Safety and Reliability – Safe Societies in a Changing World – Haugen et al. (Eds)
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A modelling methodology for the assessment of preventive maintenance on a compressor drive system

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ABSTRACT: Huge rotary machines are commonly used in oil and gas processing plants for separation, compression and boosting. Their reliability is of high importance to avoid operation downtime and production loss. In this paper, we present a modelling methodology, based on the AltaRica 3.0 modeling language and stochastic simulation, to assess the average production level of a compressor drive system. This system consists of six trains, where each of them contributes to one sixth of the total production capacity. It runs under two operation modes (full and reduced capacity) corresponding to seasonal demand periods (winter and summer). The problem at stake is to design a model at system level that captures the various degradation processes, monitoring policies, and maintenance rules involved in the system under study. The aging of units is represented by means of multiple degradation levels. Given units information provided by monitoring and inspection, preventive and corrective maintenance interventions are decided locally to each unit. Performance indicators such as the cumulative production and production loss over a certain mission time can then be assessed. This paper contributes to the development of engineering models for maintenance assessment based on framework and patterns designed to architecting some typical oil and gas systems.

1 INTRODUCTION

Huge rotary machines are commonly used in oil and gas processing plants for separation, compression and boosting. Ensuring a high reliability of these machines is of primary importance to avoid operation downtime and production loss. As of today, this high reliability is achieved thanks to robust-by-design machines, and by rigorous preventive maintenance policies (DNV-GL-RP-002 2014, API-RP-7L 2006). Nevertheless, rigorous preventive maintenance comes with a high cost. This is the reason why the oil and gas industry is currently moving to the so-called condition-based approach (Gustavsson and Eriksen 2005, Markeset et al. 2013). In order to deploy a condition-based maintenance policy, one needs to assess its potential benefit and risk over more traditional approaches.

In this paper, we present the results of a preliminary study we made on a compressor drive system. This system consists of six trains, where each of them contributes to one sixth of the total production capacity. The system runs under two operation modes (full and reduced capacity) corresponding to two distinct seasonal demand periods (winter and summer). Maintenance interventions have to be scheduled during the low demand season where some of the trains can be stopped while still fulfilling the demand.

We present here the modelling methodology we used, together with modelling patterns and simulation experiments. This methodology relies on the AltaRica 3.0 language Rauzy (2008) and Prosvirnova (2014) and stochastic simulation. It aims at developing models that make it possible to answer questions like “Will the system survive in the coming winter without loss of production? How much can we gain/lose by changing inspection interval of this component or group of components?” and so on. The key performance indicator is the expected production loss due to failures and maintenance operations over a given time period.

The object-oriented language AltaRica 3.0 makes it possible to handle the various modelling challenges at stake: It provides mechanisms to represent faithfully the various degradation processes, monitoring policies, and maintenance rules involved in the system under study. It makes it possible to represent implicitly very large state spaces;

It facilitates information propagation through the network of components and therefore the calculation of key performance indicators; It supports the reproduction of basic patterns in order to develop models of large systems by assembling seamlessly models of components; …

The main purpose of this paper is to present this modelling framework and to illustrate its application. We report here the results of a number of experiments we performed on the model in order to run what-if scenarios. We show the various possibilities to refine and optimize inspection/maintenance policies as well as to asses their impact on the production.

The use of this study is not limited to onshore installations with given maintenance problems. It helps to improve the knowledge and decisions making with a tool for future subsea installations, as there will be more and more seabed compression with equivalent and even more complex maintenance problems.

The remainder of this paper is organized as follows. Section 2 presents state of the art of Preventive Maintenance PM in compressor drive system. Section 3 describes the use case of compressor train system and its assumptions. Section 4 introduces the modelling methodology and design of components and system. Section 5 shows numerical experiments for assessing various inspection and maintenance policies. Section 6 concludes the work and discusses future research.

2 STATE OF THE ART

Compression is a common practice in Q&G processing technology. Due to the complex configuration of a compression drive system, the control over such a system turns to be of paramount importance. This section is thus dedicated to the state of art investigation on compressor drive system which is normally composed of VSD, pump, compressor, valves and so on. Findings from for instance (Andersen et al. 2006, Eriksson and Staver 2010, Eriksson and Konstantinos 2014) and interviews with industrial partners are summarized as a preparation for our model.

