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PILOT STUDY ON THE APPLICATION OF EMPLOYEE SCHEDULING FOR THE PROBLEM OF SAFETY INSTRUMENTED SYSTEM DESIGN AND MAINTENANCE PLANNING FOR REMOTELY LOCATED OIL AND GAS FACILITIES

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ABSTRACT
The technology of production, transportation, and processing of oil and gas involves various hazardous processes. To mitigate the risk that these processes pose, the technological solutions work closely with the automated control and safety systems. The design and organisation of maintenance for the automated safety instrumented systems (SIS) have a significant bearing on the overall safety of operations in this industry. Over the past few decades, many hydrocarbon resources have been discovered in unconventional environments, such as remote, offshore, and arctic locations. Transportation of engineering personnel to these remote locations and back, and thereby, the organisation of the shift work poses additional challenges for the petroleum sector. Under such circumstances, the workforce-related costs play a considerable role in the overall cost of the technological solution and thereby the decisions regarding the workforce organisation should be addressed in the framework of evaluating and choosing the appropriate safety measures. That is why the research presented in this paper aims to address the lifecycle of the technological solution integrating the problems of SIS design, maintenance planning, and employee scheduling into a single decision-making framework to optimise the set of technical and organisational safety measures inherent in the SIS. The performance and maintenance of the SIS are described with a Markov model of device failures, repairs and technological incidents occurrence. The employee scheduling part of the mathematical model utilises the set-covering formulation of maintenance crews taking particular trips. A black-box optimisation algorithm is used to find reasonable solutions to the integrated problem of engineering design and workforce planning. The decisions include the choices of the components and structures for the safety system, the facility overhaul frequencies, the maintenance personnel size, as well as the schedules of trips and shifts for the crews.

KEY WORDS
black-box optimisation, employee scheduling, maintenance planning, Markov Analysis, oil and gas industry, remote and arctic locations, risk management, safety instrumented system

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INTRODUCTION

Over the past few decades, the oil and gas industry has seen a shift to exploration, development, and production of the hydrocarbon reserves in nonconventional environments such as deep sea and Arctic locations due to many large deposits having been discovered in these locations (Bourmistrov et al., 2015). The harsh environmental conditions at such locations as well as their poor accessibility by means of transportation pose significant challenges to the industry whose processes are inherently hazardous due to the handling of toxic, flammable and explosive substances. When incidents occur on such hazardous facilities, they may result in significant economic losses, harm to the personnel and technological assets, substantial damage to the environment, and negative socio-political consequences. Proper design of the processes and the industrial instrumentation has a crucial bearing on the safety of operations in the oil and gas sector. To ensure the safe and proper performance of the hazardous technology, Safety Instrumented Systems (SIS) are put in place as an essential part of the process automation system. Safety measures inherent in SISs are defined and regulated by the international standard IEC 61508 (1997) and IEC 61511 (2003), as well as the national regulations of the petroleum producing countries, such as (STC Industrial safety, 2014) and (Norwegian Oil and Gas, 2001). The standards define safety instrumented systems through the structure of an automated system's control loop (Fig. 1), which includes process value transmitters (i.e., sensors), logic solvers (programmable logic controllers), and final control elements (actuators, e.g. valves, pump drives, switches, etc.). At any hazardous facility, several SISs are usually put in place. They act as a series of barriers protecting the personnel, technological assets, environment, etc. Some of these SISs aim to prevent the hazardous event from taking place, while others aim to mitigate the consequences in case such an event occurs. Among the safety systems at the oil and gas facilities aimed at preventing the incidents, Emergency Shutdown (ESD) systems are considered to ensure the most substantial risk reduction (CCPS, 2010). The ESD systems monitor the course of the processes and shut down the technology when they detect situations that may quickly escalate to hazards with dire consequences. Therefore, careful consideration of the measures related to the design and maintenance of the ESD systems are crucial for the smooth and safe operations.

