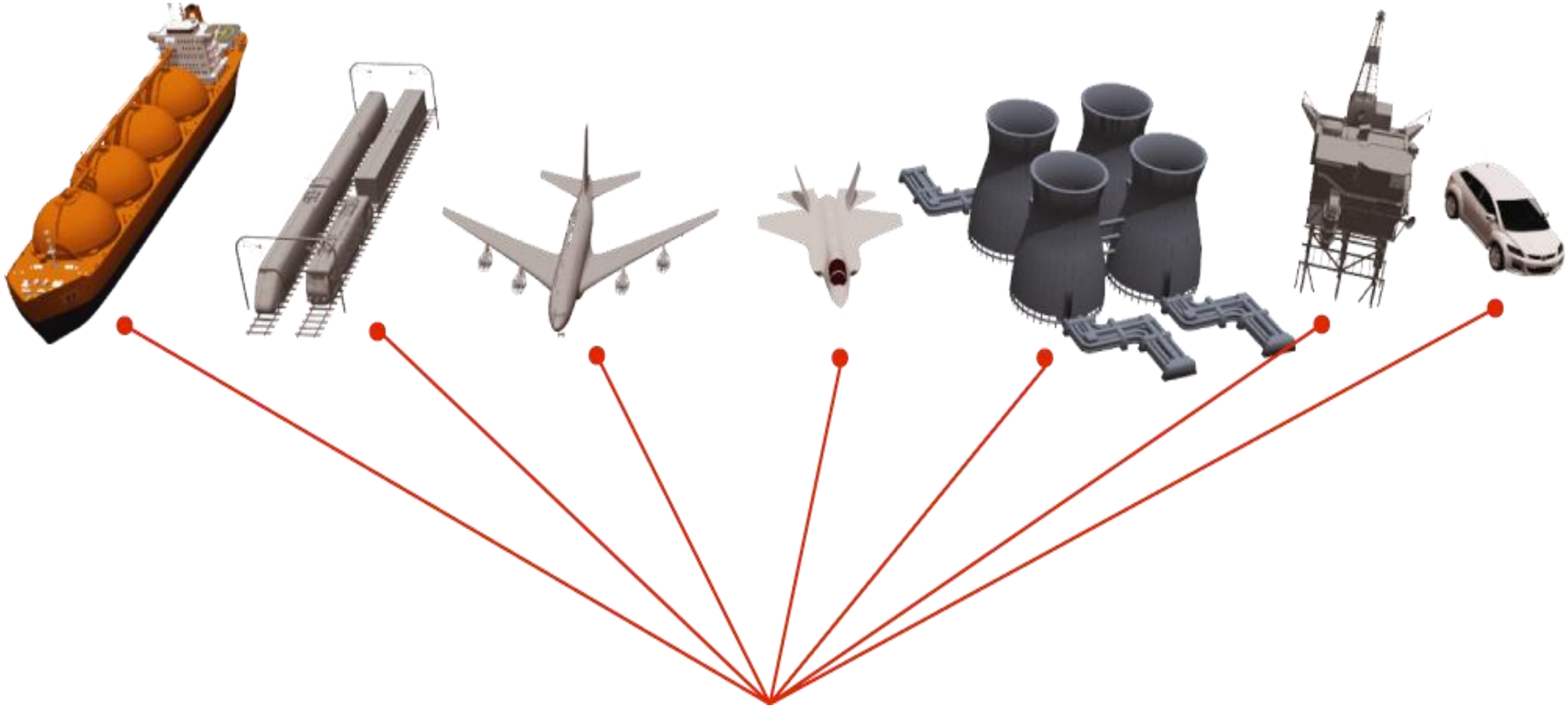

The Rise and Fall of CBM

Jacek S. Stecki

NATO RTO Workshop – "Implementation of Condition Based Maintenance"
Bucharest, Romania
4-6 October 2010

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Plan of Presentation

- Expectations
- Technological progress (sensors, techniques, methods etc.)
- Barriers to implementation
- CBM/PHM
- Risk assessment
- Modelling failure
- Taxonomy
- Sensor fusion
- Jet Engine lubrication system – example
- Concluding remarks

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Background

- Defence equipment and systems function in harsh environmental and operational conditions and must meet stringent requirements of reliability, safety, availability and maintainability – particularly with the introduction of performance based contracts (PBC)
- To reduce the high cost of development for new products, OEMs use a vast array of computer aided techniques during the design and testing stages
- Maintainability requirements, long ignored by designers and OEMs, has assumed great importance and forced a rethinking of the way the design of new systems should be carried out
- Availability is a major constraint, and it has became important to develop techniques to monitor the health of a system, to diagnose system problems prior to its failure and to prognose the system's remaining life
- Efforts have been made to justify these new design approaches with a business case that reflects PBC requirements and the current US DoD system acquisition policies that focus on the cost of sustainment over the entire system life cycle
- Maintenance Technology has become recognized as an academic discipline

Expectations

- Enhanced system reliability and equipment safety
- Reduced maintenance manpower, spares and repair costs
- Eliminate or significantly reduce scheduled inspections
- Maximised lead time for maintenance and parts
- Procurement
- Automatically isolated faults
- Real time notification of an upcoming maintenance event for the logistics chain
- Catch potentially catastrophic failures before they occur
- Detect and monitor incipient faults until just prior to failure

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The Rise of CBM

- Rapid progress was made in the 1960s - 1980s in the development of new sensors, symptom monitoring techniques and performance monitoring in aircraft, marine, railways and mining machinery applications
- During this period, monitoring techniques were seldom used together to provide comprehensive and reliable detection and diagnosis of failures
- Likewise, research on detection and diagnostic techniques and methodology was usually directed towards a single technique; for example: vibration monitoring
- The situation changed in the early eighties when the concept of On-Condition Maintenance was developed [over the years the name changed to Condition Based Maintenance (CBM)] and applied in high risk industries like aviation, mining and offshore oil production
- Since the 1990s there has been significant progress in the development of new sensing techniques, diagnostic and prognostic methodologies and the application of computer analysis techniques

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Technical Barriers to effective CBM

The Advanced Technology Program (ATP), of the National Institute of Standards and Technology (NIST), held a workshop on Condition-Based Maintenance (CBM) as part of it's November 17-18, 1998 Fall Meeting in Atlanta.

Discussions with companies identified 3 technical barriers to CBM's widespread implementation:

- The inability to accurately and reliably predict the remaining useful life of a machine (*prognostics)*
- The inability to continually monitor a machine *(sensing)*
- The inability of maintenance systems to learn and identify impending failures and recommend what action should be taken (*reasoning*).

These barriers could potentially be addressed through innovations in three technical areas:

- Prognostication capabilities
- Cost effective sensor and monitoring systems
- Reasoning or expert systems

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Systemic Barriers to effective CBM

- In many military/industrial applications the metrics for evaluating successful implementation of CBM are not clearly defined (*risk, economics, performance*)
- Lack of clear guidelines or business case for when and why CBM is preferred to other maintenance approaches (technical/economic)
- CBM programs are initiated without full knowledge of how the system can fail
- The effectiveness of a CBM program cannot be evaluated with current management tools.
- Maintenance requirements/specifications are not defined at the concept formulation stage of the design process
- Identification of an optimum level of diagnostic and prognostic requirements and specifications is not generated
- Selection of an optimum monitoring mix (s*election of sensors*) should be system oriented but is often driven by the vendors of sensors
- Maintenance management systems are inadequate
- Historical data, postmortem results not available or accessible
- Uncertainty of ROI (Plant Services Magazine (USA)"..In a survey of 500 companies, less than 3% of respondents were able to achieve a measurable return on their investment in Predictive Maintenance technologies")

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Knowledge Barriers to effective CBM

- Limited or no knowledge retention about CBM within the OEM or customer
- Skills issues are not addressed
- Education of CBM managers/engineers not available at Universities (Monash University had undergraduate/postgraduate programs in CBM supported by multidisciplinary laboratory from 1980 to 1996)
- Widespread research in CBM but it is invariably directed towards specific techniques (better mousetrap symptom)

Google "Condition based Maintenance" - 33,000,000 hits!

