^{device} \cdot N_{q,r}^{devices} \cdot x_{q,r}^{arch} + \frac{52}{TI} \\
\cdot \left( x_{par}^{maint} \cdot \max_q T_q^{repair} + x_{seq}^{maint} \cdot \sum_{q=1}^{N^{subsystems}} T_q^{repair} \right) \\
\cdot C^{prod.loss}
\end{aligned}
\qquad (3)
$$

Risk cost evaluate the potential losses due to the residual risk. This evaluation is based on a certain estimation of the potentially dangerous consequences of a hazardous event and the way the safety system's architecture improves (decreases) the probability of failure on demand, i.e. the probability of the safety system's not reacting to a hazardous situation.

$$RISK\_COST = C^{risk} \cdot f \cdot \left( PFD_{avg}^{base} - \sum_{q=1}^{N^{subsystems}} \sum_{r=1}^{N_q^{redundancy}} PFD_{q,r}^{improve} \cdot x_{q,r}^{arch} \right) \tag{4}$$

The system of constraints includes a group of logical constraints for the binary variables, a group of constraints relevant to employee scheduling, and a constraint to ensure the appropriate safety level.

The first logical constraint declares that the company headquarters are already exiting:

$$x_{HQ}^{company} = 1 \tag{5}$$

The following set of logical constraint relevant for each subsystem of the safety system says that only one architecture option may be chosen:

$$\sum_{r=1}^{N_q^{redundancy}} x_{q,r}^{arch} = 1, \quad q = \{1..N^{subsystems}\} \tag{6}$$

The following logical constraint declares that only one maintenance policy may be chosen for organizing maintenance during the periodic proof tests:

$$\sum_{p \in \{Par,Seq\}} x_p^{maint} = 1 \tag{7}$$

The following constraint is a version of the set-covering constraint for employee scheduling modified for the purposes of this problem setting. The constraint is declared for every week in any given year of the system’s operation

$$\sum_{l \in \{HQ,LC\}} \sum_{t=1}^{N^{trips}} \sum_{s=1}^{N^{shifts}} \sigma_{t,w} \cdot y_{t,s,l}^{travel} \geq y_w^{required}, \quad w = \{1..52\} \tag{8}$$

In addition to the set-covering constraint, there may be an additional constraint imposed on the number of workers required to travel from the company headquarters to assist/supervise the maintenance work, for example, during the proof tests:

$$\sum_{l\in\{HQ,LC\}} \sum_{t=1}^{N^{trips}} \sum_{s=1}^{N^{shifts}} \sigma_{t,w} \cdot y_{t,s,l}^{travel} \geq y_w^{req.from.HQ}, \ \ w = \{1..52\} \tag{9}$$

To estimate the workforce requirements, i.e. the number of workers that need to be continuously available at the facility at any given point of time, we will first consider the normal course of operations.

The requirement for continuous maintenance during the operations is keeping each of the subsystems in the good condition. This implies that at least one device in each subsystem should be working, whereas others (if they are in the failure mode) have to be repaired or replaced within a pre-defined time:

$$y_w^{required} \geq \sum_{q=1}^{N^{subsystems}} \left( \left( \sum_{r=1}^{N_q^{redundancy}} N_{q,r}^{devices} \cdot x_{q,r}^{arch} \right) - 1 \right) \cdot \frac{T_q^{repair}}{T^{repair.max}}, \tag{10}$$

$$w = \{1..52\}$$

The demand for workforce during the proof tests depends on the number of the devices chosen for each subsystem’s architecture and the maintenance policy choice:

$$y_w^{required} \geq \sum_{q=1}^{N^{subsystems}} \left( x_{par}^{maint} \cdot 1 + x_{seq}^{maint} \cdot \sum_{r=1}^{N_q^{redundancy}} N_{q,r}^{devices} \cdot x_{q,r}^{arch} \right), \tag{11}$$

$$w = \{TI; 2 \cdot TI; 3 \cdot TI; \dots; 52\}$$

The following constraint is the logical connection between the binary variable corresponding to the establishment of a local subdivision and the workers travelling from this location to the facility. To put this simply: the local employees may be used for maintenance only if the local company subdivision is established:

$$y_{t,s,LC}^{travel} \leq B \cdot x_{LC}^{company}, \quad t \in \{1..N^{trips}\}, s \in \{1..N^{shifts}\} \tag{12}$$

The next constraint limits the amount of time employees from the company headquarters are allowed to spend on maintenance of the given particular solution (due to the fact that these employees are also involved in other projects):

$$\sum_{w=1}^{52} \sum_{t=1}^{N^{trips}} \sum_{s=1}^{N^{shifts}} S_s^{crew} \cdot \sigma_{t,w} \cdot y_{t,s,l}^{travel} \leq T_{HQ}^{max}, \quad t \in \{1..N^{trips}\}, s \in \{1..N^{shifts}\} \tag{13}$$

A constraint for the employees from the local office close to the facility is not specified, because this decision-making model aims to establish the size of the staff of the local office, if it is opened at all, and the expression for this size is provided in the objective function, where the time the employees spend in the trips is already limited down to the required bound.