Maintenance of the technological solution and the automated SISs is an issue of particular importance. The safety systems' instrumentation is put in place to mitigate the risks. However, SISs themselves contribute to the uncertainty of operations. The devices may either fail to perform their function or trigger a process shutdown without any actual critical situation. To ensure the proper work of the safety barriers, first of all, the instrumentation's self-diagnostic capability is used, and second, periodic proof tests are performed. Therefore, maintenance at oil and gas facilities is conducted in two forms: continuous and periodic. The former implies repairing or replacing the devices as soon as problems become revealed by their self-diagnostics. The latter comprises the full-scale checking and repairing of the instrumentation and the technological units, which has to be performed with a particular frequency.

A certain number of engineers should be continuously available at the facility to monitor the operations and, when necessary, conduct the maintenance. As stated earlier, many production sites are nowadays located in unpopulated areas far from large cities and industrial centres. Engineering personnel in the petroleum sector has to engage in shift-type of work: workers travel to the remotely-located facility and stay there for a certain period. During these periods, the daily work is organised using a specific (i.e., work–rest) schedule. The specifics of continuous and periodic maintenance require that at any point in time, a certain number of servicepersons should be available to perform maintenance.

The purpose of this research is to address the problems of the SIS design, maintenance planning, and employee scheduling to optimise the set of technical and organisational safety measures in a single decision-making framework to explore the reliability and economic trade-offs and at the same time ensure

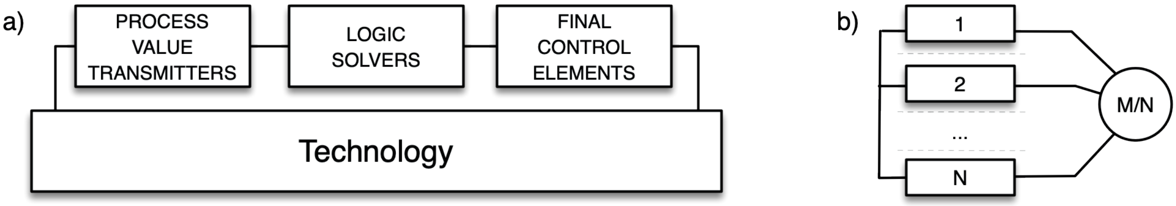

Fig. 1. Structure of a safety instrumented system: a) control loop; b) M-out-of-N redundancy architecture

Source: based on IEC 61508 (1997) and IEC 61511 (2003).

proper maintenance that the SIS requires for smooth and safe operations.

1. OVERVIEW OF THE RESEARCH AREA

The problem of safety instrumented system design has been addressed by various researchers over the past four decades. An extensive overview of modelling approaches relevant to the design and operations of industrial safety systems may be found in the book (Kuo & Zuo, 2003). The two international standards, namely IEC 61508 (1997) and IEC 61511 (2003), provide an insight into safety and reliability quantification. The standards primarily suggest applying such approaches as Reliability Block Diagrams and Fault Tree Analysis as two straightforward and visual methods. Some researchers, e.g., Bukowski (2006), Jin et al. (2011), and Redutskiy (2017) suggest applying Markov Analysis as a flexible modelling tool allowing to incorporate various nuances of device failures and repairs as well as technological incidents and restorations.

In addition to the issues of reliability of the engineering solution, this paper highlights an aspect of workforce planning and employee scheduling as they are relevant to maintenance work conducted at remotely-located hazardous facilities. As stated in (van den Bergh et al., 2013), the early models were based on a set-covering formulation proposed by Dantzig (1954). In the paper (Castillo-Salazar et al., 2016), the authors provide an overview of various applications of employee scheduling models and issues relevant to the various problem settings. Among the kinds of personnel scheduling problems named by these researchers, one class of problems (referred to as "workforce scheduling and routing problems") is perhaps most relevant to this study. This category of scheduling problems relates to certain requirements for servicepersons to arrive at a given location and perform the necessary activity. Real-life applications of such problems include nurse visitations of patients at their homes, technicians performing repairs at the clients' location, security personnel patrolling the premises, etc. A distinctive characteristic of this class of workforce problems is that the demand for personnel is deterministic and it has to be satisfied exactly, unlike many other problem settings such as call centres or retail stores where the demand is stochastic. This aspect is especially relevant to oil and gas facilities given the hazardous nature of the processes operated by this industry.