Google "Condition based Maintenance barriers" - 1,080,000 hits!.

Google "Gearbox Condition monitoring" - 44,000 hits

Google "Bearings Condition monitoring" - 350,000 hits

Google "Vibration Condition monitoring" - 351,000 hits

Google "Contamination Condition monitoring" - 304,000 hits

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CBM / PHM / RCM and other TLAs

- The methodologies and approaches of CBM evolved from On-Condition Maintenance (OCM)
- Reliability Centred Maintenance (RCM) is a variant of the CBM approach
- PHM is a further evolution of the CBM concept, and is also sometimes referred to as Vehicle Health Management (VHM)

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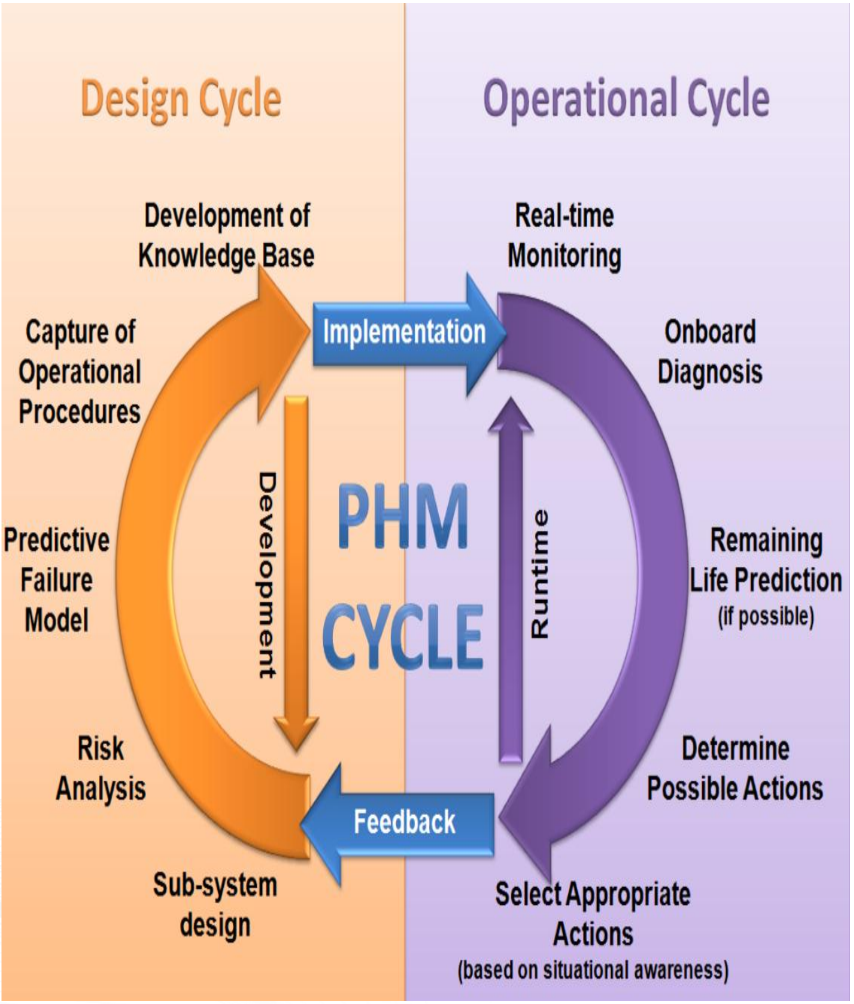
The PHM cycle

An effective PHM implementation for a system requires two main cycles of development: design and operation

- The Design Cycle is required in order to generate the knowledge base from which the PHM system can obtain its decisions.
- The Operation Cycle describes the steps taken within the PHM system from detection of faults through to conveying instructions or actions.



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CBM/PHM - what are we dealing with?

Functional Analysis

Failure modes

Training

FMECA

Production Losses

Detection

Sensors

Prognostics

Diagnosis

Reliability

BIT

Training

Simulation

Fault Tree

Condition monitoring

Risk Minimization

Downtime

Faults

Maintenance

$$$$$$$!

Hazards

Safety

Testing

Fall-back Analysis

ROI

Education

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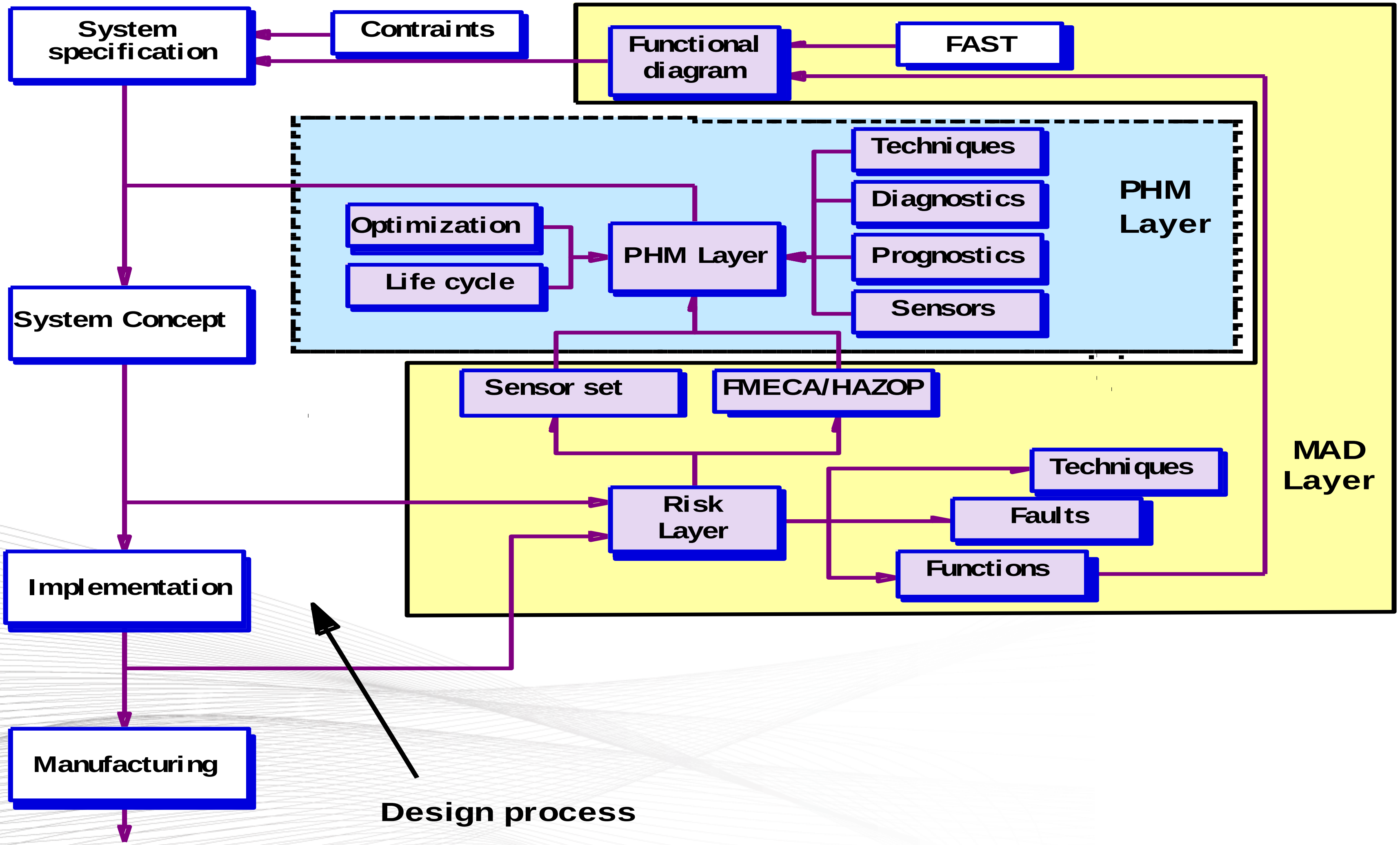
Interaction of MAD and CBM/PHM Layers at Design Stage



