MY STORY AT NTNU – IPK
(Aug. 2015 – Sep. 2016)

AGENDA

Some PhD milestones

Context of PhD in IPK

Courses

Systems Engineering Methods

A Systems Engineering Approach to the Design of a CBM System

Maintenance Optimization

Development of a Maintenance Optimization Model for a CBM System

Maintenance Management

Condition Monitoring and Diagnostics of Machines: a review and analysis

Model of the PhD's target system

- Assumptions
- Architecture
- Markovian Approach
- Simulation algorithm
- Some computational results
- Cost model discussion
- Final considerations and Next steps

RAMS Seminar – TRONDHEIM – 23/09/2016

"The psyche never thinks without an image....
the reasoning mind thinks its ideas in the form of images"

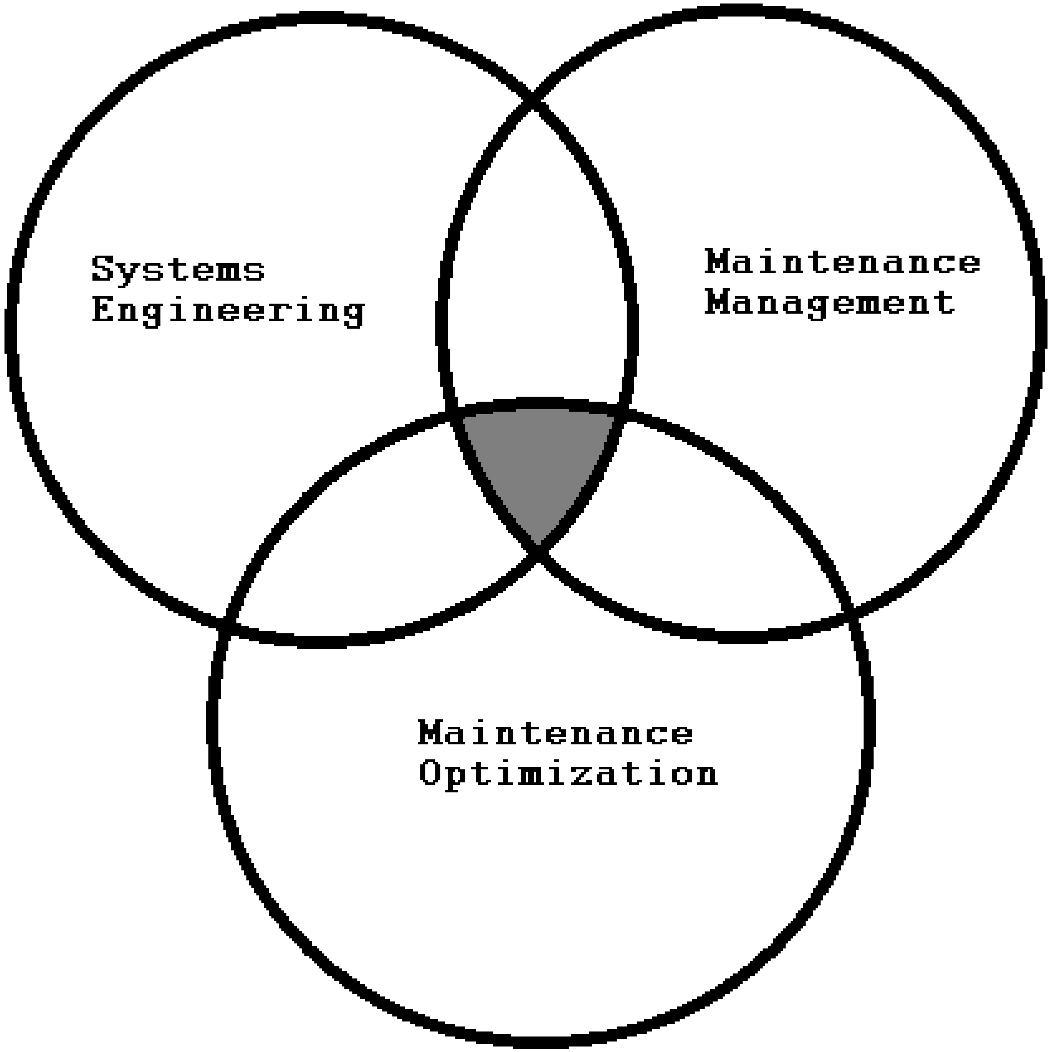
Aristotle

SOME PHD MILESTONES

- *Invitation: 2010;*
- *Application in Petrobras 2012 (2nd attempt);*
- *Acceptance from UFRJ 2013;*
- *PhD start 2014;*
- *Meeting with Prof. Jørn Vatn (May/2014);*
- *PhD Courses completion at UFRJ (March/2015);*
- *Trip to Norway (August/2015);*
- *1st RAMS seminar presentation (August/2015);*
- *Presentation at "Moderne Vedlikehold" (January/2016);*
- *Learning Activities in Trondheim (Skiing, RAMS' Courses, Mushroom hunts etc.);*
- *2nd RAMS seminar presentation (May/2016);*
- *26th INCOSE – Edinburgh (July/2016) "Maintenance Optimization Approaches for CBM: a review and analysis";*
- *Interviews and survey preparation (September/2016);*
- *3rd RAMS seminar presentation (Today).*

CONTEXT OF THE PHD STUDY IN NTNU-IPK

PROPOSAL OF A NETWORK FOR CONDITION MONITORING AND DIAGNOSTICS OF MACHINES: APLICATION TO OFFSHORE PLATFORMS



Context of the PhD study in IPK

A Systems Engineering Approach to the Design of a CBM System

PK8210 – Systems Engineering Principles and Practice
Prof. Cecilia Haskins

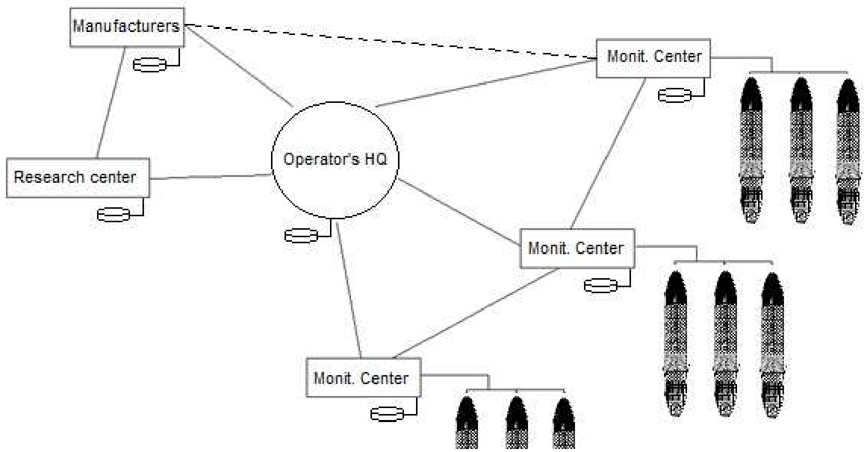
Objectives

Offer to the Oil & Gas operator, a comprehensive outlook of the maintenance decision-making process, and develop an optimized, communication structure and supporting system.

Develop a condition-monitoring network (CMN) and a decision support system for the Brazilian offshore operational environment

Contents

- Objectives and motivation
- **S**takeholders and needs
- **P**roblem statement
- Research approach
- MOEs
- **A**nalysis and **D**ecision
- Trade-Off analysis
- **E**valuation



The Emergent Condition Monitoring Scheme

Development of a Maintenance Optimization Model for a CBM System

PK8207 – Maintenance Optimization
Prof.: Anne Barros

Objectives

To develop a maintenance optimization model for an offshore power generation system, as a CBM decision-supporting tool.

Find the optimal preventive policy for minimal maintenance costs per time unit.