The research (Helber & Henken, 2010) highlights an important issue related to the broad pool of employee scheduling models. Decisions directly influencing the staffing size requirements and decisions on scheduling the shifts should be made simultaneously in one modelling framework. It would help to explore a trade-off between the quality of the process performance and the workforce-related costs.

An interested reader may refer to the paper (van den Bergh et al., 2013) as a very comprehensive overview of the personnel scheduling issues, models and solution approaches. The authors review a variety of problem settings, details regarding shift organisation, workers' qualifications, and many other aspects.

In this paper, the problem of SIS design, maintenance planning and employee scheduling is addressed with the idea of exploring a trade-off between the investments into the SIS's complexity, expected losses (due to the process downtime and the costs associated with the residual risk), as well as the costs associated with workforce organisation measures. The lifecycle cost is evaluated, and personnel requirements are estimated based on SIS design and maintenance-related decisions and the system's performance evaluated by means of Markov Analysis, while the employee scheduling is modelled as a set-covering problem considering the location of the engineering company, the duration of the trips, and the working hours. The genetic algorithm is applied to solve the problem for several experiment settings.

2. PROBLEM FORMULATION

This paper follows the research (Redutskiy, 2017) on the safety system design and maintenance, and elaborates on it with consideration of maintenance organisation decisions through employee scheduling, which is a relevant issue for modern-day oil and gas industry, while production operations move to non-conventional environments and locations. The aspect of workforce organisation becomes quite important since the personnel transportation costs from the industrial centres to these remote production sites and back starts playing a significant role in the overall costs of designed industrial solutions. Also, the data for the computational example presented in the next section, such as device options, their reliability characteristics, and costs, architecture alternatives, etc., are adopted from the mentioned research.

Further, in this section, a generalised mathematical model formulation for the aggregated decision-making on the safety system design, maintenance planning, and workforce organisation is presented.

The investment decisions comprise the automated system's components and architecture, and also, an aspect of recruitment of the workforces necessary to ensure the maintenance of the technological solutions throughout its operations. To provide this service, the company may send employees from the main offices (or headquarters), which are in many cases located in large industrial centres. The production sites, on the other hand, are located in remote areas. Sending the engineering personnel from large cities to these remote areas usually includes a combination of various means of transportation, such as airplane flight to some smaller place located closer to the production site, and afterwards, a helicopter flight to the actual production site such as an offshore platform or an Arctic location poorly attainable by transportation. Such trips usually turn out to be rather long and costly. For such situations, it has become a common practice to open a subsidiary company in a city or a town located not too far from the facility location and hire local engineers. Initial investments associated with establishing a local subsidiary are mostly related to training the newly hired personnel to operate the facilities and processes specific to the oil and gas sector. In this research, the optimisation model accounts for both options: sending the maintenance personnel from the head offices as well as opening local offices.

The operational costs include such aspects as electricity consumption, replenishment of maintenance tools and spare parts, production losses due to facility downtime, and also, workforce-related costs, such as travel costs, subsistence costs, and wages. The safety system's life is usually ten years or more. However, to account for maintenance requirements, one-year timespan is split into a set of 52 weeks to estimate the annual costs of operations.

The employee-scheduling part of the model is based on the set-covering formulation proposed by Dantzig (1954). The requirement for maintenance personnel has to be satisfied exactly given the hazardous nature of the processes in the oil and gas industry. Therefore, the "hard" demand constraint is used in the model. The workforce scheduling formulation is extended to account for the possibility of workers travelling from different locations (headquarters and subsidiary), as well as the organisation of daily work–rest schedule. The daily schedule alternatives are 8-hour daily work shifts and 12-hours shifts. Pay rates are adjusted for various trip duration options and daily work schedules to reward the employees for the longer working periods.