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Case Study - Mining

- 12 mine sites – mining trucks, conveyors, shovels etc.
- Data from mines' maintenance management systems
- Approx 500 MB of data collected over period of up to 5 years
- Limited number of detection/diagnostic/ techniques
- External contractors – no in-house knowledge
- Only 4 sites had useful information – although incomplete

Conclusions (from the report):

- Sampling/detection and diagnosis do not follow the **best practice** to achieve meaningful indication of machine state
- Any reporting should have have **deliverables**, or information will not be useful.
- Unspecified conditions before failure occurred
- Lack of information of how the system, component, part failed ie. postmortem
- Outline the reactive and pro-active activities.
- Unknown or missing – grade and quality of roads, drivers, trained, gender, mechanics, conditions, weather, material being hauled, oil used, petrol used, original parts used, shift work, 7 day week, support, underground, humidity, walk around each day, same route etc.
- Effective FMEA/FMECA Analysis should be conducted prior to monitoring
- No visible CBM design/plan
- No possibility to assess ROI

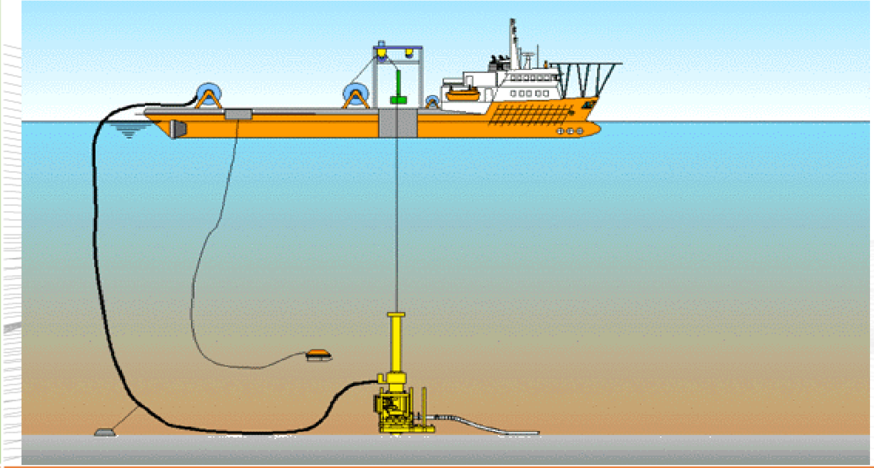
Subsea / Aerospace

Risks

- Severe operating environment
- Stringent statutory safety standards
- Safety critical systems
- Expensive maintenance
- Long innovation lead time
- High technology
- Conservative attitudes
- High reliability requirements
- Single shot operations
- Very high cost of failure

Tools to deal with risks

- Computer based design methods
- Reliability and Hazard Analysis
- Failure analysis (FMECA/FTA)
- PHM (Prognostics and Health Management)
- Condition Monitoring - CBM
- Testing



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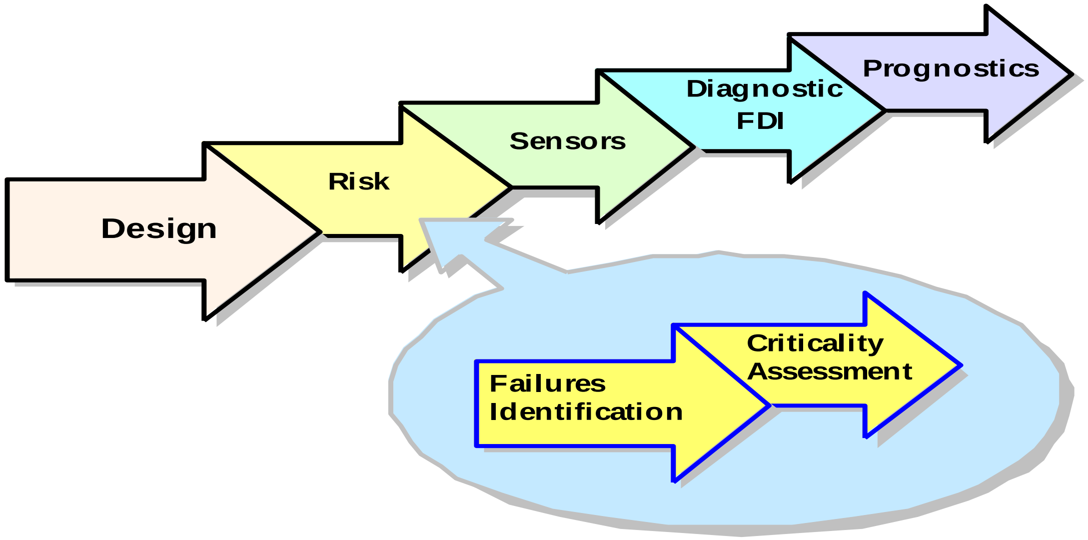
Risk reduction – CBM/PHM



What is it?

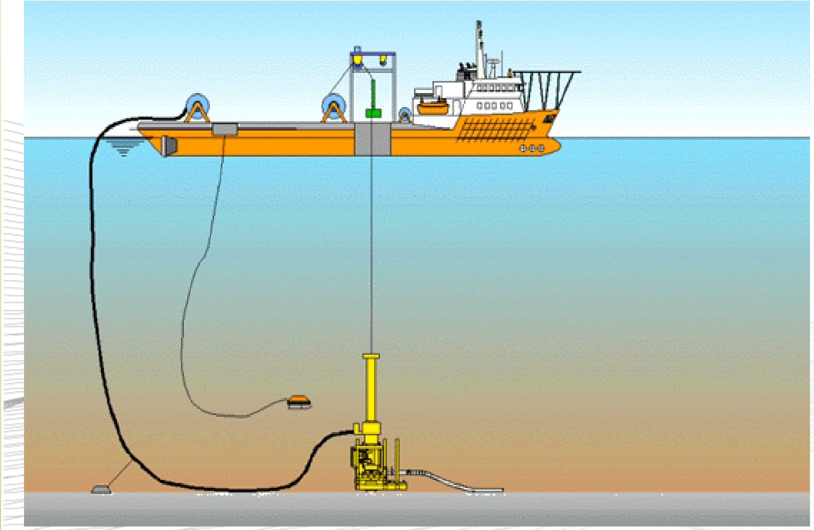
- Risk assessment using techniques like FMECA, HAZOP, RCM etc.
- Diagnostics – is the process of determining the state of a component to perform its function(s)
- Prognostics – is predictive diagnostics which includes determining the remaining life or time span of proper operation of a component
- Health Management – is the capability to make appropriate decisions about maintenance actions based on diagnostics/prognostics information, available resources and operational demand.