2.1 *Health indicator and degradation modelling*

A typical compressor drive system is arranged with multiple trains in parallel where each train consists of a number of components (e.g. VSD, gear, compressor, valve etc.). Each of them is subject to different aging processes (e.g. fouling, wear, harmonics, unbalance) which could be revealed in several condition monitoring sources as described previously. An option to aggregate these sources to formulate a single health indicator is Technical Condition Index (TCI) (Nystad 2008, Nystad & Rasmussen 2010). It is defined to represent the degree of degradation with respect to production availability. The overall TCI value of a compressor, for instance, is aggregated from bottom-level TCI for each degradation symptom revealed by its monitoring source. Its aging measurement includes but not limited to: vibration, seal wear, bearing temperature, compressor efficiency and so on. Each of them is assigned a weight based on expert judgement about its criticality, and it is further merged upwards in the hierarchy for the total TCI of the compressor. Besides, previous maintenance actions and their impact (mainly missing or incomplete working log) can be included in the model as left truncated censoring data. Given all these inputs, a parametric hazard regression model Weibull PHM model is applied in Nystad & Rasmussen (2010) to estimate parameters in the degradation model by maximum likelihood method. Once the parameters are available, the expected Remaining Useful Lifetime (RUL) given a specific time point is tractable with certain confidence.

In this paper, we rely on an alternative solution proposed by Moholt (2016). The health indicator is a discrete variable with a finite number of possible values from new to fail. It is used by guidelines to assess the health of an equipment in a more qualitative way. Such a simplified model is aligned with the amount of data that are currently available for the case under study in this paper. Moreover, it is more adapted to our modelling framework based on discrete states.

2.2 *Intervention and maintenance modelling*

Often maintenance programs are established by project teams by each companies. They propose alternative solutions, demonstrate the advantages/disadvantages for the maintenance strategies and discuss an optimal solution with manufactures. Most components are under calendar-based maintenance together with condition-based maintenance program.

For calendar-based maintenance, the frequency, content, duration and required preparations for maintenances vary in the user manual by equipment type, size and application. The components are analysed in design phase and assigned maintenance levels (L1-L4) according to their criticality (ABB 2013). Periodic maintenance is implemented according the plan.

For condition-based maintenance, there is short term preventive maintenance plan scheduled for the next low demand season based on the input from condition monitoring and inspection. Such decisions are mainly based on experience and expert judgement. Notice that for both maintenance interventions, there is no possibility to react immediately on any degradations/failures in the systems due to the time for preparing maintenance kits.

A risk based simulation approach (RBI) has been applied to develop maintenance strategy for subsea systems in Ormen Lange field (Gustavsson & Eriksen 2005). The lifetime scenario of the system is represented by discrete degradation/failure events happen for each component. The cost model quantifies intervention cost and production loss due to unexpected failures for the mission time. Then a variety of maintenance strategies are fed into the model to calculate desired performance indicators (e.g. average lost production, average repair cost) and help to assess the impact of different maintenance strategies for the subsea systems. However, it is not clear how this model is implemented technically and whether the modelling language and simulation tool are open to external users.

In our paper, we illustrate our method to model maintenance planning on a system-size compressor drive system. The model presented in this paper is authorized by integrated modelling environment AltaRicaWizard in the framework of OpenAlta Rica project. We show the possibilities to develop various maintenance strategies in the model, and demonstrate the loss/gain of these alternatives.

3 USE CASE: COMPRESSOR TRAIN

3.1 *System description*

We focus on 6 electrical trains that are used to compress the gas. Each of them contributes to one sixth of the total production capacity. Each compressor drive system consists of, from the left: a Variable Speed Drive (VSD), a Motor (M), a Gear box (G) and the compressor (C), see Figure 1.

During winter (6 months), full capacity is required and all the 6 trains are supposed to be used. During the summer, only part of the total capacity is required, for instance 1/2. Then only 3 trains are needed. The switch from full capacity to reduced one and then backwards is operated once a year (e.g. 01/10 and 01/04). At system level, once one train is failed, it is revealed naturally by production capacity. Similarly, at train level if one of the component is degrading, it reduces production capacity immediately.