The maintenance personnel requirements are modelled for the two kinds of maintenance: continuous and periodic. The former implies dealing with device failures during facility operations. For this phase, the number of workers needed at the facility is calculated based on the warranty rules stating that all the failures should be fixed within a specified amount of time. Personnel requirements for the proof tests are declared with consideration of each system's architecture and the amount of time needed to test and repair each device.

The system's reliability is quantified through the average probability of failure on demand (PFDavg) indicator specified in the standards IEC 61508 and IEC 61511. This indicator has a significant bearing on risk cost, which is associated with the likelihood of hazardous events at the facilities and with risk reduction ensured by the safety system.

To conclude, the problem addressed in this research covers decisions on the following set of safety measures:

- device models for subsystems of process value transmitters, logic solvers, and final control elements;
- MooN redundancy architectures for each subsystem (Fig. 1b);
- additional electrical separation within subsystems;
- test interval (TI), i.e., a period between two consecutive proof tests;
- establishment of a local subsidiary and hiring local engineers;
- number of maintenance workers required to be available at the facility at any point in time to conduct continuous maintenance and periodic proof tests;
- number of crews taking particular trips and working under a particular schedule;
- the daily schedule for a particular trip.

2.1. Reliability quantification

Reliability assessment is conducted in two steps. First, a birth-death Markov model is used to evaluate the device failures in each particular subsystem given the instrumentation choice and the choice of the subsystem's architecture. The modelling results allow obtaining the reliability characteristics (i.e., dangerous and safe failure rates) for each subsystem of the SIS. The second step utilises these reliability characteristics of the subsystems as well as the likelihood of technological incidents within a lifecycle model for the given SIS configuration and technology. This lifecycle evaluation is also conducted with the Markov Analysis. The outcome of this modelling approach includes the values of average probability of failure on demand (PFDavg) for the given technological solution, expected facility downtime, and yearly failure rates for the dangerous and safe failures of the entire SIS.

An interested reader is encouraged to refer to (Redutskiy, 2017) for the details of the mathematical modelling approach used for the lifecycle evaluation of the SIS performance. In this paper, the long descriptions of these models are not provided, because the focus of this research is on employee scheduling aspect.

2.2. Lifecycle modelling. Generalised mathematical model formulation

The text below presents the generalised mathematical model for the design of a safety instrumented system, and planning and organisation of its maintenance through employee scheduling . The notations are explained in Tab. 1.

The objective function (1) is a decision-making criterion for lifecycle cost minimisation. Some arguments in the expression (1) are given in the form of arrays. They are explained in (2).

The developed solution has to maintain a given safety integrity level (SIL), specified in IEC 61508 and IEC 61511. This requirement is expressed in constraint (3). Logical constraints (4) and (5) restrict the selection of the device model and redundancy architecture for each subsystem to only one alternative. The following constraints (6) – (13) are related to employee scheduling. The model decides whether to send the maintenance personnel from head offices of the engineering company or to open a local subsidiary somewhere closer to the remote facility, hire local engineers and use this local workforce for the purpose of SIS maintenance. Since there are two potential sources of the maintenance workforce in this model, it has to be specified that the headquarters of the engineering company already exist (6), whereas the local workforce may only be used if the local offices are opened (7). Constraint (8) is the extension of the Dantzig's set-covering constraint, specifying that the number of crews travelling to the remote facility should meet the demand for the personnel. Constraint (9) imposes an additional requirement for the personnel travelling from the headquarters, in the case certain special skills are needed in some periods (e.g., supervision of proof testing). Constraint (10) declares that only one alternative of the daily work–rest schedule may be chosen for any particular trip. Constraints (11) and (12) specify the required number of workers for the normal course of operations and the weeks when proof testing takes place. Constraint (13) specifies the maximum time an employee may spend on trips to the remote facility.