The last constraint aims to enforce the necessary safety requirement to the system developed. According to the international standards, the safety integrity level 3 requirement is the value of the average probability of failure on demand being no greater than 0.0001:

$$PFD_{avg}^{base} - \sum_{q=1}^{N^{subsystems}} \sum_{r=1}^{N_q^{redundancy}} PFD_{q,r}^{improve} \cdot x_{q,r}^{arch} \leq 1 \cdot 10^{-4} \tag{14}$$

## 3.3 AMPL Code

### Code for the AMPL model-file:

```
set Trips;      # possible trip alternatives
set Shifts;     # shift alternatives (daily work)
set Locations;  # set of engineering department locations
set Policies;  # set of proof testing policies
set Subsystems;
set Options;
set links within {Subsystems, Options};
param T;        # time horizon (total number of weeks)
param TI;       # number of weeks between two consequtive proof tests
set TestWeeks;
param CTrip{Trips, Locations}; # trip cost
param CrewSize{Shifts};        # 1 worker available any time means: 3 workers for 8h-shifts or 2 workers for 12h-shifts
param CmodifierShift{Shifts};  # cost modifer associated with the shift duration
```

```
param CLocation{Locations};    # cost of establishing a company at a particular location

param TrainingPerWorker;       # cost of worker training for a company established in the remote area

param UBTravelTimePerYear{Locations}; # Max travel time of head office engineers and local engineers

param covering{trip in Trips, week in 1..T} binary; # column generation

param discount <= 1;


param Cdevice{subsys in Subsystems}; # cost of one device in a particular subsystem of the SIS

param Trepair{subsys in Subsystems}; # repair time for one device in a particular subsystem of the SIS

param PFDavg_base; # PFDavg for base / minimum configuration specified in SILreq[subsys]

param Nsubsys{subsys in Subsystems, red in Options: (subsys, red) in links}; # structure of a subsystem

param Improvement{subsys in Subsystems, red in Options: (subsys, red) in links}; # PDFavg improvement coefficients

param ElConsumption{Subsystems};

param ProdLoss; #production losses per hour

param Crisk; # losses due to hazards in case it occurs

param freq; # frequency of the risk occurrence without SIS

param StartUpTime;

param SparePercent;

param MaxRepairTime; # UB on repair time for any particular subsystem of the SIS (8 hours)

param wage{Locations};


var x_architecture{subsys in Subsystems, red in Options: (subsys, red) in links} binary; # subsystems' architectures

var x_location{Locations}    binary; # if a facility is established at a location

var y_trip{Trips, Shifts, Locations} >=0 integer; # if the trip is chosen from a particular location with a particular
daily shift schedule

var x_maint_policy{Policies} binary; # choice of maintenance policy: parallel or sequential

var StaffRequired{1..T}   integer; # number of people required to be present at the facility at any time during a given
week

var StaffRequiredSpec{1..T} integer; # number of people from the headquarters required to be present at the facility at
any time during a given week


############################

#### OBJECTIVE FUNCTION ####

############################

minimize Total_Cost:

# CAPEX

sum{loc in Locations} CLocation[loc] * x_location[loc] +

sum{subsys in Subsystems, red in Options: (subsys, red) in links} Cdevice[subsys] * Nsubsys[subsys, red] *
x_architecture[subsys, red] +

TrainingPerWorker * sum{week in 1..T, trip in Trips, shift in Shifts}y_trip[trip, shift, "L2_LC"]*covering[trip,
week]*CrewSize[shift]/UBTravelTimePerYear["L2_LC"] +

# OPEX

sum{year in 1..15} 1 / ( (1+discount)^(year-1) ) * (

12 * sum{loc in Locations}wage[loc] * (sum{week in 1..T, trip in Trips, shift in Shifts} y_trip[trip, shift,
loc]*covering[trip, week]*CrewSize[shift]/UBTravelTimePerYear[loc]) +

sum{trip in Trips, shift in Shifts, loc in Locations} CTrip[trip, loc] * CmodifierShift[shift] * y_trip[trip, shift, loc]
+

sum{subsys in Subsystems, red in Options: (subsys, red) in links} ElConsumption[subsys] * Nsubsys[subsys, red] *
x_architecture[subsys, red] +

sum{subsys in Subsystems, red in Options: (subsys, red) in links} SparePercent * Cdevice[subsys] * Nsubsys[subsys, red] *
x_architecture[subsys, red] +

T/TI * ( x_maint_policy["Seq"] * sum{subsys in Subsystems}Trepair[subsys] + x_maint_policy["Par"] * max{subsys in
Subsystems}Trepair[subsys] + StartUpTime) * ProdLoss +

Crisk * freq * (PFDavg_base - sum{subsys in Subsystems, red in Options: (subsys, red) in links}Improvement[subsys, red] *
x_architecture[subsys, red]) );



#####################

#### CONSTRAINTS ####

#####################
```

```
#LOGICAL CONSTRAINTS
subject to Headquarters_already_existing:
x_location["L1_HQ"] = 1;


subject to One_architecture_for_each_subsystem{subsys in Subsystems}:
sum{red in Options: (subsys, red) in links}x_architecture[subsys, red] = 1;


subject to One_maintenance_policy:
sum{pol in Policies} x_maint_policy[pol] = 1;


# SCHEDULING
subject to Set_Covering_Constraint_Total{week in 1..T}:
sum{trip in Trips, shift in Shifts, loc in Locations} covering[trip, week] * y_trip[trip, shift, loc] >=
StaffRequired[week];


subject to Set_Covering_Constraint_From_HeadOffice{week in 1..T}:
sum{trip in Trips, shift in Shifts} covering[trip, week] * y_trip[trip, shift, "L1_HQ"] >= StaffRequiredSpec[week];


subject to Workfore_Requirements_Operations{week in 1..T}:
StaffRequired[week] >= sum{subsys in Subsystems} (sum{red in Options: (subsys, red) in links}Nsubsys[subsys,
red]*x_architecture[subsys, red] - 1) *  Trepair[subsys]  / MaxRepairTime;


subject to Workfore_Requirements_Tests_Total{week in TestWeeks}:
StaffRequired[week] >= sum{subsys in Subsystems}(  x_maint_policy["Seq"] * 1 + x_maint_policy["Par"] * sum{red in
Options: (subsys, red) in links}Nsubsys[subsys, red]*x_architecture[subsys, red]  );


subject to Workfore_Requirements_Tests_From_HeadOffice{week in TestWeeks}:
StaffRequiredSpec[week] >= 1;


subject to Local_Workers_if_there_is_a_Local_Office{trip in Trips, shift in Shifts}:
y_trip[trip, shift, "L2_LC"] <= 40 * x_location["L2_LC"];


subject to PFDavg_requirement:
PFDavg_base - sum{subsys in Subsystems, red in Options: (subsys, red) in links}Improvement[subsys, red] *
x_architecture[subsys, red] <= 1e-4;


subject to Time_in_travels_HQ:
sum{week in 1..T, trip in Trips, shift in Shifts}covering[trip, week] * y_trip[trip, shift, "L1_HQ"] * CrewSize[shift] <=
UBTravelTimePerYear["L1_HQ"];
```