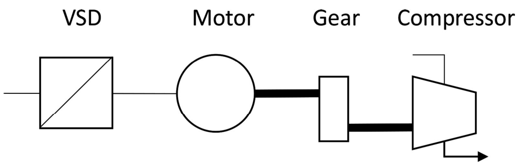

Figure 1. Diagram of one compressor train.

3.2 *Assumptions of each unit*

3.2.1 *VSD and gear*

VSD and Gear are much more reliable than motor and compressor. They have only binary states: Working (W) and Failed (F) (Figure 2). The failure time follows exponential law with low failure rate.

Both components are continuously monitored. In addition, they are easy to repair so the maintenance time is short. Only corrective but no preventive maintenance is planned on these units. The intervention can occur at any time during operation of the system.

Concerning production, it depends on working state of the unit and production flow plug into it.

3.2.2 *Compressor*

Compressor is subject to indirect continuous monitoring on the degradation process. It has four states: Working (W), Degraded 1 (D1), Degraded 2 (D2) and Failed (F). The time to change between these states follows exponential laws where the rate is respectively λ_{d1}, λ_{d2} and λ_f (Figure 3). In W state, the compressor runs at full capacity 100%; in D2 state, the compressor has fouling and it consumes more power to maintain the full production capacity; in D2 state, fouling is accumulated and compressor capacity decreases below an acceptable threshold 80%; in F state, the compressor cannot operate any longer and its capacity sinks to 0%.

When compressor reaches its D1 state, a preventive minor maintenance (e.g. cleaning) is arranged; when it reaches D2/F state, a spare part is ordered and the preventive/corrective major maintenance (e.g. replacement) will be implemented. The duration of minor and major maintenance is respectively δ_{mn} and δ_{mj}. Delay time to prepare corresponding maintenance interventions is ρ_{mn} and ρ_{mj}.

The actual production of the compressor depends on its degradation level, the operation phase and also the input production passing to it.

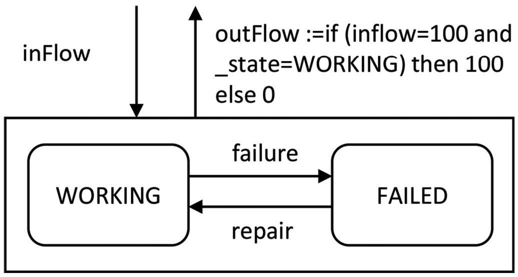

Figure 2. Automaton for VSD and Gear.

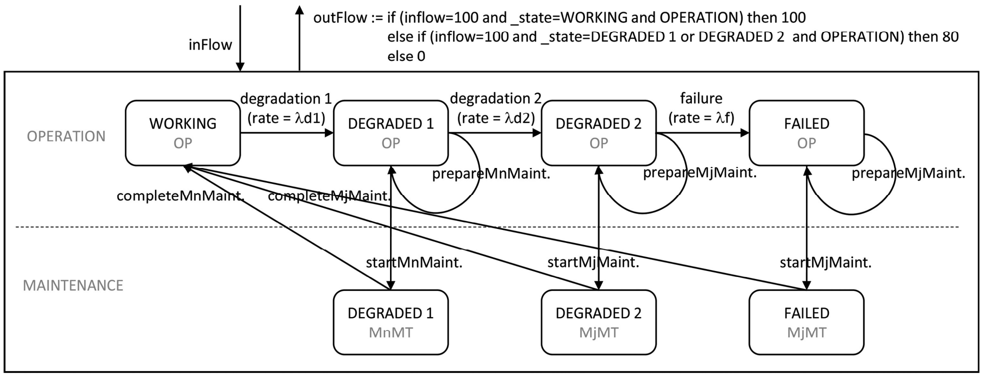

Figure 3. Automaton for compressor.