Contents

- System description
- A Markov based approach
- Discussion (maintenance cost models and approach)
- Proposal of a simulation-optimization algorithm
- Conclusion and future work

Condition Monitoring and Diagnostics of Machines: a review and analysis

TPK8207 – Maintenance Management
Prof.: Per Schjølberg

Objective

Review the international standards related to the CM&D and prepare a course material for technicians in the Oil&Gas sector

THE TARGET SYSTEM

An FPSO's power generation system

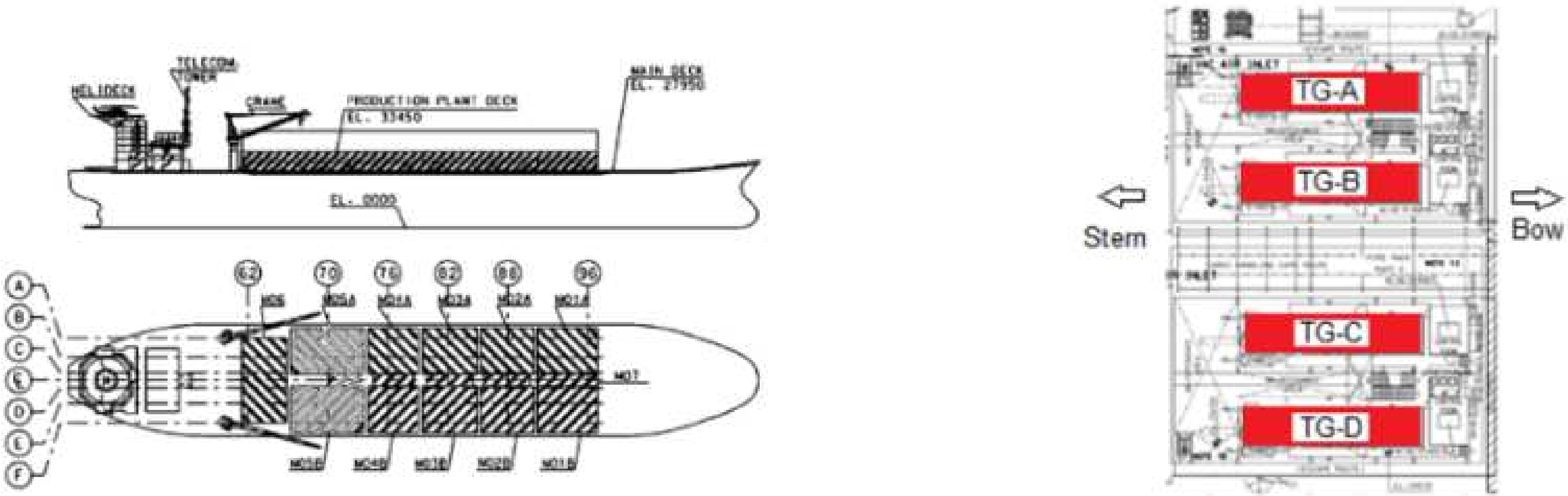
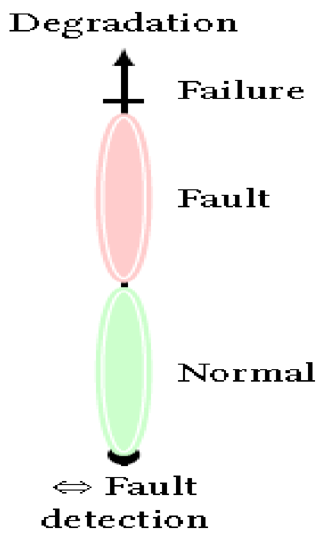


Figure 1 – Location of a Power Generation System in a typical FPSO

MODEL ASSUMPTIONS

- System's degradation and monitoring: There is a CM system installed and properly adjusted allowing detection, at least, of one level of degradation.
  - o Degradation always precedes a failure of a failure mode;
  - o Undetectable failure modes/events will be treated with corrective maintenance;
  - o For the starter switch, functional tests will represent the CM system;



- System's safety: Protective systems are in place and adjusted. There is no safety consideration in the model;

- Non-Markov states and transitions: There are non-Markovian transitions and states defined by the simulation algorithm;

- System's condition (diagnostics): The condition of the System will be defined as a combination of the states of the subsystems at instant *t* in the simulation;

- Prognostics: The Markov steady state solutions will be the "prognostics" supporting the simulation and RUL estimations should be attempted based on trend models.

MARKOV MODEL FORMULATION

Considering the maintenance and renewal process of a repairable system, a continuous-time stochastic process (Markov process) was chosen to model the system reliability and availability.

Aiming to minimize the total maintenance cost, the model will allow for computing (estimating):

- ✓ The average time the system is in each state (as basis for economic considerations);
- ✓ How many times the system in average “visits” the various states (as the need for spare parts, logistics and maintenance personnel);
- ✓ Mean time until the system enters one specific state (e.g. a critical state) and;
- ✓ System failure rate.

MODEL ARCHITECTURE

Each pair of turbo generator (TG) is serviced by one starting system.
For simplicity, half of the system will be considered and a 3 states Markov model is considered to represent the functions involved.

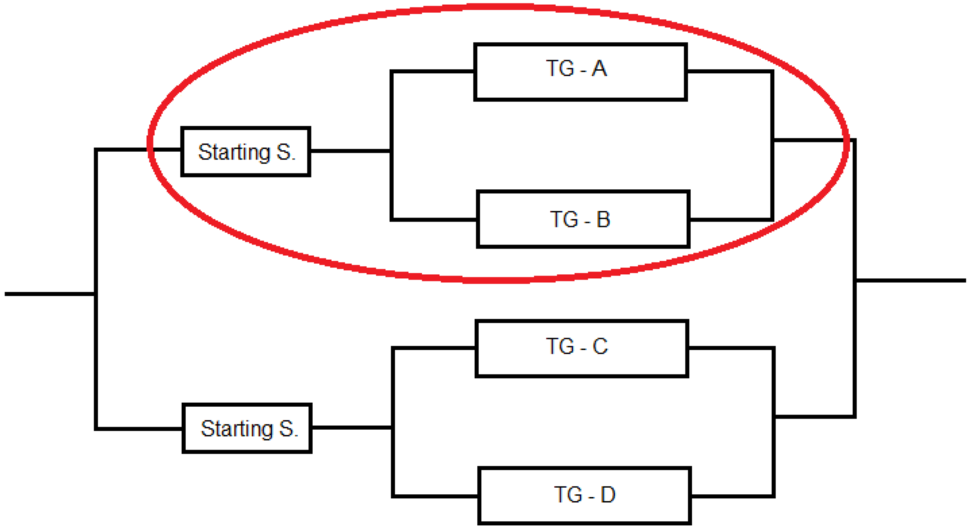


Figure 4 – Reliability block diagram RBD of the system

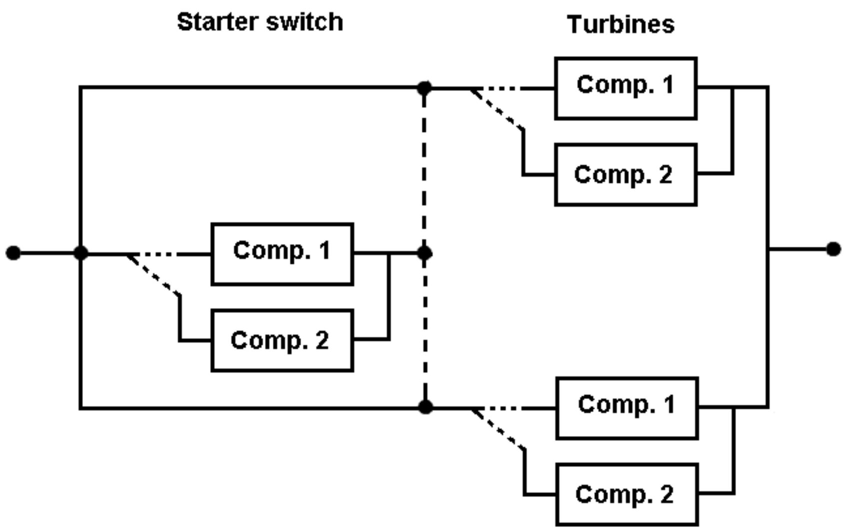


Figure 5 – Functional block diagram

SIMULATION ALGORITHM

A tree of Markov models will be considered to represent the Power Generation System.
A simple 3 states transition diagram is proposed to represent the starter switch and the turbine engine.

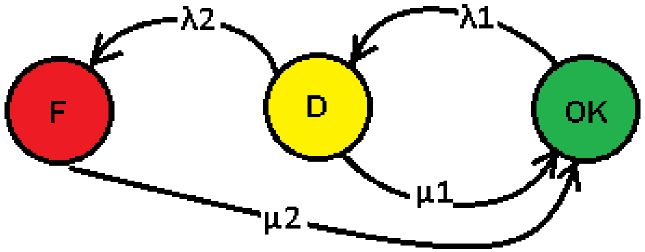


Figure 6 – Transition diagram for the Markov module

Where:

OK = Operative state
D = Degraded state
F = Failed state

A typical transition matrix fort the model in Figure 6 could be such as: $A = \begin{bmatrix} -\mu_2 & 0 & \mu_2 \\ \lambda_2 & -\mu_1 - \lambda_2 & \mu_1 \\ 0 & \lambda_1 & -\lambda_1 \end{bmatrix}$