## Code for the RUN-file:

```
reset;
model S1.mod;
data S1.dat;


option solver cplex;
solve;


printf "\n LIFE CYCLE COST \n" > S1.sol;
display Total_Cost > S1.sol;


printf "\n CAPITAL EXPENDITURES \n" > S1.sol;
display
sum{loc in Locations} CLocation[loc] * x_location[loc] +
```

```
sum{subsys in Subsystems, red in Options: (subsys, red) in links} Cdevice[subsys] * Nsubsys[subsys, red] * x_architecture[subsys, red] +

TrainingPerWorker * sum{week in 1..T, trip in Trips, shift in Shifts}y_trip[trip, shift, "L2_LC"]*covering[trip, week]*CrewSize[shift]/UBTravelTimePerYear["L2_LC"] > S1.sol;


printf "\n OPERATIONAL EXPENDITURES \n" > S1.sol;

display

sum{year in 1..15} 1 / ( (1+discount)^(year-1) ) * (

12*wage["L2_LC"]*(sum{week in 1..T, trip in Trips, shift in Shifts}y_trip[trip, shift, "L2_LC"]*covering[trip, week]*CrewSize[shift]/UBTravelTimePerYear["L2_LC"]) +

12*wage["L1_HQ"]*(sum{week in 1..T, trip in Trips, shift in Shifts}y_trip[trip, shift, "L1_HQ"]*covering[trip, week]*CrewSize[shift]/UBTravelTimePerYear["L1_HQ"]) +

sum{trip in Trips, shift in Shifts, loc in Locations} CTrip[trip, loc] * CmodifierShift[shift] * y_trip[trip, shift, loc] +

sum{subsys in Subsystems, red in Options: (subsys, red) in links} ElConsumption[subsys] * Nsubsys[subsys, red] * x_architecture[subsys, red] +

sum{subsys in Subsystems, red in Options: (subsys, red) in links} SparePercent * Cdevice[subsys] * Nsubsys[subsys, red] * x_architecture[subsys, red] +

T/TI * ( x_maint_policy["Seq"] * sum{subsys in Subsystems}Trepair[subsys] + x_maint_policy["Par"] * max{subsys in Subsystems}Trepair[subsys] + StartUpTime) * ProdLoss +

Crisk * freq * (PFDavg_base - sum{subsys in Subsystems, red in Options: (subsys, red) in links}Improvement[subsys, red] * x_architecture[subsys, red]) ) > S1.sol;


printf "\n WORKFORCE EXPENDITURES \n" > S1.sol;

display

sum{year in 1..15} 1 / ( (1+discount)^(year-1) ) * (

12*wage["L2_LC"]*(sum{week in 1..T, trip in Trips, shift in Shifts}y_trip[trip, shift, "L2_LC"]*covering[trip, week]*CrewSize[shift]/UBTravelTimePerYear["L2_LC"]) +

12*wage["L1_HQ"]*(sum{week in 1..T, trip in Trips, shift in Shifts}y_trip[trip, shift, "L1_HQ"]*covering[trip, week]*CrewSize[shift]/UBTravelTimePerYear["L1_HQ"]) +

sum{trip in Trips, shift in Shifts, loc in Locations} CTrip[trip, loc] * CmodifierShift[shift] * y_trip[trip, shift, loc] ) > S1.sol;


printf "\n RISK COSTS \n" > S1.sol;

display

sum{year in 1..15} 1 / ( (1+discount)^(year-1) ) * (

Crisk * freq * (PFDavg_base - sum{subsys in Subsystems, red in Options: (subsys, red) in links}Improvement[subsys, red] * x_architecture[subsys, red]) ) > S1.sol;



printf "\n\n\n SAFETY SYSTEM'S ARCHITECTURE \n" > S1.sol;

display x_architecture > S1.sol;


printf "\n COMPANIES' LOCATIONS \n" > S1.sol;

display x_location > S1.sol;


printf "\n STAFF REQUIREMENTS \n" > S1.sol;

display StaffRequired > S1.sol;


printf "\n NUMBER OF WORKERS TRAVELLING GIVEN TRIPS AND WORKING GIVEN SHIFTS \n" > S1.sol;

display y_trip > S1.sol;


printf "\n PROOF TESTING POLICY \n" > S1.sol;

display x_maint_policy > S1.sol;


printf "\n STAFF SIZE AT THE LOCAL COMPANY \n" > S1.sol;

display sum{week in 1..T, trip in Trips, shift in Shifts}y_trip[trip, shift, "L2_LC"]*covering[trip, week]*CrewSize[shift]/UBTravelTimePerYear["L2_LC"] > S1.sol;


printf "\n STAFF SIZE DEVOTED TO THAT PROJECT AT THE HEADQUARTERS \n" > S1.sol;
```

```
display sum{week in 1..T, trip in Trips, shift in Shifts}y_trip[trip, shift, "L1_HQ"]*covering[trip, week]*CrewSize[shift]/UBTravelTimePerYear["L1_HQ"] > S1.sol;
```