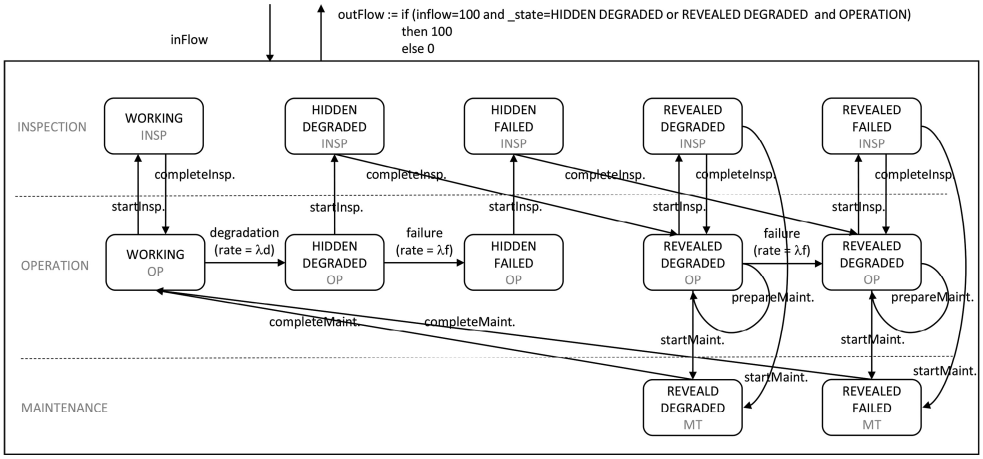

Figure 4. Automaton for motor.

3.2.3 *Motor*

Motor is under periodic inspection. It has six states: Working (W), Hidden Degraded (HD), Revealed Degraded (RD), Hidden Failed (HF), Revealed Failed (RF) (Figure 4). A periodic inspection is perfect and it reveals all the hidden degradations and failures. The inspection occurs every τ and it lasts for Δ unit time. After detection of degradation (RD), the condition can deteriorate further to a failure (RF).

There could be discrepancy between observed state and actual state of the unit. However, the maintenance planning is made based on observed state of the unit. In W/HD/HF, no action is taken; in RD/RF, a spare unit is ordered and the proactive/corrective maintenance is implemented which lasts for δ. The delay to prepare the intervention is ρ.

The actual production of the motor depends on its working state, the operation phase together with the upstream production passing to it.

As a first study of the compressor drive system, we simplify the model by saying that we have enough maintenance teams. We do not consider system-level diagnosis neither maintenance planning. For the mentioned units, any maintenance and inspection stops the production of the intervened train, but do not interfere behaviours of the units on the same line or the other trains. All the components are independent of each other and interventions are decided locally.

4 MODELLING METHODOLOGY

The modelling formalism that we use here is Alta Rica 3.0 and its underlying mathematical framework, Guarded Transitions Systems (GTS). For formal presentation see (Rauzy 2008, Prosvirnova 2014). The formalism can handle complex systems with four main Modules as explained in (Zhang et al. 2017):

1. description of individual behaviours of units
2. description of the actual state of the system
3. diagnosis on the state of the system
4. description of maintenance planning and actions

In our case, we simplify the situation by saying that components are independent and maintenance decisions are made local. Therefore, there is no system-level diagnosis netiher decision making. We only use part of the framework (Module 1, 2) while Module 4 can be further embedded into Module 1. The model constituting two parts: modelling units and modelling system are explained as follows:

4.1 *Modelling units*

The first part describes behaviours of each unit. The purpose is to translate finite state automata as Figures 2, 3 and 4 into AltaRica language. GTS of each unit describes indigenous events that happen locally by itself, for example degradation and failure. Meanwhile, it can embed foreign interventions that posed on top when the local condition or clock reaches certain trigging point, for instance start maintenance and start inspection. To clarify the mechanism, we use motor (Figure 4) as an example. The AltaRica code implementing the GTS for the motor is given in Figure 12.

The class of a generic inspected unit is designed and named as `Motor` (line 5). The motor can be in one of the following states: Working (W), Hidden Degraded (HD), Revealed Degraded (RD), Hidden Failed (HF) and Revealed Failed (RF) (line 1). It experiences three alternating stages in its life cycle: Operation (OP), Inspection (INSP) and Maintenance (MAINT) (line 2). In addition, it runs under winter and summer profile (line 3). Line 10–16 assign names to events and declare their duration by keyword `delay`.

The definition of a `transition` (line 20–33) starts with the name assigned to it, then comes several pre-conditions of the transition with are connected by logic operators `and,or`. After a transition sign comes the final effect of the event, e.g. state or phase values are modified. Under such mechanism, the fireable events and their transitions mimic the behaviour of the component as time elapses.