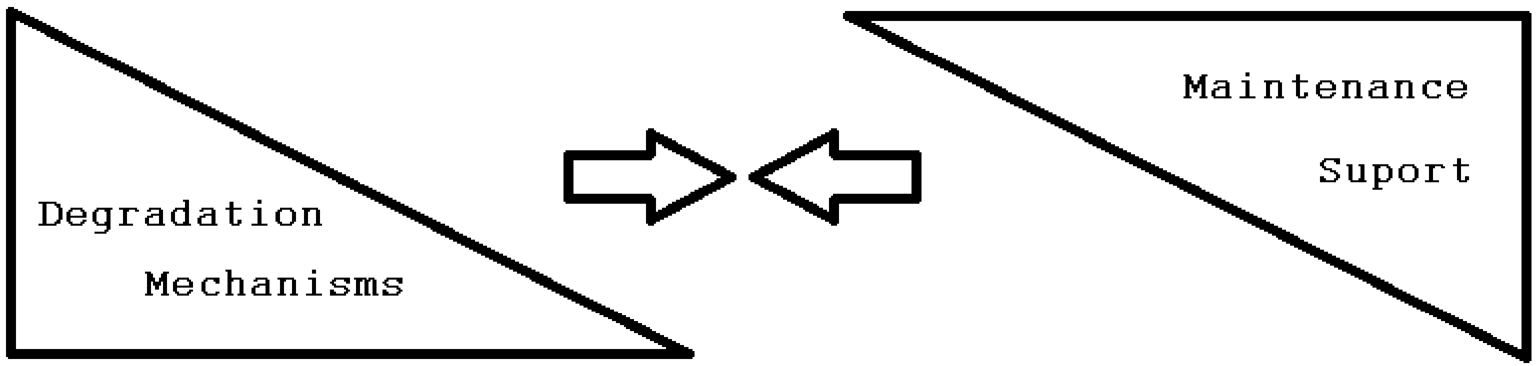
Where:

λ_1 = Degradation rate (Minor failure rate)
λ_2 = Failure rate
μ_1 = Restoration rate (condition based maintenance)
μ_2 = Repair rate (corrective maintenance)

IN OTHER WORDS…

$$A = \begin{vmatrix} -(a_{12}+a_{13}) & \textbf{\textit{Imperfect Repair}} & \textbf{\textit{Total Repair}} \\ \textbf{\textit{Failure}} & -(a_{21}+a_{23}) & \textbf{\textit{Restoration}}\ (CBM) \\ \textbf{\textit{Random Failure}} & \textbf{\textit{Degradation}} & -(a_{31}+a_{32}) \end{vmatrix}$$

Transitions related to random failure and imperfect repair (terms a_{31} and a_{12} respectively), will be governed by the simulation algorithm.



The opposing forces in a “Maintenance and Renewal System”

ADDITIONAL STATES AND TRANSITIONS

The simulation algorithm will “switch” the Markov module creating two non-Markov states and transitions according to the simulation rules.

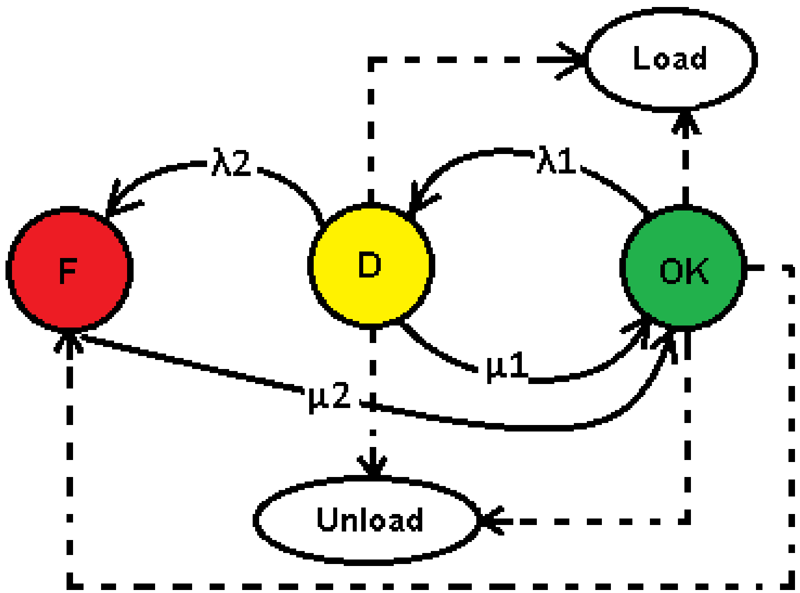


Figure 8 – Transition diagram including the non-Markovian transitions

The idea of using the 3 States Markov model manipulated by the simulation algorithm is to represent a deteriorating system in different levels (D1, D2 and so on), by replicating degraded states.