Criteria for RCM Processes

SAE JA1011 “Evaluation Criteria for RCM Processes” defines seven questions for RCM:

- What are the functions…of the asset…(functions)?
- In what ways can it fail…(functional failures)?
- What causes each functional failure (failure modes)?
- What happens when each failure occurs (failure effects)?
- In what way does each failure matter (failure consequences)?
- What should be done…(proactive tasks and intervals)?
- What should be done if a suitable proactive task cannot be found?

Risk Assessment - FMECA



Failure Modes

Possible Failures FMECA

Effects

What effect does the failure have? FMECA

Criticality Analysis

Criticality Analysis of each failure FMECA

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Risk Assessment – e.g. FMECA

Why FMECA is carried out

- Statutory requirement – must be done
- We need to have audit trail in case of problems
- A need to know of how to improve system safety
- The integrator insisted on it
- Reliability people need it

Why FMECA should be carried out

- We need to know what to monitor and what sensors to use
- We need to have capability to detect, diagnose and prognose the state of the system
- To design-out failures
- We need to know how the system can fail so we are prepared to deal with it
- To enhance diagnostic capabilities

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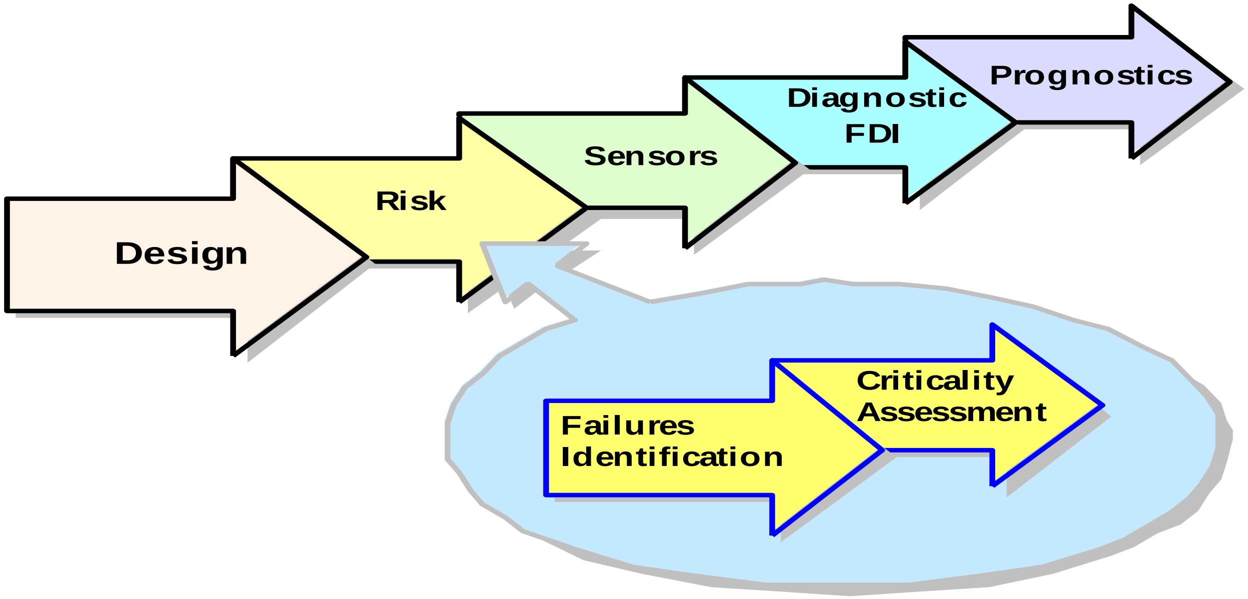
Reasons for failure of Risk Assessment

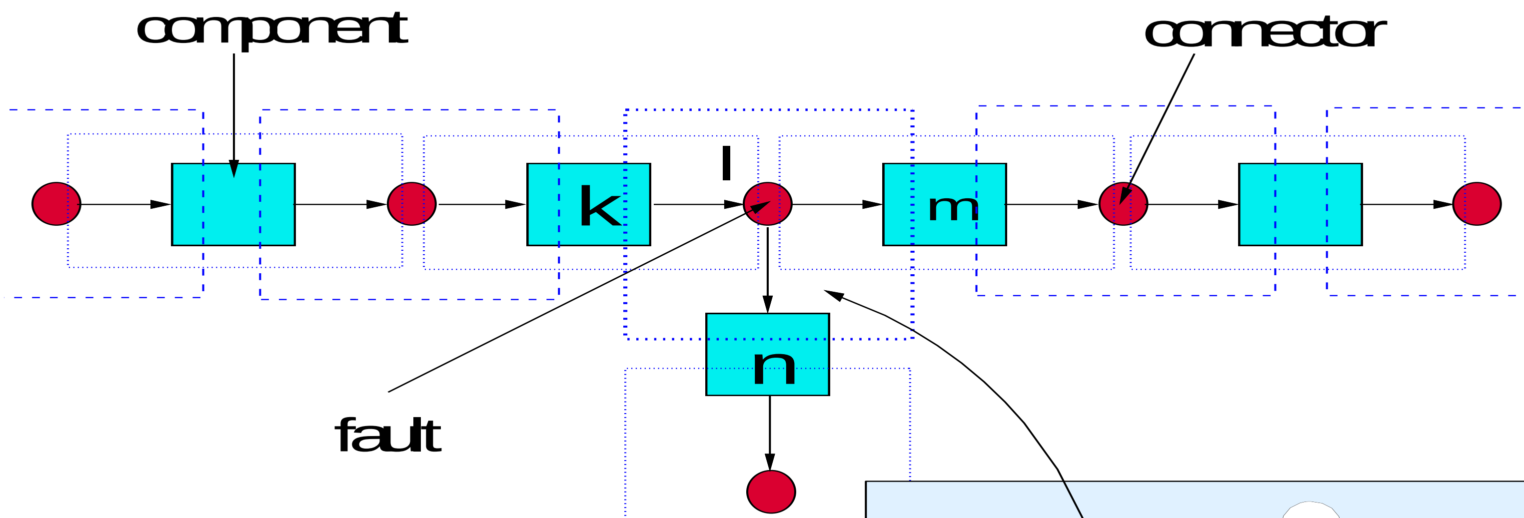
- Dependencies of failures not identified – spreadsheet vs model based
- Inadequate Identification of Risks - functional failures (failure modes) vs physical failures
- Incomplete database of failures (deficient FMECA)
- Taxonomy – confusion what is the cause, mechanism of failure, fault, symptom and/or failure mode
- Symptom vs Syndrome approach
- Sensor fusion not based on failures dependencies (fall-back – testability)
- Diagnostic rules not based on dependencies
- Reliability of Hardware not the same as Functional Reliability
- Different models for Criticality and Reliability Assessment

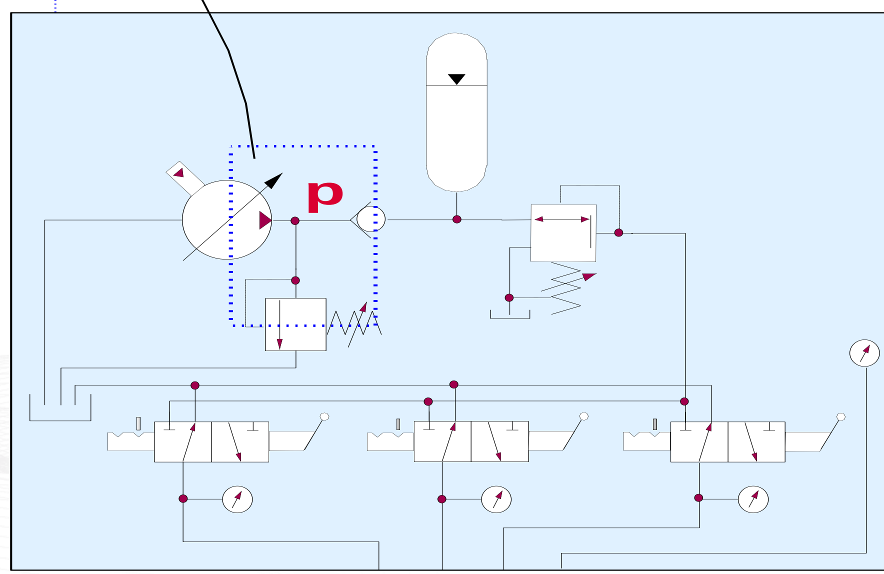
Risk reduction or is it?