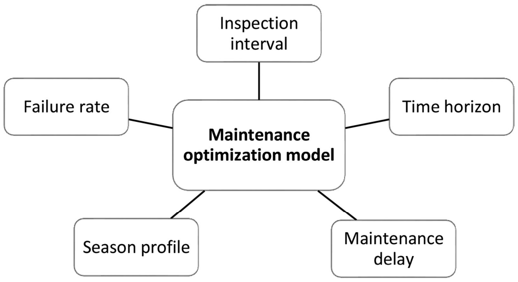

Figure 5. A map of maintenance optimization scenarios.

According to the assumptions, motor degrades and fails only in operation phase. Therefore the state changes are preconditioned with `_phase==OP` (line 20–22). The initiation of an inspection follows fixed interval. Upon completion, a hidden degradation or failure is detected and meanwhile a clock starts to count the time for maintenance preparation (line 26–29). The counting, however, does not stop further degradation of the motor, so the event `prepareMaint` is defined by state indicator `_clock` independent of motor `_state` (line 30). Once the preparation is ready, all the maintenance resources are ready for use but we have to check that it is the low demand season (e.g. summer) to launch an actual campaign. If the `_season==SUMMER`, the maintenance starts immediately and the completion brings state back to working and resets clock again (line 31–33).

The assertion part (line 35–36) describes how to update flow variables after each transition firing. The production of the motor is 100% when it is in operation and not failed, otherwise it produces nothing.

In summary, classes of generic automata can be designed for each unit (VSD, Gear, Motor, Compressor) and season demand following the same routine.

4.2 *Modelling system*

The codes in section 4.1 defines actually several classes of continuously monitored (VSD, Gear, Compressor) and periodically inspected units (Motor) that can be reused for many times. Instantiations of these classes provide the basic elements for constructing a class or prototype of a bigger system. For instance, one train of a CDS can be described in Figure 10.

The code declares a class of `Train` which consists of two instances of the basic `RepairableUnit,` one instance of `COMPRESSOR` and one instance of `MOTOR` (line 2–5). Similarly, for a complete CDS with 6 identical trains, the class `Train` can be recalled for 6 times (`Train T1, Train T2,...`) to instantiate the real structure. The production of one train is determined by input and output flows passing through the series of the units. Namely, the input of a unit is plugged, by the equation `sign:=`,into the output of the precedent unit (line 9–13). Therefore, the equation means that the production of one train depends on the upstream production and availability of each unit in series.

4.3 *Performance indicators*

In practice, maintenances have a cost, just as shutdowns of systems due to failures. It is however very difficult to get realistic figures for these costs, because they depend on too many factors. More obviously, there is a discrepancy between the production expectation and the actual production of the system throughout the mission time. Here, we consider the average production and the loss of the system (per unit time) as relevant performance indicators. The GTS representation of these indicators are shown in Figure 11.

The defined observers are real numbers. Potential capacity of the CDS is normalized summation of each train (line 8–9). It is then compared with the actual demand according to the season. If the potential capacity satisfies the demand, then there is no production loss; otherwise the production loss equals the demand minus potential capacity of the CDS.

5 NUMERICAL EXPERIMENT

The mentioned modelling methodology is applied to the use case of CDS. A set of illustrative data (Table 1) is fed into the model. The mission time is 87600 h (10 years). We set the maximum production capacity for all six working trains to 100 per hour. For 10 years that would add up to $8.76e + 6$, and with nominal seasonal production profile in summer (*0.5) we get $4.38e + 6$. We assume that at the beginning of simulation, the production capacity of each unit is 100% per hour and the operation starts from winter.

The GTS model can thus be able to run a variety of what-if scenarios and the result can be assessed by the stochastic simulator embedded in AltaRicaWizard. The map in Figure 5 shows possible experiments that we can simulate with the model. Due to scientific focus of this paper, only selected experiments are discussed in the following subsections.

Table 1. Input parameters for each unit.