The economic criterion (1) used in this model is described in detail in (Redutskiy, 2017). The three main components of the lifecycle cost are procurement cost (project start-up costs, cost of the devices and additional measures), cost of operations (electricity consumption, test costs, production losses, workforce-related costs), and risk costs (expected losses associated with residual risk). The cost structure for this research has been expanded by including the relevant aspects of employee scheduling into the capital expenditures (i.e., establishing a local engineering subsidiary, its staffing size, and training the newly hired employees), as well as operational expenditures (i.e., travel costs from headquarters and local offices, pay rates, and trip durations for maintaining the remote facility.

$$\min C_{lifecycle}(X^{dev}, X^{arch}, X^{sep}, Y^{trip}, TI) \tag{1}$$

$$X^{dev} = \{x_{d,q}^{dev}\},\ X^{arch} = \{x_{r,q}^{arch}\},\ X^{sep} = \{x_{q}^{sep}\},\ Y^{trip} = \{y_{t,l}^{trip}, x_{t,s}^{DS}\} \tag{2}$$

$$SIL^{REQ}(X^{dev}, X^{arch}, X^{sep}, TI) = SIL^{*} \tag{3}$$

$$\sum\nolimits_{d \in S_q^{dev}} x_{d,q}^{dev} = 1,\ \ \forall q \tag{4}$$

$$\sum\nolimits_{r \in S_q^{arch}} x_{r,q}^{arch} = 1,\ \ \forall q \tag{5}$$

Tab. 1. Notations for the SIS design, maintenance planning, and employee scheduling optimisation problem

NOTATION	**DESCRIPTION**
	INDICES AND SETS
w	index of weeks in the technological solution's lifecycle
q	index for subsystems of the SIS: q = 1: sensors; q = 2: logic solvers; q = 3: final control elements
d	index for device models
r	index for redundancy architecture options
t	index for trips
s	index for daily schedule options
l	index for locations, from which the maintenance personnel is travelling to the remotely located facility: either headquarters or a locally established subsidiary company $l \in \{HQ, LS\}$
S_q^{dev}	set of device alternatives for subsystem q
S_q^{arch}	set of redundancy architecture alternatives for subsystem q
S^{trip}	set of trips (given all possible trip start times and durations)
S^{DS}	set of alternative daily work schedules (work–rest schedule during each day)
	PARAMETERS
$N_{r,q}$	the total number of devices in subsystem q given the redundancy option r
$M_{r,q}$	number of devices in subsystem q given the redundancy option r required to be operating
$T_{d,q}^{repair}$	repair time of chosen device model d in in subsystem q
$T^{UBrepair}$	the upper bound on the repair time for the entire SIS (for continuous maintenance)
$\sigma_{w,t}$	a binary parameter indicating whether week w is covered by the trip option p or not.
$y_w^{req.fromHQ}$	number of workers from the headquarters of the engineering company (special requirement for employees) who need to be present at the facility during week w
S_s^{crew}	crew size associated with any particular daily work schedule alternative s
T_l^{UBtrip}	upper bound on the time workers from location l spend annually in trips to the remote facility
	FUNCTIONS
$C_{lifecycle}$	lifecycle cost of the solution, [currency units (CU)]
SIL^{REQ}	risk reduction requirement for achieving a certain safety integrity level defined in [7] and [8]
	DECISION VARIABLES
$x_{d,q}^{dev}$	binary variable: equals 1, if device model l is chosen for subsystem q; 0, otherwise
$x_{r,q}^{arch}$	binary variable: equals 1, if redundancy option r is chosen for subsystem q; 0, otherwise
x_q^{sep}	binary variable: equals 1, if additional electrical/physical separation is introduced for subsystem q; 0, otherwise
x_l^{est}	binary variable: equals 1, if a company is established at location l; 0, otherwise
$y_{t,l}^{trip}$	integer variable: number of service crews taking trip t to travel to the facility from location l to ensure maintenance (for each t^{th} trip, the duration of the trip and the starting time is specified)
$x_{t,s}^{DS}$	binary variable for daily schedules: equals 1, if crews taking trip t are to work under daily schedule s
y_w^{req}	integer variable: number of workers whose presence is required at the facility during week w
TI	integer variable: time between two consecutive proof tests, [weeks]