# 4 COMPUTATIONAL RUN OF THE EMPLOYEE SCHEDULING MODEL

## 4.1 Data for the Computations

The data for the computational example presented below is based on the real example provided in (Redutskiy, 2017d) with the necessary information added from the same project. The original data is adopted from one of the Rosneft's projects in Western Siberia.

Table 5 contains the data regarding the devices used in the safety instrumented systems that are considered for this example. In this table and further, the costs are adjusted to fictional currency units (CU). This is done for two reasons: first, there is no formal agreement between the company who shared the data for this research, therefore, the real information regarding the devices should not be disclosed. And second, the original values of the prices in this example are relevant for the year 2012 when the actual engineering and IT solution entered the phase of implementation. Ever since 2012 there were significant changes in the prices in Russia due to political conflicts and also, some fluctuation of oil prices and the currency exchange rates in 2015.

In addition, the cost of the spare parts necessary for maintenance is taken as 20% of the overall device purchase costs.

The base configuration for every subsystem of the SIS is considered to be 1oo2 architecture which implies having at least two devices in each subsystem at least one of which should be working for the whole subsystem to perform its function properly.

The alternatives for the trips and daily schedules (shifts) are provided in Table 6. The pay rates provided are the daily subsistence payments provided by the company sending their employees on a business trip to a remote location. The travel costs are calculated as the costs of airplane and helicopter flight tickets.

*Table 5: Data about the devices used in the safety system*

| # | Subsystem | Basic configuration | Architecture options | Device costs, CU | Electricity consumption CU per year |
|---|---|---|---|---|---|
| 1 | Level transmitters | 1oo2 | 1oo2, 1oo3, 1oo4, 1oo5 | 850 | 1 |
| 2 | Fire detectors | 1oo2 | 1oo2, 1oo3, 1oo4, 1oo5, 1oo6, 1oo7, 1oo8 | 85 | 0.5 |
| 3 | Programmable logic controllers | 1oo2 | 1oo2, 1oo3, 1oo4 | 12500 | 500 |
| 4 | Safety valves (group 1) | 1oo2 | 1oo2, 1oo3, 1oo4, 1oo5 | 1750 | 200 |
| 5 | Safety valves (group 2) | 1oo2 | 1oo2, 1oo3, 1oo4, 1oo5 | 1750 | 200 |
| 6 | Pump drives | 1oo2 | 1oo2, 1oo3, 1oo4, 1oo5 | 1250 | 75 |

The airplane ticket from Moscow to the regional center in the area where the oilfield is located costs 1000 CU per one trip per person. In addition, the helicopter flight from that regional center to the production site (to the facility location) costs 150 CU per person per one flight. There is also a system of rewards introduced by the company based on how long employees stay at the production site during the business trip. The rewards are calculated based on the quarterly bonuses policy that the engineering company uses. All these data from Table __ are used to calculate the cost of each trip alternative for the model. The trip alternatives are generated as all possible trips of the specified duration that can start at any week during the time horizon of one year (52 weeks). The set-covering matrix is provided further in this chapter in the text of the data-file for AMPL model.

Monthly wages for the employees were taken as 1500 CU per employee per month at the company's headquarters, and 500 CU per employee per month at the local offices.