- Risk is still there if failures are missed
- We cannot design a diagnostic system without knowledge of failures
- We do not really know what we should monitor
- Sensors cover only identified failures

Dependencies Modelling





pressure p down

- Q_l down (eg. pipe leakage)
- Q_k down (e.g.. pump leakage)
- Q_m up (e.g.. check valve leakage)
- Q_n up (e.g. relief valve open

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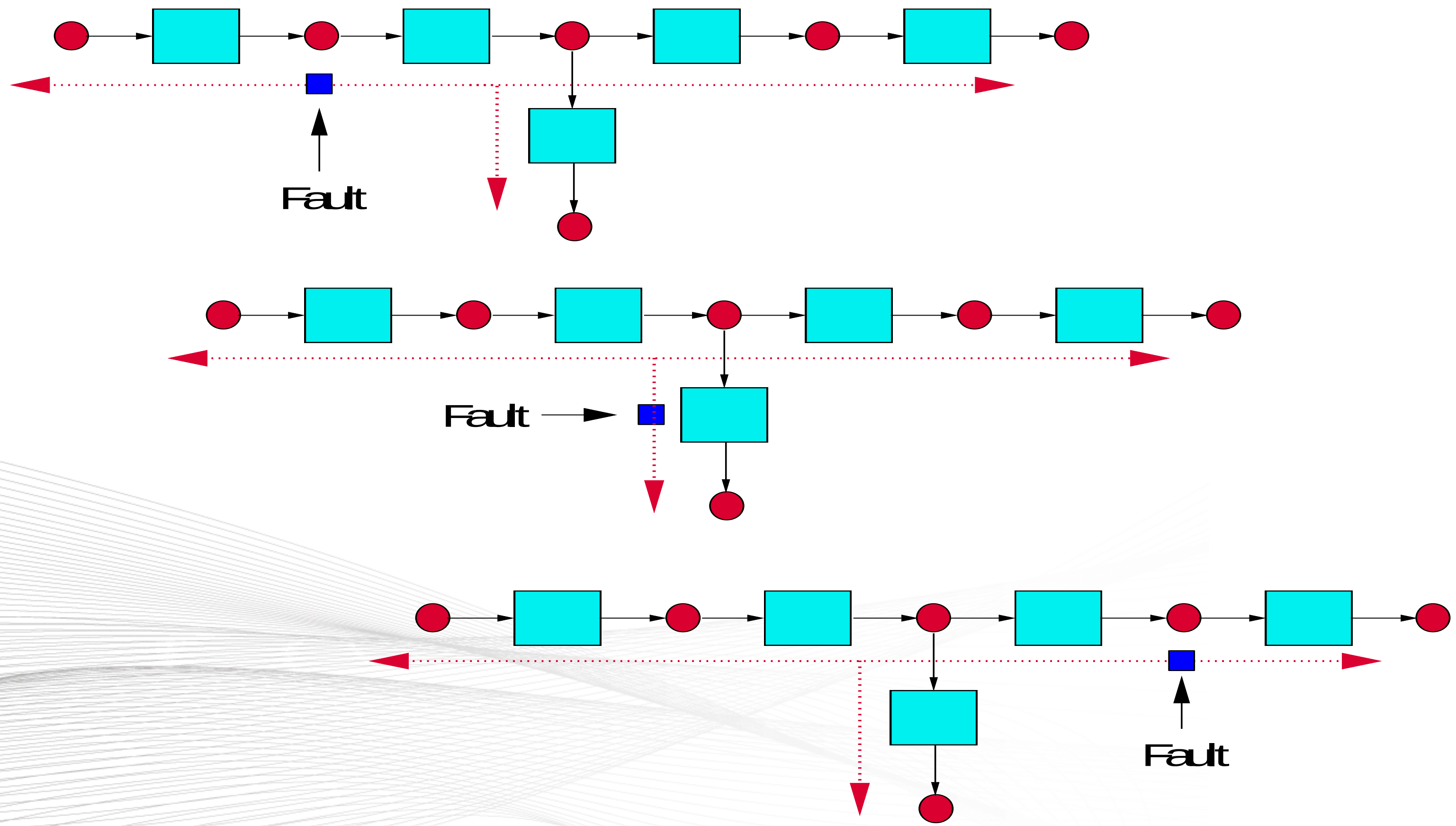
Fault propagation - dependability

- All faults are enumerated.
- Transient and steady-state responses to faults are identified



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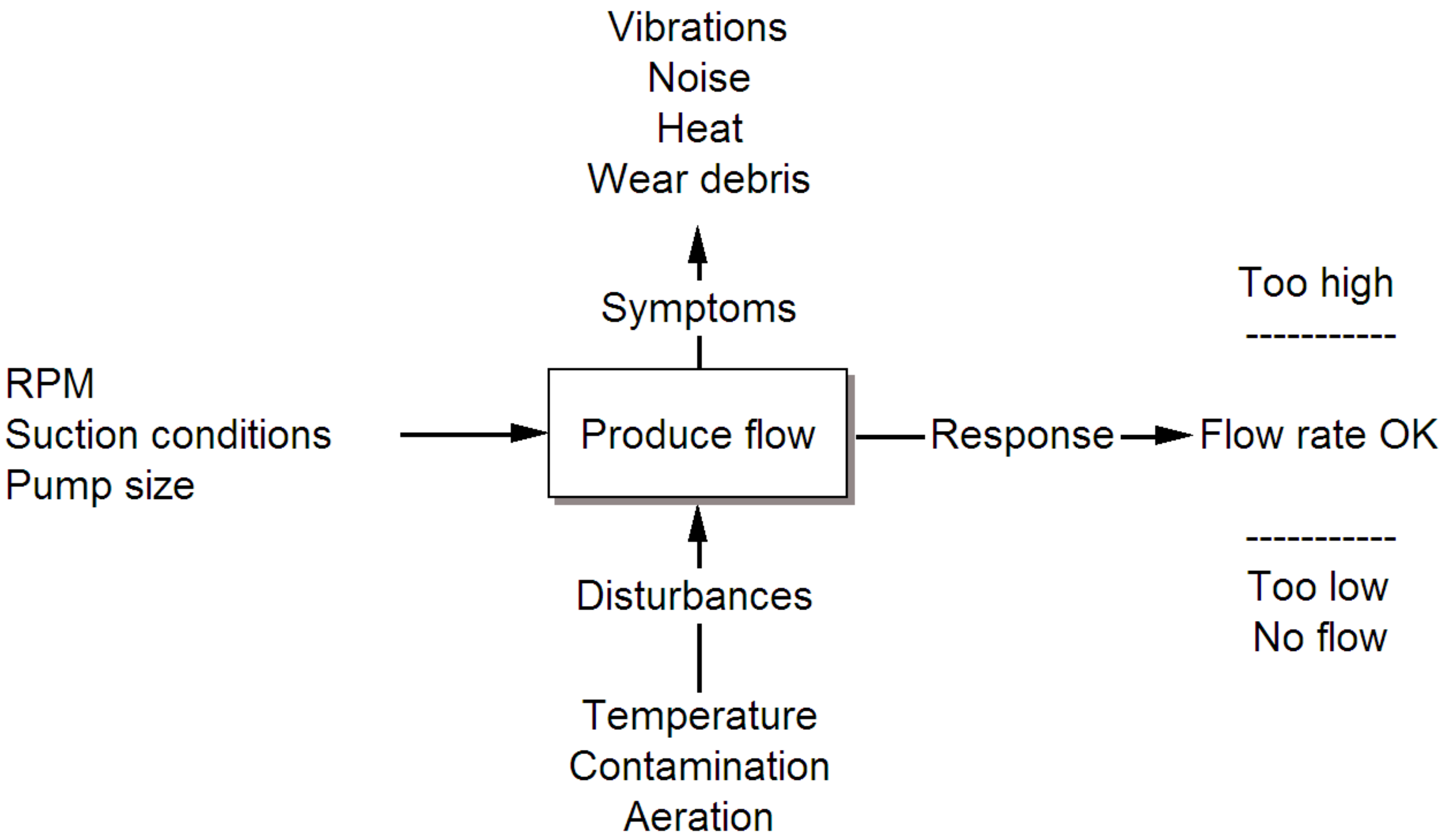
Model of a Pump