$$y_{t,LC}^{trip} \le B \cdot x_{LC}^{est}, \ \ t \in S^{trip} \tag{7}$$

$$\sum_{l \in \{HQ,LS\}} \sum_{t \in S^{trip}} \sigma_{w,t} \cdot y_{t,l}^{trip} \ge y_w^{req}, \ \ \forall w \tag{8}$$

$$\sum_{t \in S^{trip}} \sigma_{w,t} \cdot y_{t,HQ}^{trip} \ge y_w^{req.fromHQ}, \ \ \forall w \tag{9}$$

$$\sum_{s \in S^{DS}} x_{t,s}^{DS} = 1, \ \ \forall t \tag{10}$$

$$y_w^{required} \ge \sum_q \sum_{r \in S_q^{arch}} x_{r,q}^{arch} \cdot \sum_{d \in S_q^{dev}} \left(N_{r,q} - M_{r,q}\right) \cdot \frac{T_{d,q}^{repair}}{T^{UBrepair}}, \ \ w = \{1..52\} \tag{11}$$

$$y_w^{req} \ge \sum_q \sum_{r \in S_q^{arch}} N_{q,r} \cdot x_{r,q}^{arch}, \ \ w = \{TI; 2 \cdot TI; 3 \cdot TI; \dots; 52\} \tag{12}$$

$$\sum_w \sum_{t \in S^{trip}} \sum_{s \in S^{DS}} S_s^{crew} \cdot x_{t,s}^{DS} \cdot \sigma_{w,t} \cdot y_{t,l}^{trip} \le T_l^{UBtrip}, \ \ \forall l \tag{13}$$

4. Computational experiment

The model of the SIS design, maintenance planning, and employee scheduling demonstrated in the previous section of this paper, cannot be used in the general form for solutions that require the use of classical algorithms applied for integer programming problems. This model utilises the solution to ordinary differential equations (Markov Analysis for reliability quantification) whose dimension depends on the decision variables, and also, the safety integrity level requirement constraint represented in a table form (refer to IEC 61508 and IEC 61511), part of which needs to consider conditional statements. The programming environment of Mathworks Matlab has been used to develop a script function for this model. The developed script includes (Fig. 2):

- two Markov models for reliability assessment of the SIS design, included in the objective function (1) and the SIL requirement constraint (3), as well as logical constraints (4) and (5);
- staffing size evaluation represented in constraints (11) and (12) of the generalised model;
- employee scheduling model minimising the workforce-related costs, which are a part of the objective function (1), whereas the constraints are represented by set-covering formulation (8) and (9), logical expression (10) for the daily work schedule choice, additional logical expressions (6) and (7) related to the establishment of local offices, as well as limitation of the time the personnel has to spend in trips (13);
- the overall lifecycle cost evaluation represented by the objective (1).

A black-box optimisation algorithm, namely a genetic algorithm run by ga solver in Matlab's optimisation toolbox, has been used to solve the problem.

The case data for the experiments, as well as the instrumentation alternatives, have been used from the example provided in the paper (Redutskiy, 2017). The additional data regarding the shift work is provided in Tab. 2. Each employee either works for 8 hours a day (thereby, a crew must consist of three workers to cover all 24 hours in a day) or 12 hours a day (a crew must include two engineers). Each crew can come to the remotely located facility for a duration of one, two, four or six weeks. Each trip may start at any given week of the year (from week 1 to week 52). The company has a system of bonuses in place aimed to reward the employees taking long trips (hence the pay rate cost modifiers). All the costs that are further given and calculated are provided in the artificial currency units (CU), same as in the paper, where the data for the SIS design problem is adopted.

The algorithm for the problem was run three times for three different approaches to periodic testing frequency choice:

- test interval (TI) within the range between 4 and 52 weeks;
- test interval (TI) within the range between 26 and 52 weeks;
- test interval (TI) fixed at the value of 52 weeks.