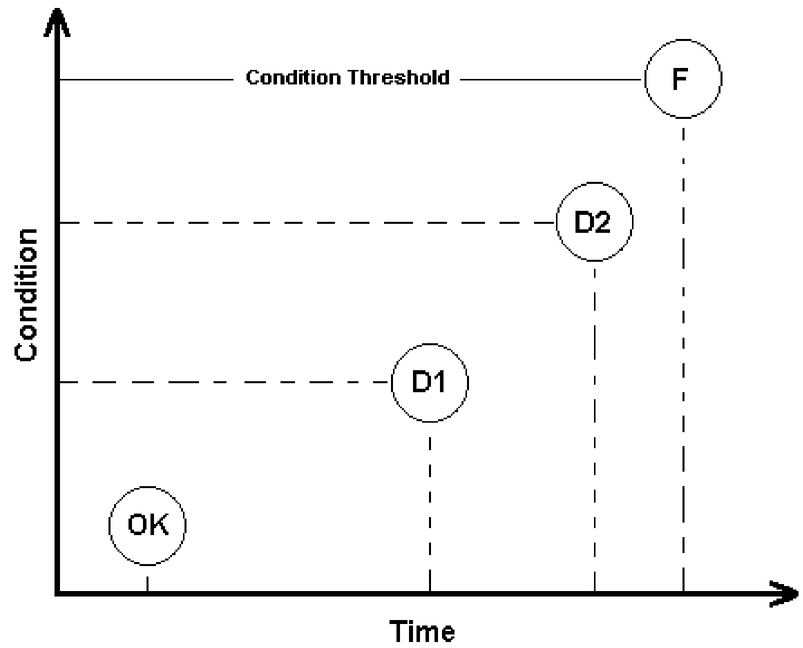


Figure 7 – State space of a deteriorating system

A SIMULATION ALGORITHM

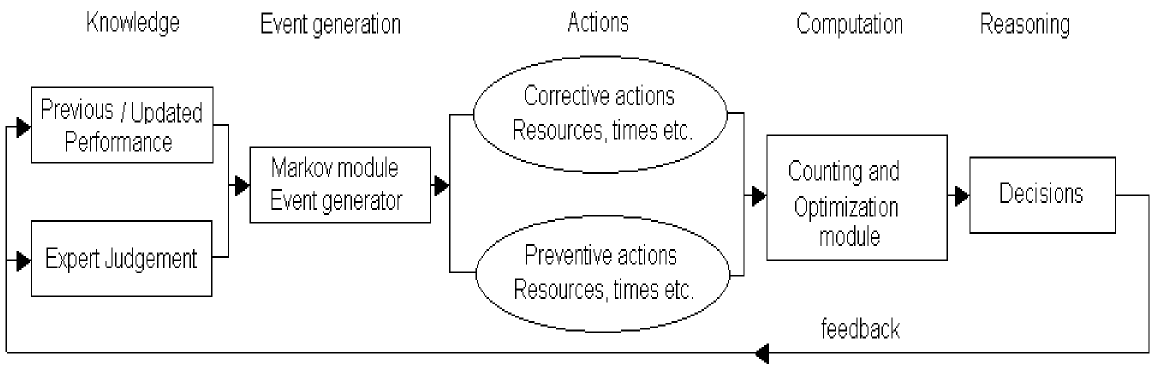


Figure 10 – Concept map for the Simulation

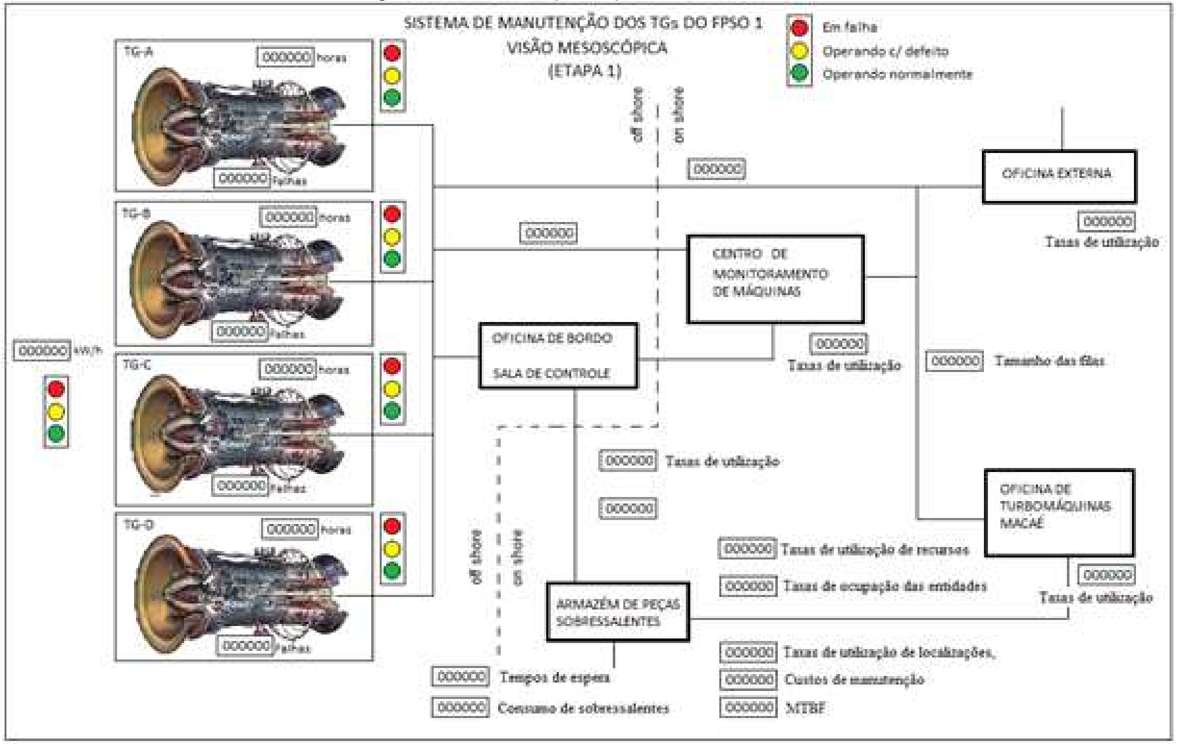


Figure 7 – Sketch for one simulation interface

A SIMULATION ALGORITHM

Activity Cycle Diagram

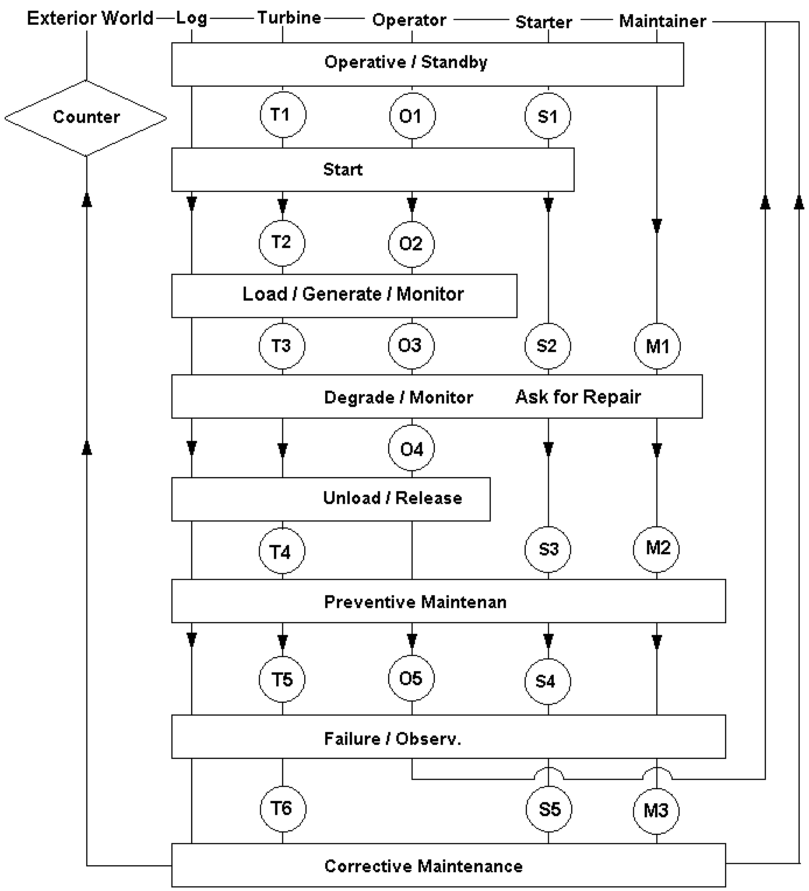


Figure 9 – Activity Cycle Diagram of the main entities

Simulation Flowchart

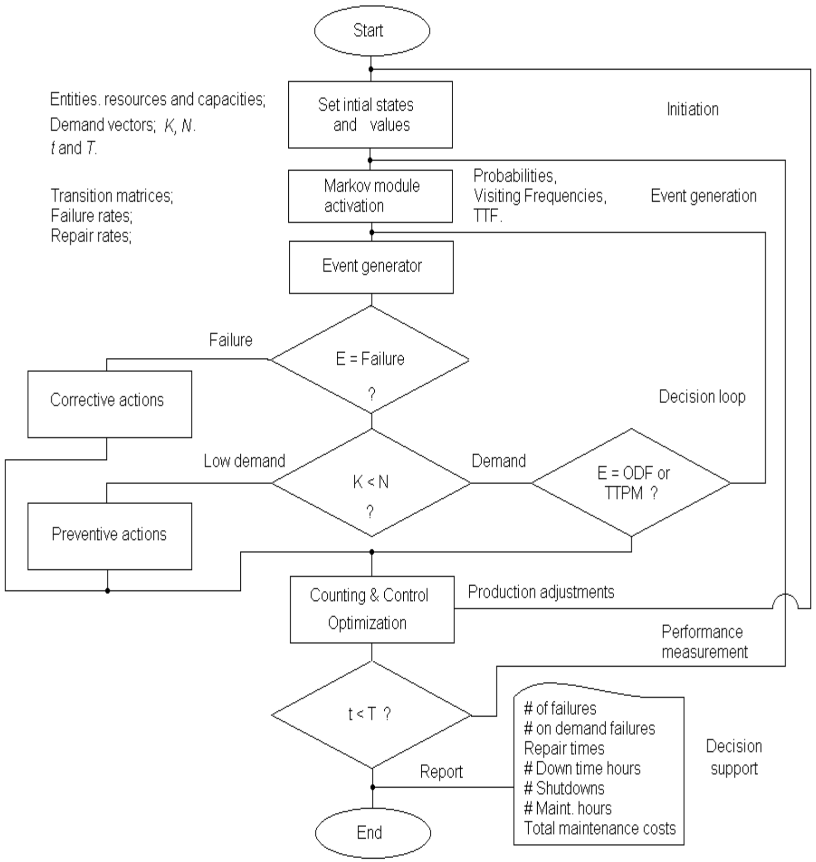


Figure 11 – Simulation flowchart

MARKOV MODEL COMPUTATION

The Markov models, solutions and methods were extracted from (Vatn, 2007) and (Rausand and Høyland, 2004).

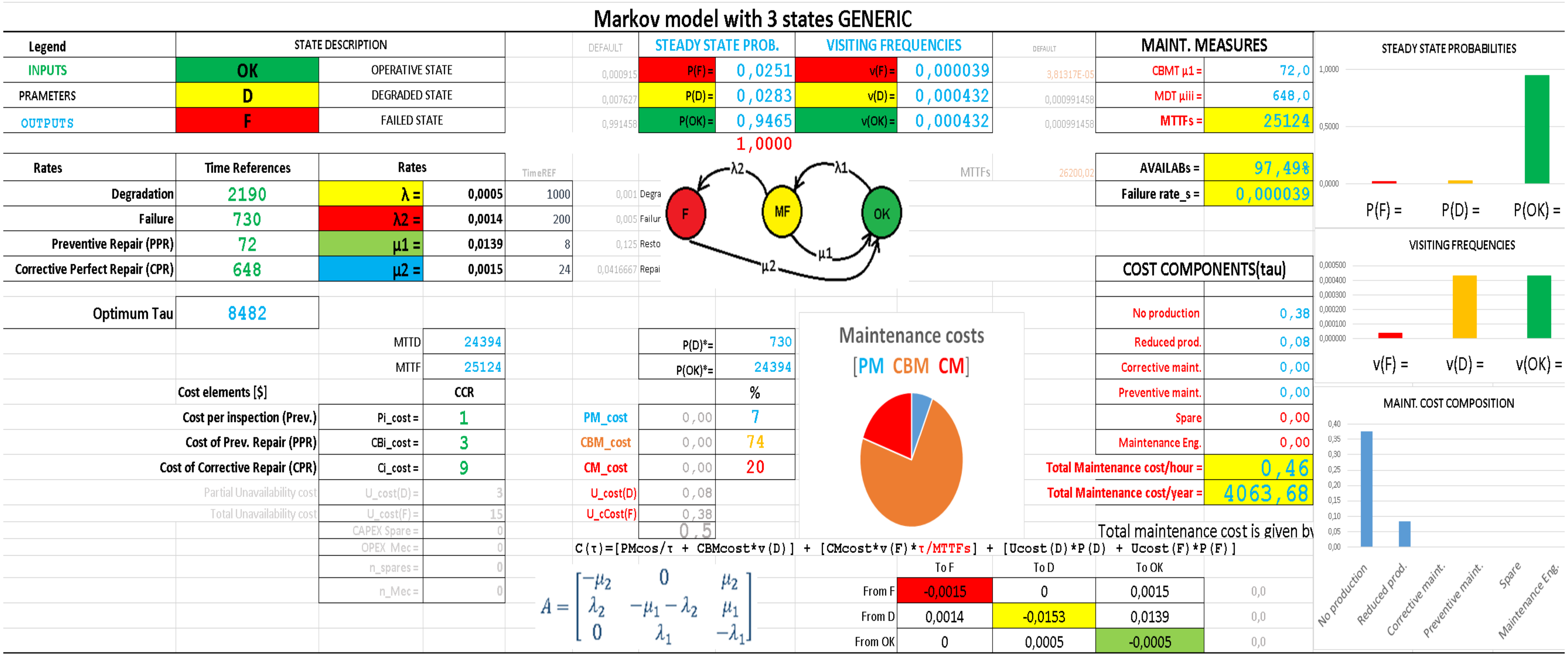


Figure 13 – A 3 states Markovian model implemented in Excel

COST MODELS

Objective-function:
Minimize the total maintenance cost $C_{(\tau)}$, in a 3 states Markov model.