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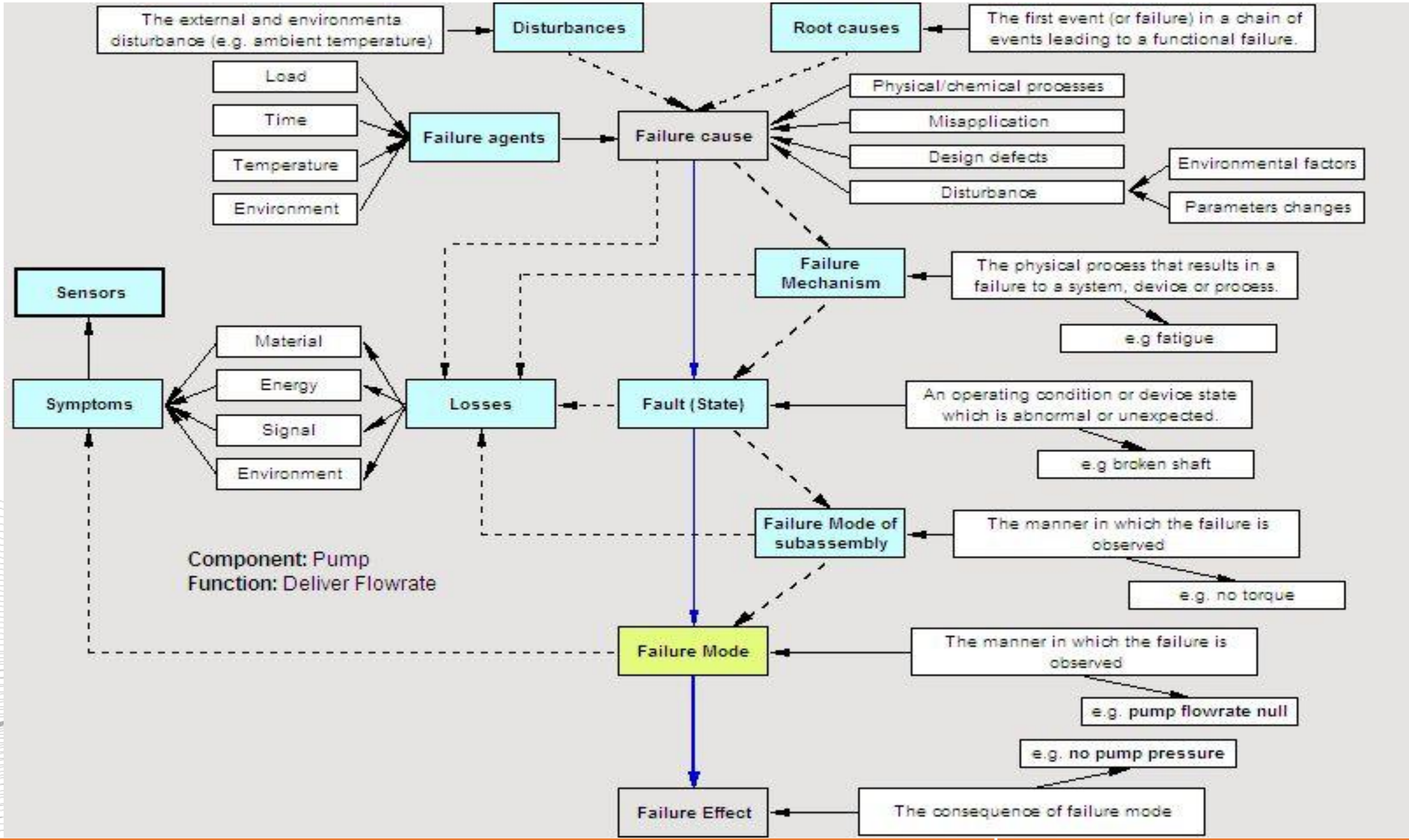
Modelling of failure



Taxonomy problems

Source - Item	Failure term	Cause	Mechanism	Fault	L/S	FF	No Class	LIF
RAC - failure modes								
Pump, hydraulic	Leaking			x				
	Improper flow					x		
	No flow					x		
Electric Motor, AC	Winding failure					x		x
	bearing failure					x		x
	fails to run, after start					x		
	fails to start					x		
NSWC - failure modes								
Electric Motor, AC	worn bearing			x				x
	open winding			x				x
	shorted winding			x				x
	cracked housing			x				x
	sheared armature shaft			x				x
	cracked rotor laminations			x				x
	worn brushes			x				x
	worn sleeve bearing			x				x
Pump, hydraulic	Pump cavitation		x					
	component corrosion		x					
	Low net postive suction head	x						
	shaft unbalance			x				x
	external leakage			x				x
	mechanical noise				x			
	positive suction head to low	x						
	pump discharge head to high					x		
	suction line clogged	x						
	pressure surges	x						
	increased fluid temperature	x						