The results of the algorithm are summarised in Tab. 3. From these results, one may observe that workforce-related expenditures (establishing a local

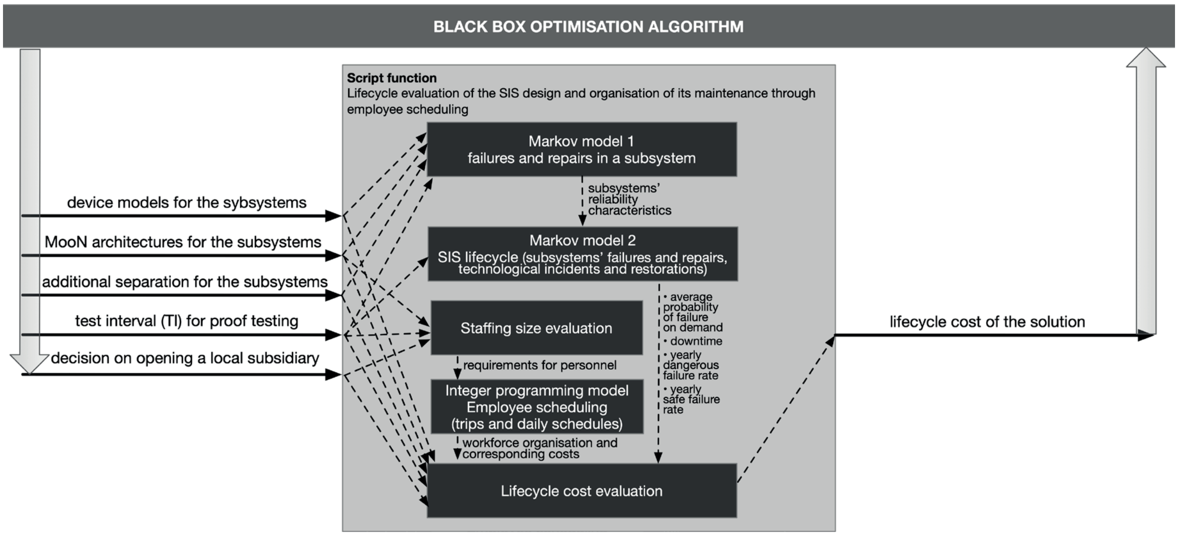

Fig. 2. Summary of the optimisation approach

Tab. 2. Alternatives for trips and daily work schedules

Daily work schedule alternatives			
#	Description	# of workers in a crew	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			
#	Description	Pay rate modifier	
1	1-week trip	1.00	
2	2-week trip	1.25	
3	4-week trip	1.50	
4	6-week trip	2.00	

Tab. 3. Optimisation results for the three experiment settings

Results	**Experiment 1**	**Experiment 2**	**Experiment 3**
	TI choice within range		
	between 4 and 52 weeks	between 26 and 52 weeks	fixed at 52 weeks
Costs, mln CU:			
Lifecycle cost	9.05	10.62	11.59
Procurement cost	1.08	1.12	1.16
Cost of operations	7.76	7.96	8.57
including workforce-related costs	5.18	4.75	4.40
Risk costs	0.21	1.54	1.86
Opening a local subsidiary	yes	yes	yes
Reliability inductors:			
Average probability of failure on demand	6.175·10-5	5.531·10-4	7.017·10-4
Expected facility downtime yearly, h	374	605	837
Choice of TI, [weeks]	12	28	52

subsidiary, hiring and training engineers, transportation of personnel to the facility location and back, wages, etc.) constitute more than 50% of the operational costs of the SIS. Therefore, it appears reasonable that the employee scheduling decisions are made based on the concern of the travel costs. In every experiment, the algorithm suggests opening a local subsidiary and organising the majority of trips from these local offices. "One-shot" arrangement of establishing a local company and training a number of engineers proves to provide considerable savings on travelling to the remote facility in comparison to organising the maintenance entirely from the engineering company headquarters. For all the three experiment settings, the algorithm has determined that no more than 20 maintenance engineers need to be hired for the local subsidiary.