*Table 6: Shift and trip types with associated costs*

| | | | |
|---|---|---|---|
| ***Daily shift alternatives:*** | | | |
| | | **# of workers for continuous service** | **Pay rate, CU/day** |
| 1 | 8 hours of work, 16 hours of rest | 3 | 125 |
| 2 | 12 hours of work, 12 hours of rest | 2 | 250 |
| ***Trip alternatives:*** | | | |
| | | **Pay rate cost modifier** | |
| 1 | 1 week trip | 1 | |
| 2 | 2 weeks trip | 1.25 | |
| 3 | 4 weeks trip | 1.5 | |
| 4 | 6 weeks trip | 2 | |

Among the data necessary for the model, we also have the test interval (TI) options: these are

- every 8 weeks,
- every 12 weeks,
- every 26 weeks,
- every 40 weeks, and
- every 52 weeks.

As mentioned earlier, the choice of TI significantly influences the solution's reliability expressed in the form of the indicator $PFD_{avg}$.

The values of the $PFD_{avg}$ for the base configuration of the safety system (with 1oo2 redundancy in every subsystem) and for every option of TI have been calculated in Matlab according to the model developed by (Redutskiy, 2017d). In addition, the same model was used to produce the values of the improvements in $PFD_{avg}$ with adding more devices into the subsystems' architecture. The numbers are provided in the AMPL data file further in this chapter.

Other data used for this model includes evaluation of production losses as 50000 CU per hour of the facility downtime. The risk cost (or the cost of an incident) has been assumed as

1 000 000 000 CU per incident. The frequency of the incidents without the safety systems has been evaluated as 0.105 incidents per year.

The facility downtime is evaluated partly as the time spent on proof testing the system, and partly as a pre-defined start-up time necessary to run the technology again after a shutdown. This start-up time is 12 hours. As for the continuous maintenance, we are assuming that during the normal course of operations all the devices have to be restored within 8 hours.