The total maintenance costs is the summation, in respect to the preventive interval (τ), of the preventive, corrective and downtime related costs of the item considered.

$$C_{(\tau)} = [\frac{PM_c}{\tau} + CBM_c * v_D] + [CM_c * \frac{\tau}{MTTF}] + [U_{c(\tau)} * P_F] \quad (4.1)$$

Where:

PM_c = *Cost of the preventive inspection in respect to* (τ);
CBM_c = *Cost of the Condition-Based intervention;*
CM_c = *Cost of the corrective intervention;*
$\frac{\tau}{MTTF}$ = *Relation between preventive interval (effective Failure Rate);*
v_D = *Visiting frequency for the Degraded state;*
v_F = *Visiting frequency for the Faulty state;*
U_{cost} = *Cost of unavailability (Down Time Cost);*
P_F = *Probability of Failed state.*

Figure 15 was obtained by using the model in equation 4.1.

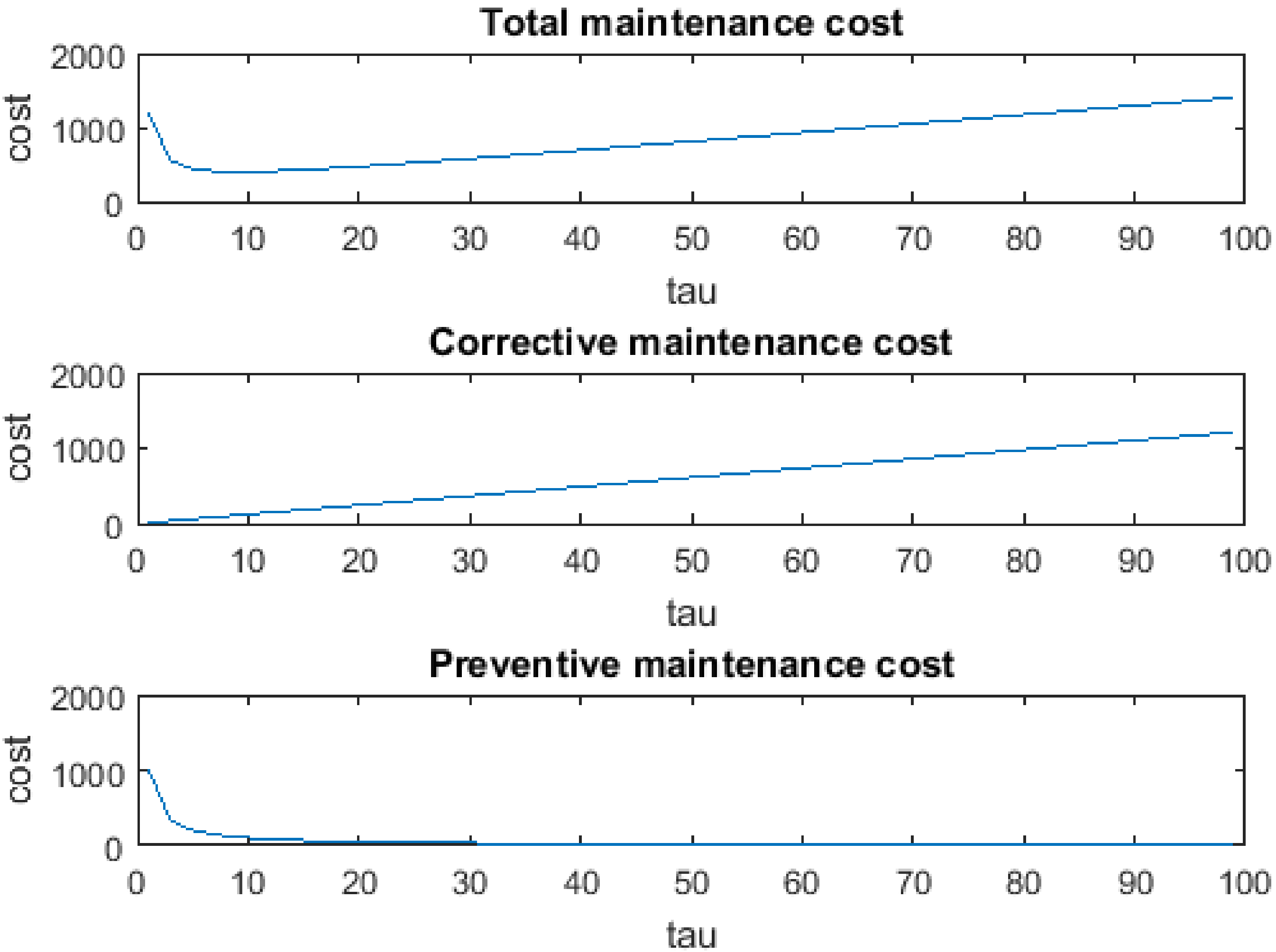


Figure 15 – Total maintenance cost (corrective + preventive) per maintenance interval (tau) for the 3 states model (starter switch)

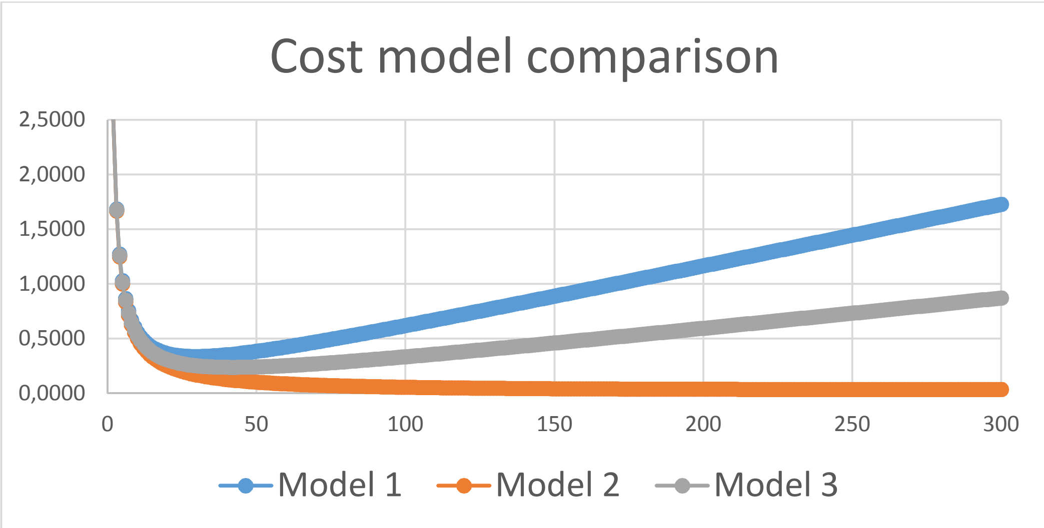
COST MODELS

Using the 2 states Markov model again,

$$C(\tau) = Pi_{cost} / \tau + Ci_{cost} * \tau / MTBF \quad \text{(Model 1)}$$

$$C(\tau) = Pi_{cost} / \tau + Ci_{cost} * V0 * \tau / MTBF \quad \text{(Model 2)}$$

$$C(\tau) = Pi_{cost} / \tau + Ci_{cost} * 0{,}5 * \tau / MTBF \quad \text{(Model 3)}$$



Cicost=	€	50,00	Model 1	Model 2	Model 3
Picost=	€	5,00	0,3379	0,0360	0,2389
		tau	30	277	42

Figure 17 – Comparison of cost models
(λ = 0,000114; μ = 0,0417; CMcost= 50; PMcost= 5)

DISCUSSION

Discussion 1 – Non-exponential Repair Times

How to deal with systems of non-exponential repair-times?

Discussion 2 – Model Architecture and Transitions

What would be a model architecture to represent the system under study?

Discussion 3 – Alternatives to investigate

How to connect simple Markov models “Markov layers” from small units to system level?