Based on the reliability quantification (the Markov models), the algorithm has determined that four servicepersons are required to be available at the facility at any time to maintain the safety system, whereas during the periodic proof tests, the requirement is 20 workers.

When it comes to the details of employee scheduling, the preferable decision from the alternatives (Tab. 2) is chosen as follows. For the normal course of operations, four crews are used with the four-week shifts with 8-hour daily work schedule (therefore, three people in a crew). For the weeks when the proof tests are conducted, the algorithm suggests one-week shifts with an additional 16 crews of two workers each working on a 12-hour daily schedule.

The workforce-related cost is the highest for Experiment 1 and the lowest for Experiment 3. It may be explained by the decreasing frequency of proof tests in the experiments which leads to fewer expenses for the additional crews travelling to the remote facility for these periodic overhauls.

Another significant component of the operational expenditures is production losses due to the facility downtime. One may observe from Tab. 3 that in the case the proof testing of the SIS is conducted rarely, the expected downtime is quite long. It is attributed to the relatively big chances of the safety system's self-diagnosed dangerous failures and its spurious tripping. On the other hand, the more often the proof testing takes place, the less these two failure mechanisms influence the performance of the SIS, and, thereby, the shorter is the expected downtime and the lower the corresponding production losses.

In addition, according to Tab. 3, the procurement costs for the SIS grow with the choice of a larger TI, which may be explained by the need for more elaborate architectures of the SIS, and, therefore, more significant capital investments into the safety measures.

From these modelling results, one may conclude that the best test interval alternative is three months. Despite the significant role of the workforce-related expenditures, the rapid growth of expected production losses due to downtime has a great bearing on operational costs, and by extension, on the total lifecycle cost of the solution. The demonstrated results indeed reflect the real-life situation: the companies operating the facilities are concerned not only with the investments and hiring decision, but the overall cost evaluation for the solution's lifecycle, with the continuity of operations (little downtime), and also, such things as the preventing the incidents and avoiding the hazardous consequences of the incidents. In this case, the best solution is the most reliable one, i.e., demonstrating the lowest value of the average probability of failure on demand.

These results also prompt companies concerned with uninterrupted operations to pay attention to all possible causes of the facilities' downtime. In some cases, decision-makers' focus on the facility downtime may solely concern the proof testing frequency. Following such an approach, the managers want to restrict the frequency of testing to no more than once every six months or once a year (our Experiments 2 and 3). The modelling results suggest that it is reasonable to consider all possible causes for the downtime: proof tests, self-diagnosed failures, and spurious tripping, to figure out the best solution.

CONCLUSIONS

This research has combined the problems of design of a safety system with planning the workforce to maintain this system. It contributes to the areas of engineering design and employee scheduling. Addressing these issues with the consideration of conducting the maintenance at remotely located facilities and organising the work in shifts, brings up the importance of workforce-related decisions in the lifecycle of the technological solution in the petroleum sector as it faces the new challenges of the non-conventional environments where the resources are nowadays developed. Connecting the employee scheduling decisions with the SIS design and maintenance decisions allows exploring the reliability and economic trade-offs while aiming to ensure the safety of operations at hazardous industrial facilities by properly organising its maintenance.

Employee scheduling as part of this research has been based on the required staffing level suggested by an SIS design decision-making framework with Markov models incorporated in it. In real-life projects of the petroleum sector, the maintenance decisions may be more complex. One of the directions to improve this model is to incorporate various maintenance policies, such as sequential, parallel, staggered, partial and mixed testing policies. These considerations would directly influence the personnel requirements as well as the overall system's performance in terms of reliability.

Finally, this research has been limited to the issues related to the workforce providing the maintenance to the emergency shutdown system alone. As mentioned earlier, in practice, there are several process control systems and automated safety systems deployed for any hazardous industrial facility. All these systems are maintained by the engineering personnel with similar skills. Therefore, it makes sense to approach the problem of a facility personnel planning and scheduling from a broader perspective of the entire process automation solution deployed on a given facility.

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