## 4.2 Representation of the Data in AMPL

```
set Subsystems := LT FD PLC SV1 SV2 PD;

set Options := LT_2 LT_3 LT_4 LT_5 FD_2 FD_3 FD_4 FD_5 FD_6 FD_7 FD_8 PLC_2 PLC_3 PLC_4 SV1_2 SV1_3 SV1_4 SV1_5 SV2_2
SV2_3 SV2_4 SV2_5 PD_2 PD_3 PD_4 PD_5;

set links :=

LT  LT_2   LT  LT_3   LT   LT_4   LT  LT_5

FD  FD_2   FD  FD_3   FD   FD_4   FD  FD_5  FD FD_6  FD FD_7  FD FD_8

PLC PLC_2  PLC PLC_3  PLC  PLC_4

SV1 SV1_2  SV1 SV1_3  SV1  SV1_4  SV1 SV1_5

SV2 SV2_2  SV2 SV2_3  SV2  SV2_4  SV2 SV2_5

PD  PD_2   PD  PD_3   PD   PD_4   PD  PD_5;


set Trips := T001 T002 T003 T004 T005 T006 T007 T008 T009 T010 T011 T012 T013 T014 T015 T016 T017 T018 T019 T020
             T021 T022 T023 T024 T025 T026 T027 T028 T029 T030 T031 T032 T033 T034 T035 T036 T037 T038 T039 T040
             T041 T042 T043 T044 T045 T046 T047 T048 T049 T050 T051 T052 T053 T054 T055 T056 T057 T058 T059 T060
             T061 T062 T063 T064 T065 T066 T067 T068 T069 T070 T071 T072 T073 T074 T075 T076 T077 T078 T079 T080
             T081 T082 T083 T084 T085 T086 T087 T088 T089 T090 T091 T092 T093 T094 T095 T096 T097 T098 T099 T100
             T101 T102 T103 T104 T105 T106 T107 T108 T109 T110 T111 T112 T113 T114 T115 T116 T117 T118 T119 T120
             T121 T122 T123 T124 T125 T126 T127 T128 T129 T130 T131 T132 T133 T134 T135 T136 T137 T138 T139 T140
             T141 T142 T143 T144 T145 T146 T147 T148 T149 T150 T151 T152 T153 T154 T155 T156 T157 T158 T159 T160
             T161 T162 T163 T164 T165 T166 T167 T168 T169 T170 T171 T172 T173 T174 T175 T176 T177 T178 T179 T180
             T181 T182 T183 T184 T185 T186 T187 T188 T189 T190 T191 T192 T193 T194 T195 T196 T197 T198 T199;

set Shifts := S1_8h S2_12h;

set Locations := L1_HQ L2_LC;

set Policies := Seq Par;

param T := 52;

param TI := 8; # options 8  12  26  40  52;

set TestWeeks :=  8 16 24 32 40 48;

#set TestWeeks := 12 24 36 48;

#set TestWeeks := 26 52;

#set TestWeeks := 40;

#set TestWeeks := 52;


param discount = 0.05;


param CrewSize       := S1_8h 3       S2_12h 2;

param CmodifierShift := S1_8h 1.0     S2_12h 1.5;

param CLocation := L1_HQ 0     L2_LC 1e6;

param TrainingPerWorker := 6000;

param UBTravelTimePerYear := L1_HQ 8     L2_LC 36;


param Cdevice:= LT 850  FD 85  PLC 12500  SV1 1750  SV2 1750  PD 1250;
```

```
param Trepair:= LT 1    FD 1   PLC 4      SV1 2     SV2 2     PD 2;
param PFDavg_base := 6.589e-05;
#param PFDavg_base := 1.349e-04;
#param PFDavg_base := 5.245e-04;
#param PFDavg_base := 1.083e-03;
#param PFDavg_base := 2.280e-03;
param Nsubsys :=    LT LT_2 2  LT LT_3 3  LT LT_4 4  LT LT_5 5
                    FD FD_2 2  FD FD_3 3  FD FD_4 4  FD FD_5 5  FD FD_6 6  FD FD_7 7  FD FD_8 8
                    PLC PLC_2 2  PLC PLC_3 3  PLC PLC_4 4
                    SV1 SV1_2 2  SV1 SV1_3 3  SV1 SV1_4 4  SV1 SV1_5 5
                    SV2 SV2_2 2  SV2 SV2_3 3  SV2 SV2_4 4  SV2 SV2_5 5
                    PD  PD_2 2   PD  PD_3 3   PD  PD_4 4   PD  PD_5 5;

param Improvement:= LT LT_2 0    LT LT_3 0.328706e-7    LT LT_4 0.329540e-7  LT LT_5 0.329543e-7
                    FD FD_2 0    FD FD_3 0.243245e-6    FD FD_4 0.486490e-6  FD FD_5 0.594831e-6  FD FD_6 0.689178e-6  FD
FD_7 0.778610e-6  FD FD_8 0.859130e-6
                    PLC PLC_2 0  PLC PLC_3 0.453133e-7  PLC PLC_4 0.453209e-7
                    SV1 SV1_2 0  SV1 SV1_3 0.133291e-4  SV1 SV1_4 0.140945e-4  SV1 SV1_5 0.141412e-4
                    SV2 SV2_2 0  SV2 SV2_3 0.133291e-4  SV2 SV2_4 0.140945e-4  SV2 SV2_5 0.141412e-4
                    PD  PD_2 0   PD  PD_3 0.133315e-4   PD  PD_4 0.141448e-4   PD  PD_5 0.141448e-4;
/*
param Improvement:= LT LT_2 0    LT LT_3 0.775481e-7  LT LT_4 0.778105e-7  LT LT_5 0.778113e-7
                    FD FD_2 0    FD FD_3 0.193245e-6  FD FD_4 0.436490e-6  FD FD_5 0.544831e-6  FD FD_6 0.639178e-6  FD
FD_7 0.728610e-6  FD FD_8 0.809130e-6
                    PLC PLC_2 0  PLC PLC_3 0.542889e-7  PLC PLC_4 0.543019e-7
                    SV1 SV1_2 0  SV1 SV1_3 0.303754e-4  SV1 SV1_4 0.326788e-4  SV1 SV1_5 0.328682e-4
                    SV2 SV2_2 0  SV2 SV2_3 0.303754e-4  SV2 SV2_4 0.326788e-4  SV2 SV2_5 0.328682e-4
                    PD  PD_2 0   PD  PD_3 0.303908e-4   PD  PD_4 0.328863e-4   PD  PD_5 0.328863e-4;



param Improvement:= LT LT_2   0  LT LT_3   0.411406e-6   LT LT_4  0.413840e-6  LT LT_5 0.413854e-6
                    FD FD_2   0  FD FD_3   0.143245e-5   FD FD_4  0.386490e-5  FD FD_5 0.494831e-5  FD FD_6 0.589178e-
5  FD FD_7 0.678610e-5  FD FD_8 0.759130e-5
                    PLC PLC_2 0  PLC PLC_3 0.114588e-7  PLC PLC_4 0.114664e-7
                    SV1 SV1_2 0  SV1 SV1_3 0.146029e-3  SV1 SV1_4 0.164810e-3  SV1 SV1_5 0.167594e-3
                    SV2 SV2_2 0  SV2 SV2_3 0.146029e-3  SV2 SV2_4 0.164810e-3  SV2 SV2_5 0.167594e-3
                    PD  PD_2  0  PD  PD_3  0.146098e-3  PD  PD_4  0.167676e-3   PD  PD_5 0.167676e-3;
    */
       /*
param Improvement:= LT LT_2 0  LT LT_3 0.848993e-6  LT LT_4 0.855447e-6  LT LT_5 0.855494e-6
                    FD FD_2 0  FD FD_3 0.203245e-5  FD FD_4 0.446490e-5  FD FD_5 0.554831e-5  FD FD_6 0.649178e-5  FD
FD_7 0.738610e-5  FD FD_8 0.819130e-5
                    PLC PLC_2 0  PLC PLC_3 0.190262e-7  PLC PLC_4 0.190457e-7
                    SV1 SV1_2 0  SV1 SV1_3 0.283178e-3  SV1 SV1_4 0.329003e-3  SV1 SV1_5 0.337911e-3
                    SV2 SV2_2 0  SV2 SV2_3 0.283178e-3  SV2 SV2_4 0.329003e-3  SV2 SV2_5 0.337911e-3
                    PD  PD_2 0   PD  PD_3 0.283288e-3   PD  PD_4 0.338045e-3   PD  PD_5 0.338045e-3;

param Improvement:= LT LT_2 0  LT LT_3 0.191978e-5  LT LT_4 0.193949e-5  LT LT_5 0.193969e-5
                    FD FD_2 0  FD FD_3 0.443245e-5  FD FD_4 0.686490e-5  FD FD_5 0.794831e-5  FD FD_6 0.889178e-5  FD
FD_7 0.978610e-5  FD FD_8 1.159130e-5
                    PLC PLC_2 0  PLC PLC_3 0.374781e-7  PLC PLC_4 0.375374e-7
                    SV1 SV1_2 0  SV1 SV1_3 0.583234e-3  SV1 SV1_4 0.706455e-3  SV1 SV1_5 0.739855e-3
                    SV2 SV2_2 0  SV2 SV2_3 0.583234e-3  SV2 SV2_4 0.706455e-3  SV2 SV2_5 0.739855e-3
                    PD  PD_2 0   PD  PD_3 0.583410e-3   PD  PD_4 0.740083e-3   PD  PD_5 0.740083e-3;
  */
```

```
param ElConsumption := LT 1 FD 0.5 PLC 500 SV1 200 SV2 200 PD 75;
param ProdLoss := 50000;
param Crisk := 1000000000;
param freq := 0.105;
param StartUpTime := 12;
param SparePercent := 0.2;
param MaxRepairTime := 8;
param wage := L1_HQ 1500   L2_LC 500;


param covering:
     1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52:=
T001 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T002 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T003 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T004 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T005 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T006 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T007 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T008 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T009 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T010 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T011 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T012 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T013 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T014 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T015 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T016 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T017 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T018 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T019 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T020 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T021 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T022 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T023 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T024 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T025 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T026 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T027 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T028 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T029 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T030 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T031 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T032 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T033 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T034 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T035 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T036 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T037 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T038 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
T039 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0
T040 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0
T041 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0
T042 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0
```