Component	VSD	Motor	Gear	Compressor
λ_{d1}		$1.0e-6$		$1.0e-6$
λ_{d2}				$1.0e-5$
λ_f	$1.0e-7$	$1.0e-5$	$1.0e-7$	$1.5e-4$
ρ_{mn}		4380		2190
ρ_{mj}				4380
δ_{mn}	6	365	6	182.5
δ_{mj}				365
τ		730		
Δ		12		

5.1 *Inspection interval*

Figure 6 plots 1 million realizations of the process for accumulated production and loss versus different inspection interval values $730 \leq \tau \leq 11680$ (1 to 16 months). When inspection interval is less than 4 months, the production loss increases dramatically. This is because with too frequent inspections, operations are dominated by unnecessary shutdowns to check still functioning components. After this point, the total production approaches a stable high level and it reaches the peak value when τ is around 12 months. Notice that the curve is almost flat when τ is from 4 to 16 months. It implies that the total production may be not so sensitive to the inspection interval in such range given our assumptions and input parameters.

5.2 *Time horizon*

Figure 7 shows Monte Carlo simulation for accumulated production and production loss from 1 to 10 years with 1 million realizations at each year. As time elapses, the production and loss increase almost linearly. It quantifies the provided overall production and revenue reduction over a period of mission time and thus gives decision makers a look-ahead horizon of the production profile of the whole CDS system.

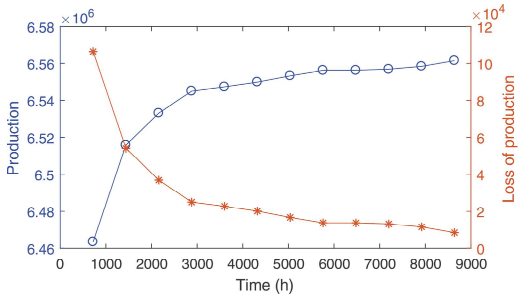

Figure 6. Production and loss versus inspection interval τ.

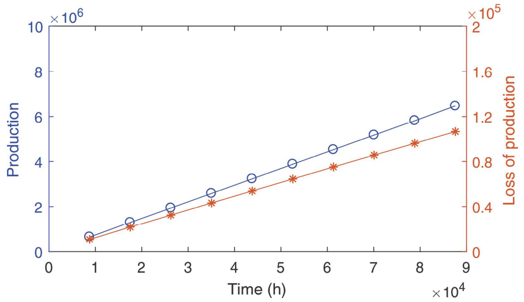

Figure 7. Production and loss versus mission time.

5.3 *Maintenance delay*

Figure 8 presents consequence of reducing minor PM preparation time (delay). Here, we assume that delay of major preventive/corrective maintenance interventions remain as it was ρ_{mj} and the changes only apply to ρ_{mn} of inspected components. From the figure we see that as minor preventive maintenance delay decreases from 10 to 1 year, the total production increases around 0.045%. The production loss with ($\rho_{mn} < 87600$) and without minor PM ($\rho_{mn} = 87600$) does not differ much. The link between instant reaction and increased production is obvious, but the gain of having maintenance resource immediately ready can be questionable. This is relevant for deciding an optimal spare parts strategy, when the cost of contracting maintenance service and storing spare parts has to be evaluated against the benefits of income.

5.4 *Seaon profile*

Figure 8 presents consequence of extending low demand period (i.e. summer) from 1 to 12 months. This time corresponds to the window when maintenance intervention is allowed. As the window extends, the system spends more time in reduced operation mode, and thus the total production decreases. Yet, production loss is reducing rather than increasing because the potential loss is compensated by relaxed requirement of production in the extended summer period. As such, we quantify the effect of a changing season profile on the accumulated production of the system.

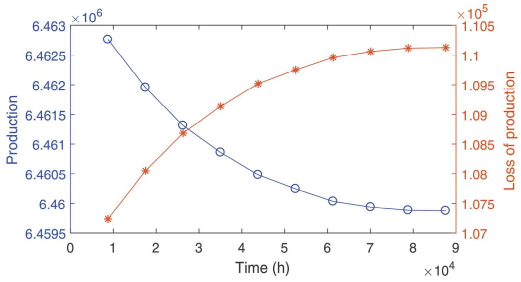

Figure 8. Production and loss versus maintenance delay.

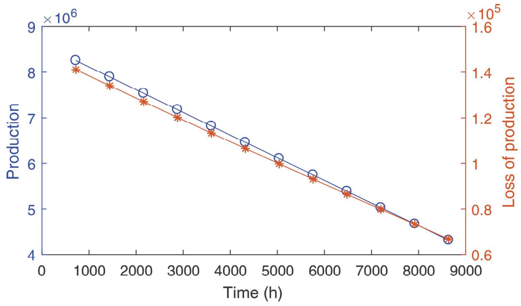

Figure 9. Production and loss versus low demand duration.