DEFINING CATEGORIES FOR THE SIMULATION

Inspired by (Rausand & Royland 2004, p.93), categories of Failure Rate were considered as presented in Table 8.

Table 8 – Categories for system failure rate

Failure Rate categories (MTBF)	Equivalent Parameter (1/#hours - Failure Rate λ)	
Highly Frequent (Once per month)	1/730 h	0,0013699
Very Frequent (once per 3 months)	1/2190 h	0,0004562
Frequent (Once per 6 months)	1/4380 h	0,0002283
Less Frequent (once per 9 months)	1/6570 h	0,0001522
Probable (Once per year)	1/8760 h	0,0001142
Less Probable (Once per 5 years)	1/43800 h	0,0000228
Occasional (Once per 10 years)	1/87600 h	0,0000114

Defining categories for TTR, inspired by Bukowski, 2006 (see Table 8) we prepared the Table 9.

Table 9 – Categories for times to repair

Time-to-Repair categories	Average repair time (hours)	Equivalent Parameter (Repair Rate μ)	
Short TTR	8 h	1/8	0,125
Moderate TTR	24 h (one day)	1/24	0,042
Large TTR	72 h (3 days)	1/72	0,014
Very-Large TTR	216 h (9days)	1/216	0,005
Ultra-Large TTR	648 h (27 days)	1/648	0,0015

THE MAINTENANCE COST CONSEQUENCE RATIO

Regarding maintenance costs and to find the optimum preventive interval (tau), the ratio between the costs of the interventions (corrective and preventive) was established.

Table 10 – Categories for system maintenance cost consequence ratio CCR

CCR	Corrective / Preventive (Inspection/action cost ratio)
Very-Low CCR	1
Low CCR	2/1
Moderate CCR	5/1
High CCR	10/1
Very-High CCR	50/1
Ultra-High CCR	100/1

The aforementioned categories have been applied in order to populate a database for further sensitivity analysis.

FROM THE MARKOV MODEL

As known (in a constant failure rate) MTBF is a function (inverse) of the Failure Rate, MTBF= λ-1:

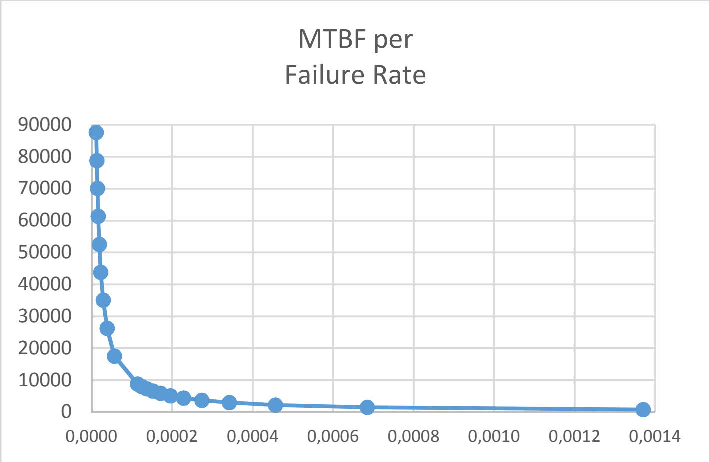


Figure 19 – MTBF per Failure Rate

MDT is a function (inverse) of the Repair Rate, MDT= μ-1 and;

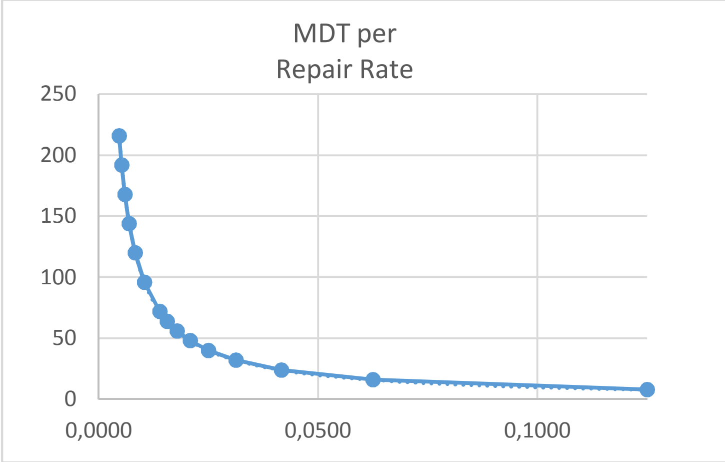


Figure 20 – MDT per Repair Rate

Visiting frequency presented a direct linear function with Availability:

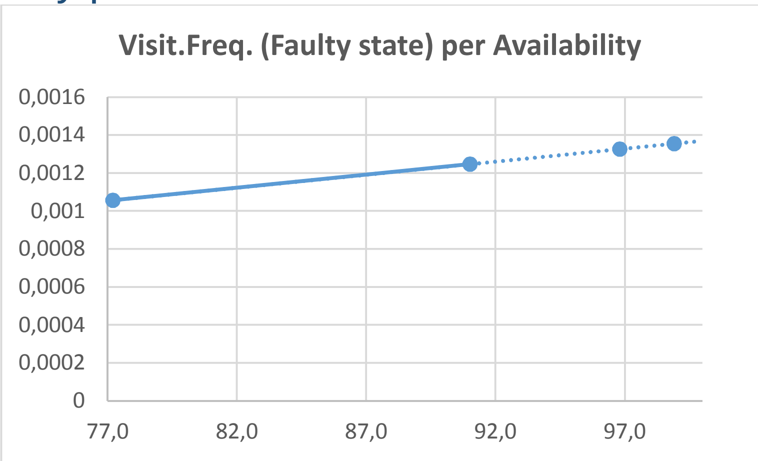


Figure 21 – Visiting Frequency (Faulty state) per Availability

THE EFFECT OF MTBF ON COSTS

Another important trade-off is the effect of the MTBF on the average maintenance costs. Figure 22 presents the MTBF-Maintenance Cost trade-off for a nominal MTBF on 8760h (one failure per year).

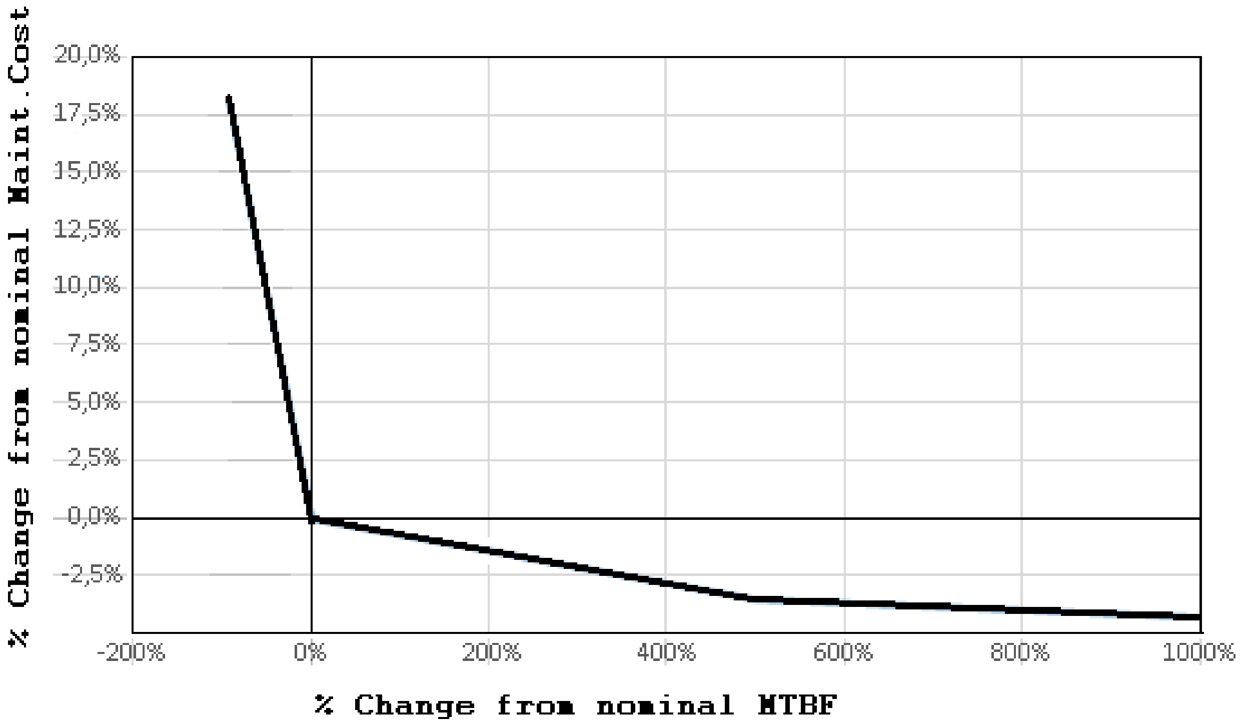


Figure 22 – Effect of MTBF on average maintenance costs
(Nominal MTBF = 8760h and average cost of models 1,2 and 3)