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|T043|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|0|0|0|0|0|0|0|0|0|
|T044|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|0|0|0|0|0|0|0|0|
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|T046|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|0|0|0|0|0|0|
|T047|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|0|0|0|0|0|
|T048|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|0|0|0|0|
|T049|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|0|0|0|
|T050|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|0|0|
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|T061|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
|T062|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
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|T067|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
|T068|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
|T069|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
|T070|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
|T071|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
|T072|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
|T073|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
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|T080|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
|T081|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
|T082|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
|T083|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
|T084|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
|T085|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
|T086|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
|T087|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
|T088|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|1|1|0|0|0|0|0|0|0|0|0|0|0|0|0|0|0|
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## 4.3 Results of the Optimization Run

The model described in the previous sections has been run in AMPL five times for the different values of the test interval: 8, 12, 26, 40, and 52 weeks between the proof tests. The linear model has been solved with the help of CPLEX solver. The results are summarized in Table 7, Table 8 and Table 9 and further, some discussion is provided.

*Table 7: Modeling results: life cycle cost and its components*

| TI, weeks | Life Cycle Cost, CU | CAPEX, CU | OPEX, CU | Workforce costs, CU | Risk costs, CU |
|---|---|---|---|---|---|
| 8 | 61 827 516 | 1 119 620 | 57 048 200 | 3 599 550 | 60 146 |

| | | | | | |
|---|---|---|---|---|---|
| 12 | 43 531 055 | 1 135 120 | 38 210 000 | 4 127 860 | 50 075 |
| 26 | 22 529 693 | 1 143 120 | 17 807 600 | 3 524 350 | 62 623 |
| 40 | 17 255 888 | 1 163 210 | 11 778 900 | 4 244 880 | 68 898 |
| 52 | 14 562 304 | 1 163 210 | 9 155 550 | 4 171 860 | 71 684 |

*Table 8: Modeling results: opening a local facility and staffing requirements*

| **TI, weeks** | **Staff required during operations** | **Staff required during proof tests** | **Local offices** | **Staff size at the local offices** |
|---|---|---|---|---|
| 8 | 2 | 13 | yes | 14 |
| 12 | 3 | 16 | yes | 17 |
| 26 | 3 | 17 | yes | 17 |
| 40 | 4 | 24 | yes | 19 |
| 52 | 4 | 20 | yes | 19 |

*Table 9: Modeling results: architecture choice for the subsystems*

| **TI, weeks** | **Level transmitters** | **Fire detectors** | **Controllers** | **Safety valves 1** | **Safety valves 2** | **Pump drives** |
|---|---|---|---|---|---|---|
| 8 | 1oo2 | 1oo2 | 1oo2 | 1oo2 | 1oo2 | 1oo3 |
| 12 | 1oo2 | 1oo2 | 1oo2 | 1oo3 | 1oo3 | 1oo3 |
| 26 | 1oo2 | 1oo2 | 1oo2 | 1oo3 | 1oo4 | 1oo4 |
| 40 | 1oo2 | 1oo6 | 1oo2 | 1oo5 | 1oo5 | 1oo4 |
| 52 | 1oo2 | 1oo6 | 1oo2 | 1oo5 | 1oo5 | 1oo4 |

As for the choices of number of employees travelling on particular trips and working particular daily schedules, the algorithms chooses to cover most of the maintenance service required by one-week trips from the local offices. The solution prioritizes crews of three employees travelling to work 8-hour shifts.