6 CONCLUSIONS

In this paper, we present a preventive maintenance model on a compressor drive system. The model relies on the formal modelling formalism AltaRica 3.0 and its mathematical framework guarded transitions systems. They provide mechanisms to represent state and transitions of local units, enable composition of multi-unit systems and allow information flows (e.g. production, observed condition) circulating through them. We illustrate how our modelling methodology handle the various modelling challenges in our CDS case, like multiple unit types, huge state space, monitoring together with inspection policies, multi-level maintenance actions and so on. We pose on top of the model different maintenance and inspection policies and perform numerical experiments using Monte Carlo simulations. The simulator, as a decision support tool, demonstrates how the health of components in the system affect the kind of intervention decisions need to make now/soon. The model calculates accumulated production and its loss in a certain mission time. It can provide practitioners motivation with respect to, for instance, intensifying/relieving work on condition monitoring so that interventions become efficient and necessary.

However, this work is very preliminary and there are several directions that can be further investigated.

Direction 1. Degradation profile We assume that components deterioration follow exponential laws with its respective degradation or failure rate lambda. However, if the plant data is available and tractable for more accurate estimation of component degradation, we may introduce multiple degradation states, or fit the data with other laws (e.g. Weibull, empirical distribution). In addition, if the operation mode changes, we may need to consider different degradation profiles (e.g. failure rate) under normal production, increased production, decreased production.

Direction 2. Season profile The current season profile is simplified with only two modes and constant production requirement for each mode. However, there could be fluctuations of production requirement given that it follows a mean within each season. For instance, in summer the production demands is 52% for 20 days, 65% for 40 days, and then 43% for 7 days and so on. Such fluctuations in the seasonally demand profile can be introduced if a general abstraction of time dependent plant data is available.

Direction 3. Monitoring policy In practice, the inspection dates cannot be freely fixed, because they depend on many factors external to system such as the availability of the maintenance crew. Inspection may be destructive to the component. Certain inspections may take some predictable time and the system may be partly or totally shutdown during inspections. Meanwhile, other inspections do not interrupt operation. In addition, as we have 6 trains in parallel, the inspection can be conducted for all at the same time or only certain pieces at a time. These situations can be further introduced to the model to make it more realistic as implemented in O&G industry.

Direction 4. Maintenance policy It is important to sustain production all the mission time, especially in summer period when window is open for interventions. Therefore, in the occurrence of several degradations or failures in a system, we may need to decide when to react and which ones to intervene in priority. For instance, we can decide to maintain when we lose 3 compressors, or 2 compressors plus 1 motor, or wait for more failures and so on. When there are 1 working, 3 degraded, and 2 failed trains, we can decide to repair the 2 failed trains first and then repair the 3 degraded ones later to ensure highest possible production capacity. System level maintenance planning can be considered in these cases.

ACKNOWLEDGEMENT

This work was carried out as a part of SUBPRO, a Research-based Innovation Centre within Subsea Production and Processing. The authors gratefully acknowledge the financial support from SUBPRO, which is financed by the Research Council of Norway, major industry partners and NTNU.

REFERENCES

ABB (2013). Maintenance for motors and generators. IFEA Høstarrangement Borregaard.

Andersen, T.M., L. Thuestad, & T.A. Thorstensen (2006). Rapid: A new approach for improved regularity and decreased maintenance costs. In *OnePetro*, pp. 1–3. Offshore Technology Conference.

API-RP-7 L (2006). Procedures for inspection, maintenance, repair, and remanufacture of drilling equipment. Technical report, American Petroleum Institute, USA.

DNV-GL-RP-002 (2014). Integrity management of subsea production systems. Technical report, Det Norske Veritas (Norway) and Germanischer Lloyd (Germany), Norway.

Eriksson, K.G. & A. Konstantinos (2014). Subsea processing systems: Optimising the maintenance, maximising the production. In *OnePetro*. Offshore Technology Conference.

Eriksson, K.G. & K.O. Staver (2010). Large scale condition monitoring for a subsea gas compression system pilot. In *OnePetro*. Offshore Technology Conference.