THE EFFECT OF MAINTENANCE EQUALITY ON MAINTENANCE COSTS

If we consider the MTBF as one of the quality measurement of a given maintenance system…

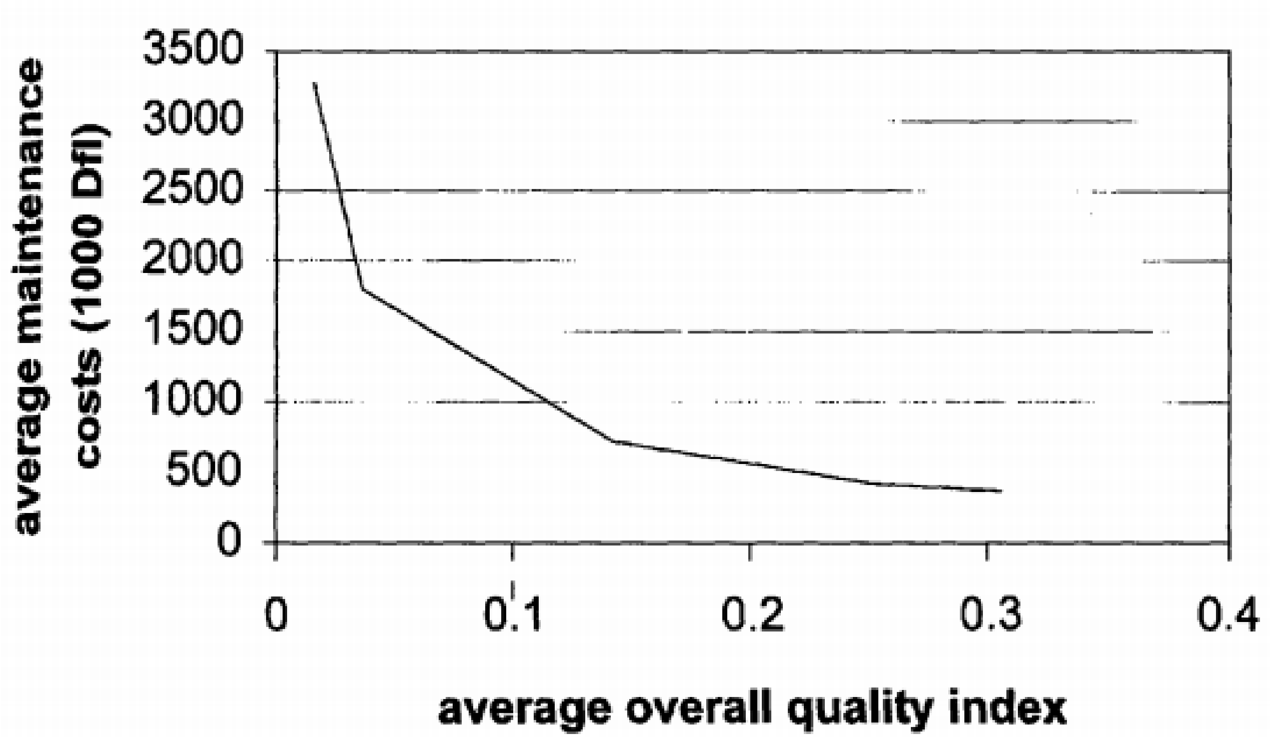


Figure 23 – Trade-off between average maintenance costs and quality (related to paintings of 500 buildings)
Source: (Van Winden and Dekker, 1998)

"This is typically the kind of graph that strategic decision makers would like to have."

Van Winden and Dekker (1998)

EFFECT OF MTBF ON TOTAL OPERATING COSTS

Thinking about the effect of MTBF in the total operating costs (TOCs) …

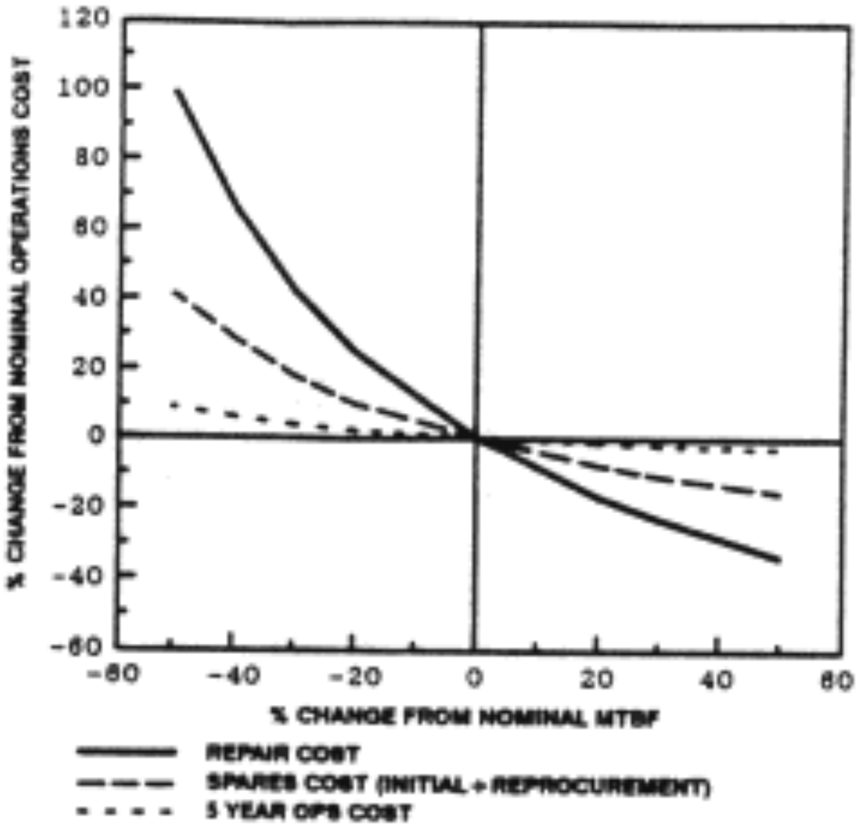
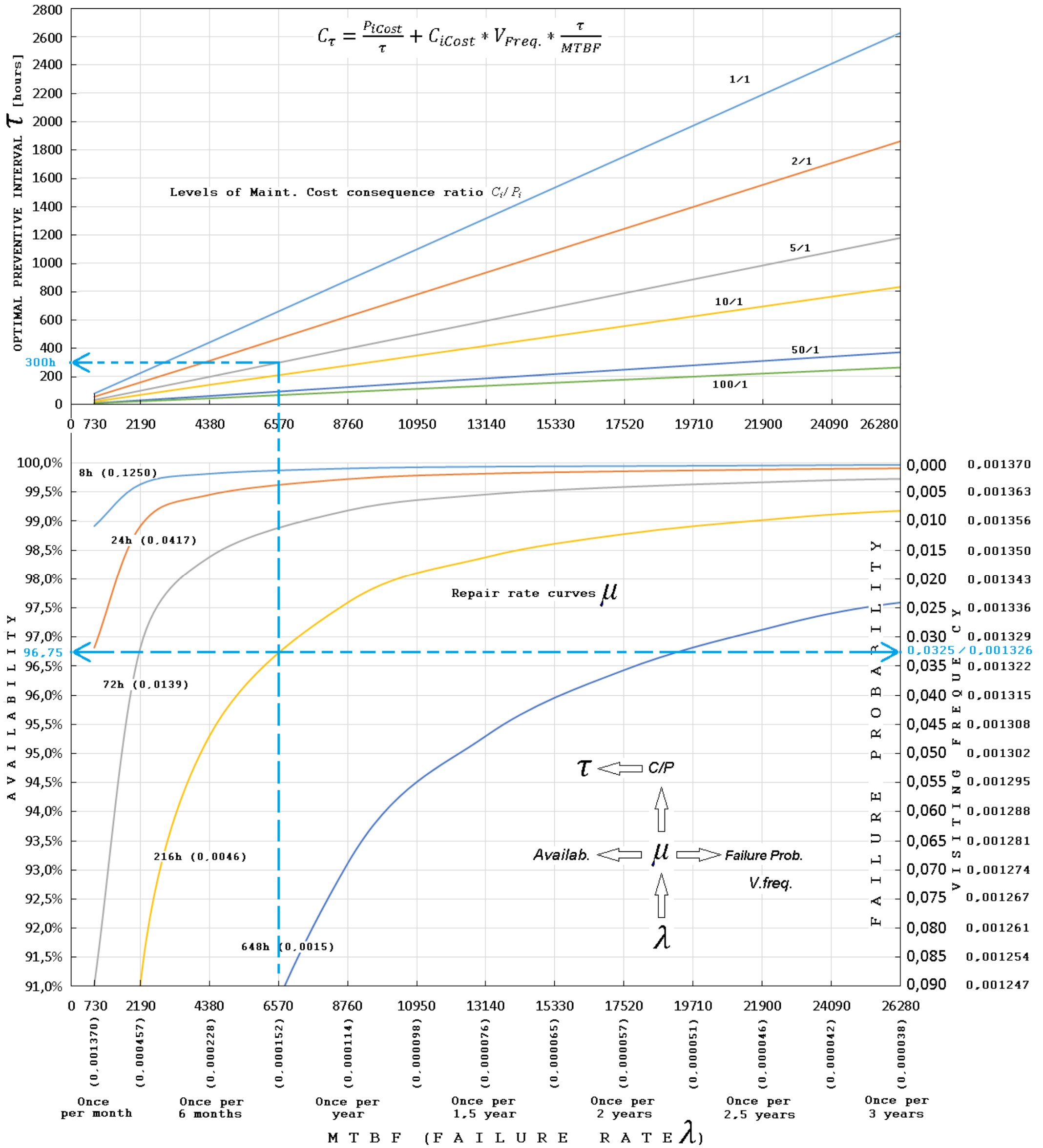


Figure 24 – Nomogram showing the effect of MTBF in operations cost of a space station - Source: (NASA Systems Engineering Handbook, 1995) Produced by Dr. William F. Fisher and Charles Price in the SSF External Maintenance Task Team Final Report (JSC, July 1990).