L/S=Loss/Sympton

FF=Functional Failure

LIF=Lower Indenture Level Failure

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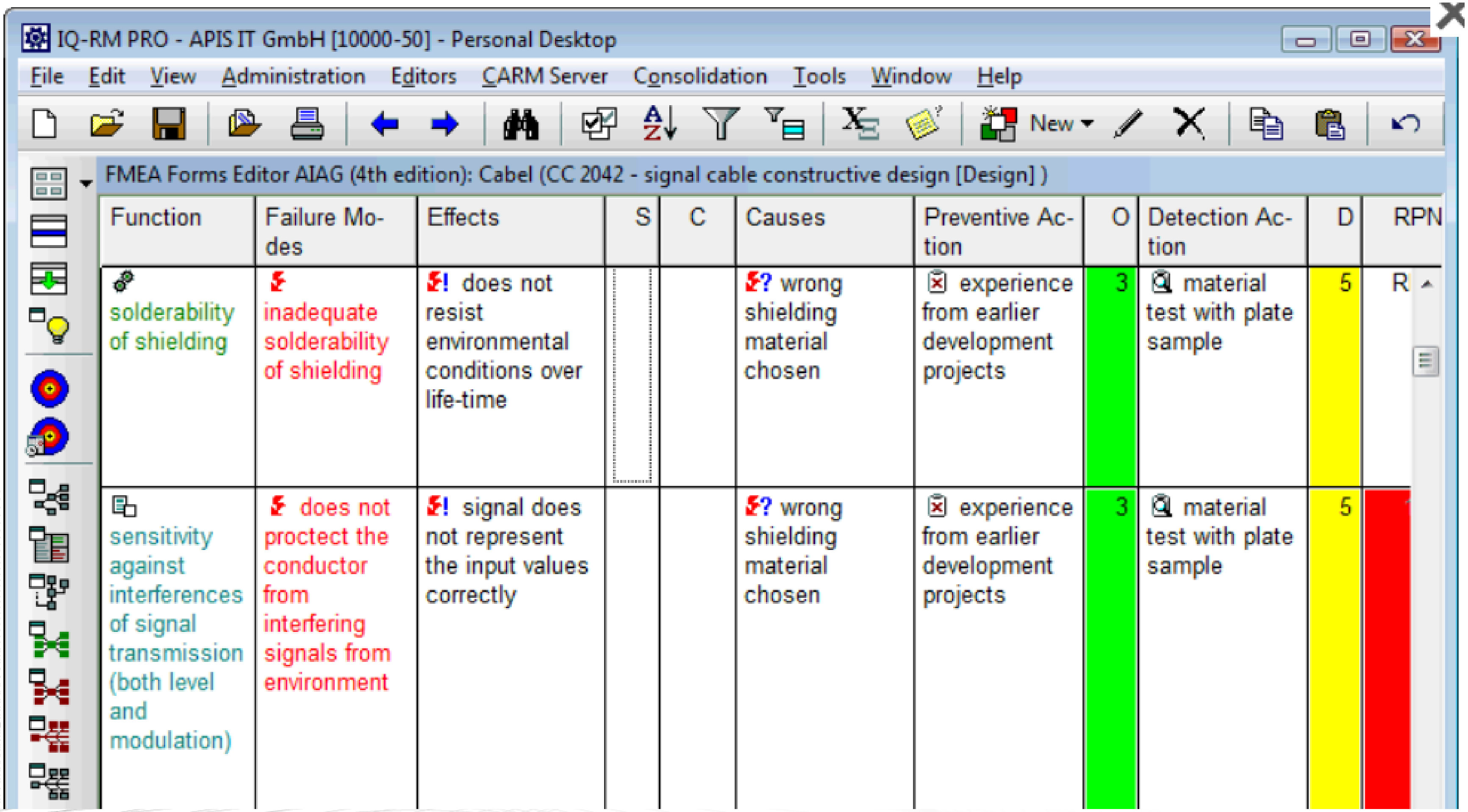
Taxonomy problems



Function	Failure Modes	Effects	S	C	Causes	Preventive Action	O	Detection Action	D	RPN
solderability of shielding	inadequate solderability of shielding	does not resist environmental conditions over life-time			wrong shielding material chosen	experience from earlier development projects	3	material test with plate sample	5	R
sensitivity against interferences of signal transmission (both level and modulation)	does not proctect the conductor from interfering signals from environment	signal does not represent the input values correctly			wrong shielding material chosen	experience from earlier development projects	3	material test with plate sample	5	

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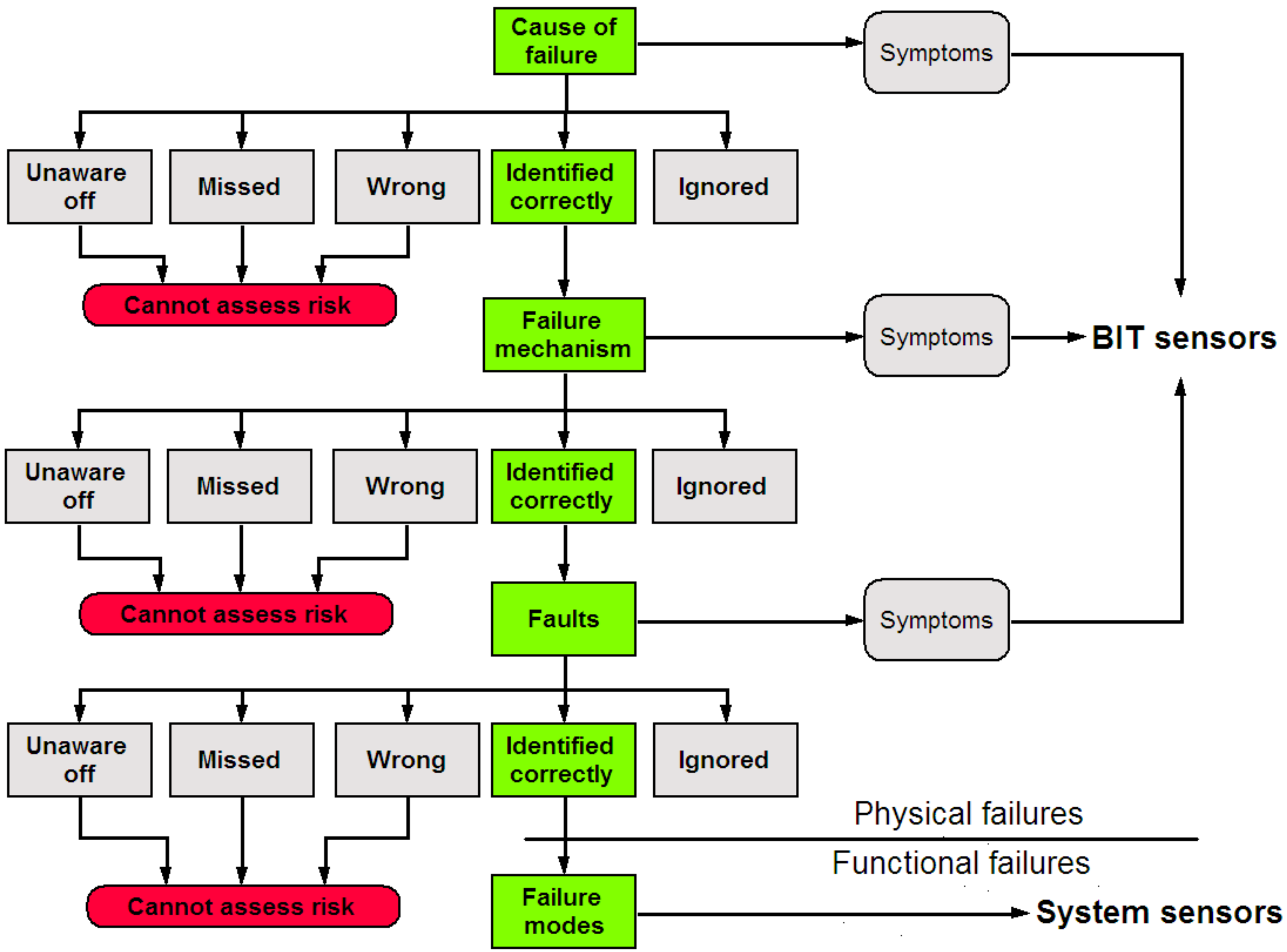
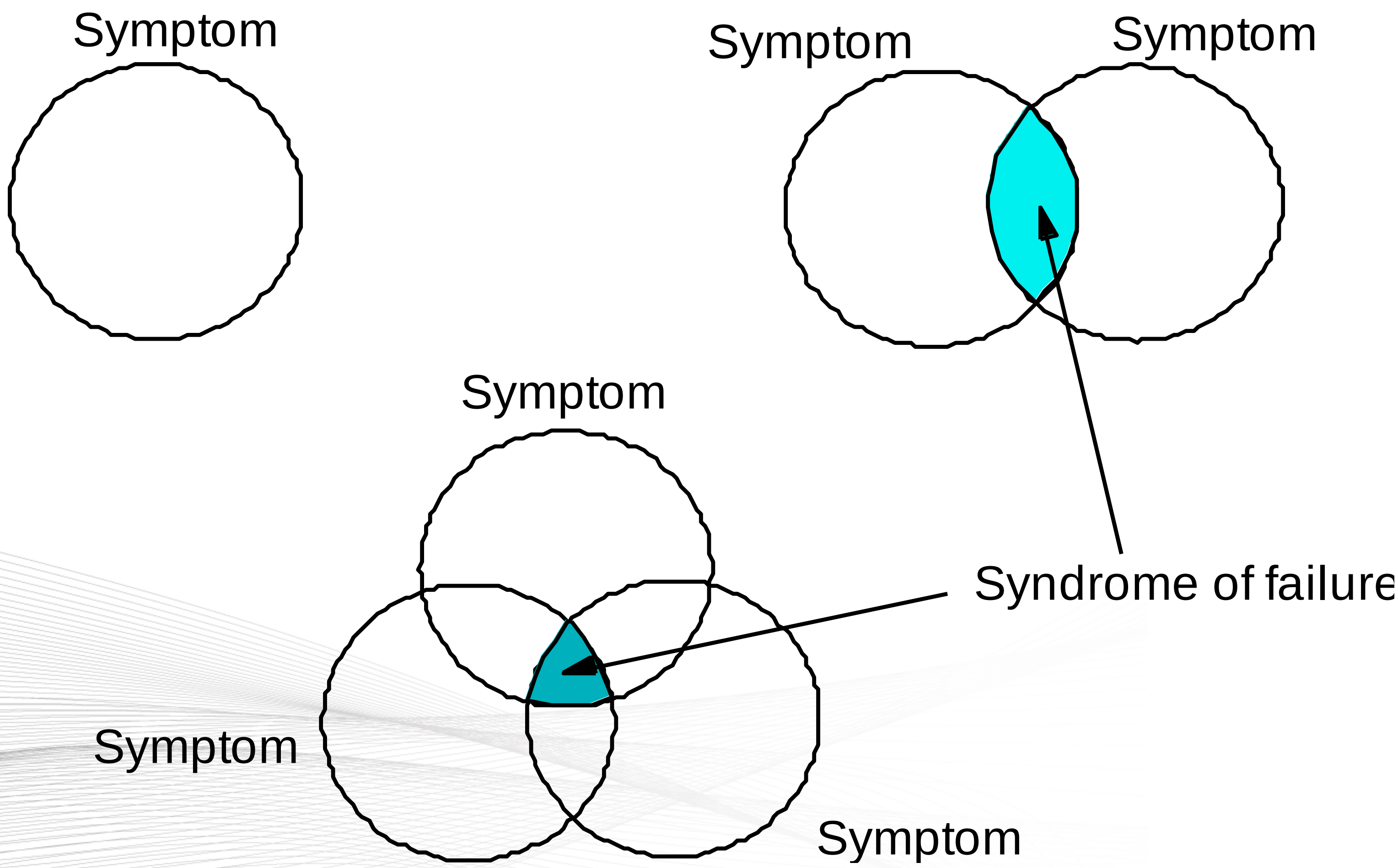
Identifying Risk