Gustavsson, F. & R.H. Eriksen (2005). Developing an intervention, maintenance and repair strategy for ormen lange. In *OnePetro*. Society of Petroleum Engineers.

Markeset, T., J. Moreno-Trejo, & R. Kumar (2013). Maintenance of subsea petroleum production systems: a case study. *Journal of Quality in Maintenance Engineering 19*(2), 128–143.

Moholt, K. (2016). Insulation quality measured in partial discharge. Internal presentation at NTNU, Trondheim.

Nystad, B.H. (2008). *Technical Condition Indexes and Remaining Useful Life of Aggregated Systems*. Ph.D. thesis, Norwegian University of Science and Technology.

Nystad, B.H. & M. Rasmussen (2010). Remaining useful life of natural gas export compressors. *Journal of Quality in Maintenance Engineering 16*(2), 129–143.

Prosvirnova, T. (2014, November). *AltaRica 3.0: a Model-Based Approach for Safety Analyses*. Thèse de doctorat, École Polytechnique, Palaiseau, France.

Rauzy, A. (2008). Guarded transition systems: a new states/events formalism for reliability studies. *Journal of Risk and Reliability 222*(4), 495–505.

Zhang, Y., A. Barros, & A. Rauzy (2017). Assessment of operational performance of multi-unit production systems using altarica 3.0: a case study.

ANNEX

```
class Train
    RepairableUnit VSD;
    RepairableUnit Gear;
    COMPRESSOR Compressor;
    MOTOR Motor;
    Real inflow (reset = 100);
    Real outflow (reset = 100);
    assertion
        VSD.inflow := inflow;
        Motor.inflow := VSD.outflow;
        Gear.inflow := Motor.outflow;
        Compressor.inflow :=Gear.outflow;
        outflow := Compressor.outflow;
    ...
end
```

Figure 10. The AltaRica 3.0 code implementing the GTS pictured Figure 1.

```
block Plant
    ...
    Real capacity (reset = 100);
    observer Real Production = production;
    observer Real ProductionLoss = C.demand - production;
    assertion
        ...
        capacity := (T1.outflow + T2.outflow + T3.outflow + T4.outflow +
                    T5.outflow + T6.outflow)/6.0;
        production := if C.demand<capacity then C.demand else capacity;
end
```

Figure 11. The AltaRica 3.0 code implementing the GTS for performance indicators.

```
domain State{W, HD, RD, HF, RF}
domain Phase {OP, MAINT, INSP}
domain Season {WINTER, SUMMER}
domain Clock {STB, CALL, READY}
class MOTOR
    State _state (init = WORKING);
    Phase _phase (init = OPERATION);
    Season _season (reset = WINTER);
    Clock _clock (init = STB);
    event degradation (delay = exponential(lambda_d));
    event failure (delay = exponential(lambda_f));
    event startInsp (delay = Dirac(tau), policy = MEMORY);
    event completeInsp (delay = Dirac(Delta));
    event prepareMaint (delay = Dirac(rho));
    event startMaint (delay = Dirac(0));
    event completeMaint (delay = Dirac(delta));
    Real inflow (reset = 100);
    Real outflow (reset = 100);
    transition
        degradation: _state==W and _phase==OP -> _state := HD;
        failure: _state==HD and _phase==OP -> _state := HF;
        failure: _state==RD and _phase==OP -> _state := RF;
        startInsp: _phase==OP -> _phase := TEST;
        completeInsp: (_state==W or _state==RD or _state==RF) and
                      _phase==INSP -> _phase:=OPERATION;
        completeInsp: _state==HD and _phase==INSP -> {_phase:=OP;_state:=RD;
                      _clock:=CALL;}
        completeInsp: _state==HF and _phase==INSP -> {_phase:=OP;_state:=RF;
                      _clock:=CALL;}
        prepareMaint: _clock==CALL -> _clock := READY;
        startMaint: (_state==RD or _state==RF) and _phase!=MAINT and
                    _clock==READY and _season==SUMMER -> _phase := MAINT;
        completeMaint: _phase==MAINT -> {_state:=W; _phase:=OP;_clock:=STB;}
    assertion
        outflow := if inflow==100 and ((_state==W or _state==HD or _state==RD) and
                   _phase==OP) then 100 else 0;
end
```

Figure 12. The AltaRica 3.0 code implementing the GTS pictured Figure 4.