A DEPENDABILITY NOMOGRAM

(Immediate Detection, Corrective Perfect Repair – Two states Markov process)



Prepared By: Mario Marcondes Machado - Based on standard Markov methods in Rausand & Høyland (2004) and Vatn (2007)

Figure 25 – A Dependability Nomogram

EXPLORING THE 3 STATES MARKOV MODELS

As a first simulation experiment, one run (with 100 replications) was performed. In a second runt, now keeping Lambda 1 and 2 fixed and limiting Mu1 and Mu2 as the maximum, i.e. allowing for random repair times greater or equal to the mean (see Figure 27).

```
Lambda1 = 0.005 (randomly generated);
Lambda2 = 0.001 (randomly generated);
Mu1     = 0.125 (randomly generated);
Mu2     = 0.0139 (randomly generated);
Initial State = 3 (OK);
```

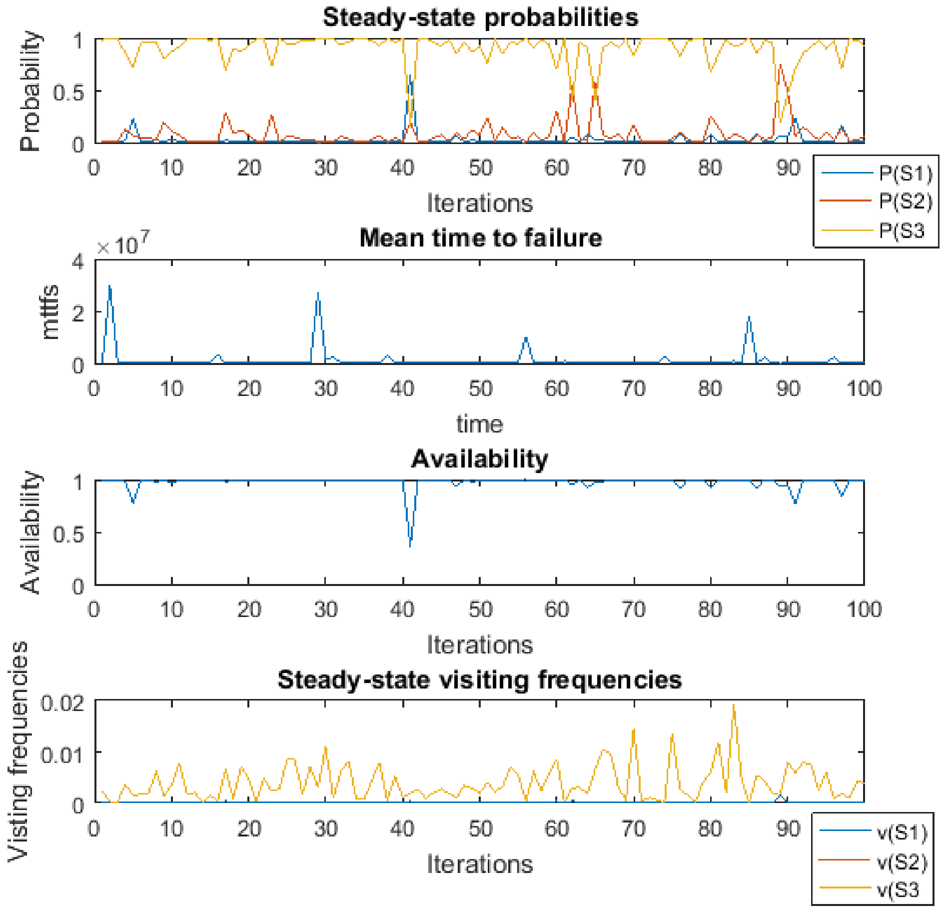


Figure 26 – Simulation 1 (total freedom)

```
Lambda1 = 0.005 (fixed);
Lambda2 = 0.001 (fixed);
Mu1 <= 0.125 (randomly generated left side);
Mu2 <= 0.0139 (randomly generated left side);
Initial State = 3 (OK);
```

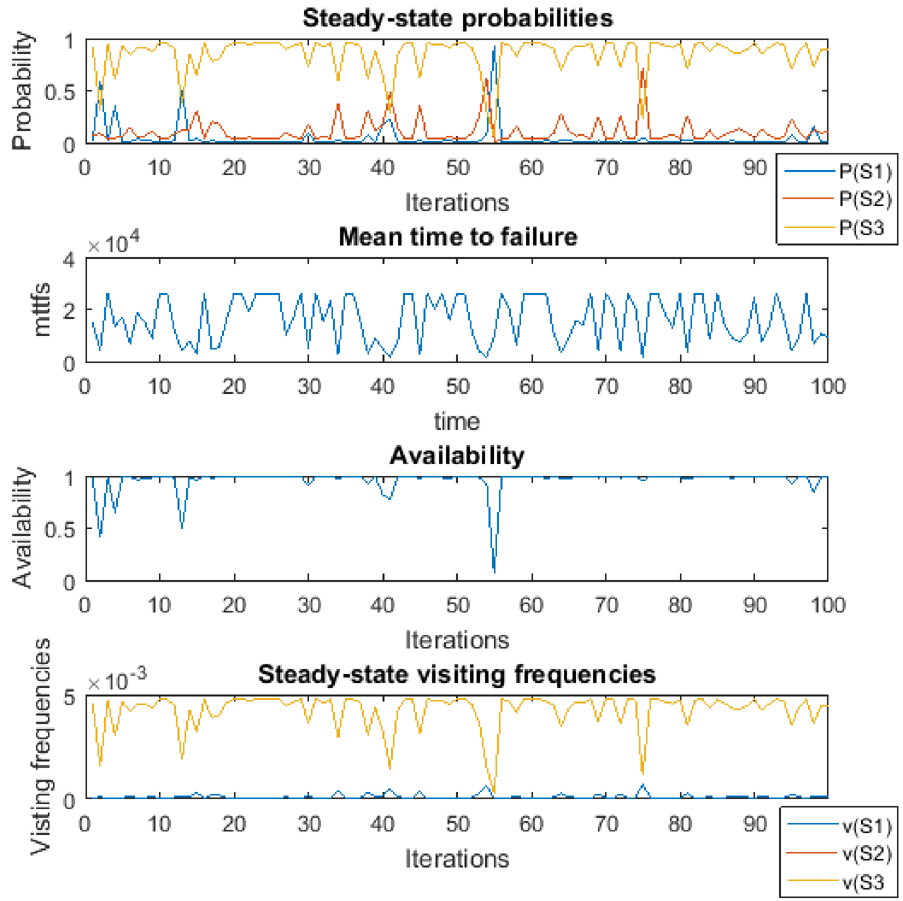


Figure 27 – Simulation 2 (minimum Failure Rates limited)

FINAL CONSIDERATIONS AND NEXT STEPS

Markov analysis is a powerful approach in the development of predictive models. The question is how to assess input data from real systems.

The two states Markov model (our explanatory model) provided useful insights in the learning process due to its great observability and consistency.

More research is needed (i.e. other experiments including, common cause failures, random failures and ageing factors).

Next steps:

- Continue with experiments (different architecture and maintenance cost models including spare parts considerations, common cause failures etc.;
- Prepare a paper from the reports (MO and SE);
- Develop the (if then) rules for the algorithm to connect the “Markov layers” in a discrete event simulation;
- Report respective results as part of the PhD study;
- Conclude the interviews and surveys;
- Analysis and synthesis;
- Submit the PhD monograph;
- Defense.

THANKS FOR YOUR ATTENTION

Mario Marcondes Machado

mariomarcondes2000@yahoo.com.br
mmarcondes@petrobras.com.br