In addition, while preparing the model in AMPL, a requirement has been enforced that during the periodic overhauls (proof tests) at least one automation systems engineer from the headquarters should be available at any time. To comply with this requirement, the algorithm chose to the minimal number of crews with minimal number of people travelling from the headquarters, i.e. two people working 12-hour shifts.

## 4.4 Discussion of the Results

Analyzing the resulting costs in Table 7, we may conclude that the cost of hiring and transportation of the employees is a significant component of the operational expenditures.

It may be pointed out that the choices of trips and shifts are made entirely from the viewpoint of minimizing the travel costs. The overwhelming majority of the trips are made from the local offices, which is explained by significantly less travel costs from the local offices in comparison to the travels from the headquarters. All the trips are chosen to be one week long. This may be attributed to the increasing cost modifiers for longer trip durations which were introduced earlier. The choice of the 12-hour shift for the workers who travel from the headquarters for the proof testing is explained again by saving on the travel costs: the expensive long-distance flight for the crew of two workers is cheaper than for the crew of three workers.

The most significant component of the operational expenditures is, in case of our example, is production losses due to the facility downtime. We observe the notable reduction in these operational costs when we increase the TI (thereby decreasing the test frequency). The less often the shutdowns are conducted, the less production losses there are. That is why we observe significant savings (in OPEX, and by extension, in the life cycle cost) for the cases of less frequent periodic proof tests.

Capital expenditures grow with the choice of a greater TI, which may be explained by the need for a greater redundancy in the subsystems' architecture (refer to Table 9), and therefore greater investments into purchasing the devices.

The risk costs exhibit interesting trend: with increase of TI, the risk cost first decreases, and then starts increasing again. When the proof tests are chosen to be conducted frequently (the TI is the smallest possible), the higher risk costs may be explained by the choice of the minimal possible architecture of the safety system. When the proof tests are conducted seldom (one every 6 months or even less often) the risk cost is growing due to the fact that maintenance plays beings to play less and less of a role in the overall safety system's reliability.

There is a point, when the risk cost is minimal, which corresponds to conducting the maintenance every 12 weeks (every three months). This non-linear behavior of the risk cost must be attributed to the evaluations of the $PFD_{avg}$ parameter, that was taken as a given input for this model. It is obvious that evaluation of this parameter is a complex procedure, which is not possible to be fit into the linear modeling framework in any way other than how it has been done in the model in this thesis.

From these modeling results, we can conclude that the best choice of test interval is conducting the tests once a year, since the production losses due to the downtime play the most important role in the cost evaluation. However, in real-life situation, the companies are often concerned not only in the overall cost evaluation, but also in such things as the public image. In this case, the companies would definitely consider the risk costs behavior when making their decisions.

Evaluation of the $PFD_{avg}$ reliability indicator, and by extension, evaluation of the risk costs is an area of reliability modelling and risk management, which often employs multi-objective optimization. In such problems, some objectives represent the reliability indicators while others represent various cost indicators. Development of the multi-objective model with detailed calculation of $PFD_{avg}$ and incorporating the employee scheduling would be a worthy direction for future research.

# 5 CONCLUSIONS

In this master thesis project covers the area of risk management, reliability, workforce planning and scheduling and life cycle evaluation of an engineering solution within one framework. A mathematical model for simultaneously making decisions regarding the structure of an automated safety system, its maintenance and organizing the workforce to conduct this maintenance, have been covered within one mixed integer linear programming model.

This linear modelling approach to such a broad scale of decision-making is quite efficient. The CPLEX solver is able to produce a solution to this developed model within a few seconds, therefore such an approach may be applicable to large systems and large-scale problem settings. This is especially relevant given that fact that automated control and safety systems usually have to process tens, hundreds or even thousand technological parameter values continuously during the operations.

The limitation of the presented decision-making approach is in avoiding the calculation of the crucially important reliability indicator: the average probability of failure on demand, which is calculated via complex procedures given the safety system's configuration and the choices on its maintenance.

Another limitation of this work is concentrating on merely two possible testing policies: parallel or sequential testing. In reality, there are other testing approaches, such as staggered testing or partial testing, which allow for the subsystems to be proof-tested while the operations are conducted and thereby to reduce the overall downtime. These maintenance policy decisions have a significant impact on the workforce requirements, as it has been observed from the modelling results. Therefore, consideration of such complex maintenance policies could provide better and more realistic decision, relevant to actual engineering practice.

As it has been stated before, one of the directions to develop and expand this research in future is to address these decision-making problems in the multi-objective formulation. In this thesis, only the system's life cycle cost has been addressed, which does not clearly represent the priorities of all the parties involved in the engineering projects in oil and gas industry. A multi-objective formulation would allow to explore the trade-offs between the reliability and the economic indicators of an industrial solution's performance.

To conclude, this research project attempts to highlight the importance of the employee scheduling issues for the context of oil and gas industry which moves more and more to the unconventional, remote, offshore and Arctic locations. The transportation of the personnel to these locations and back proves to play a substantial role in the life cycle of the engineering projects.

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