Failures - Symptoms/Syndromes



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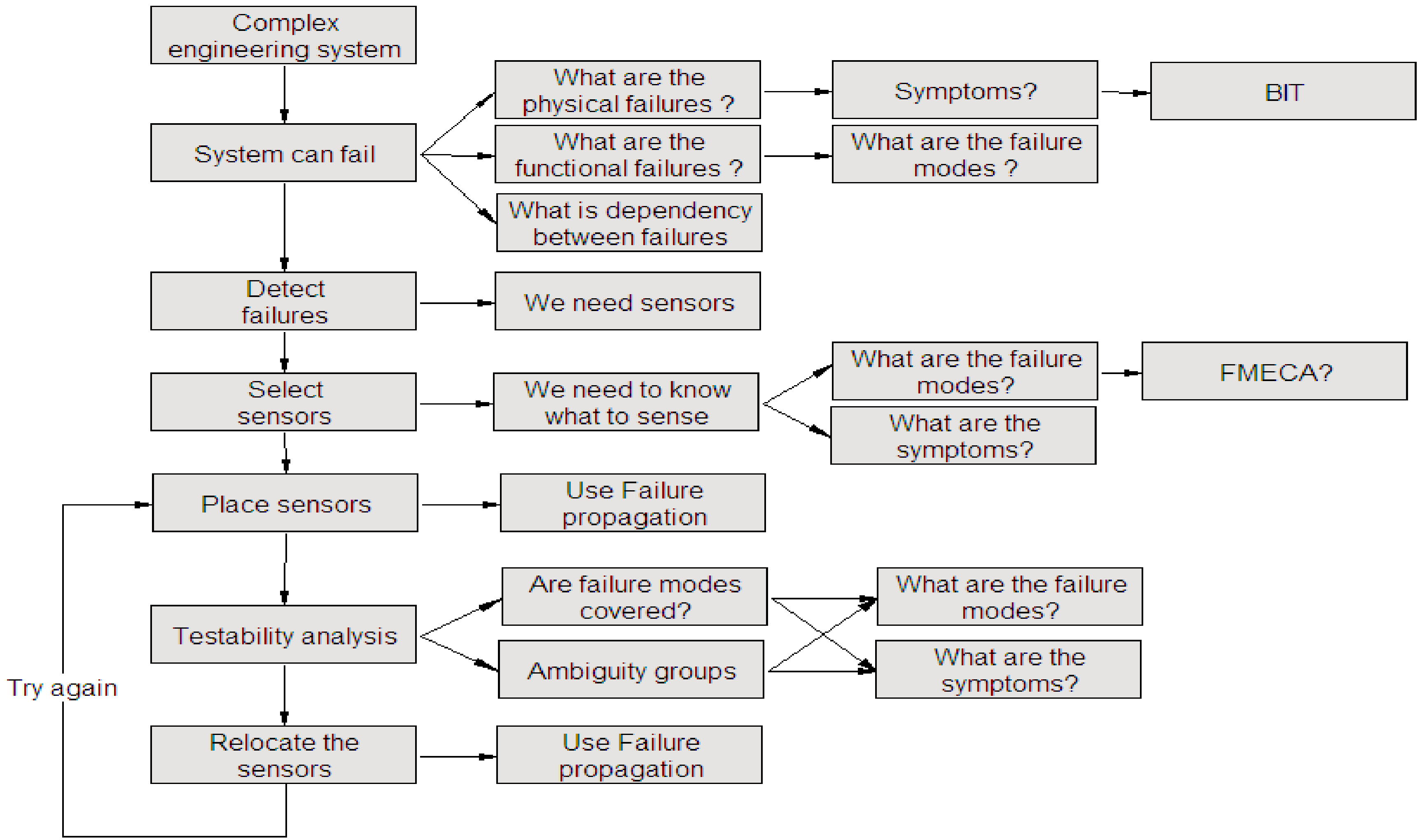
Sensor selection



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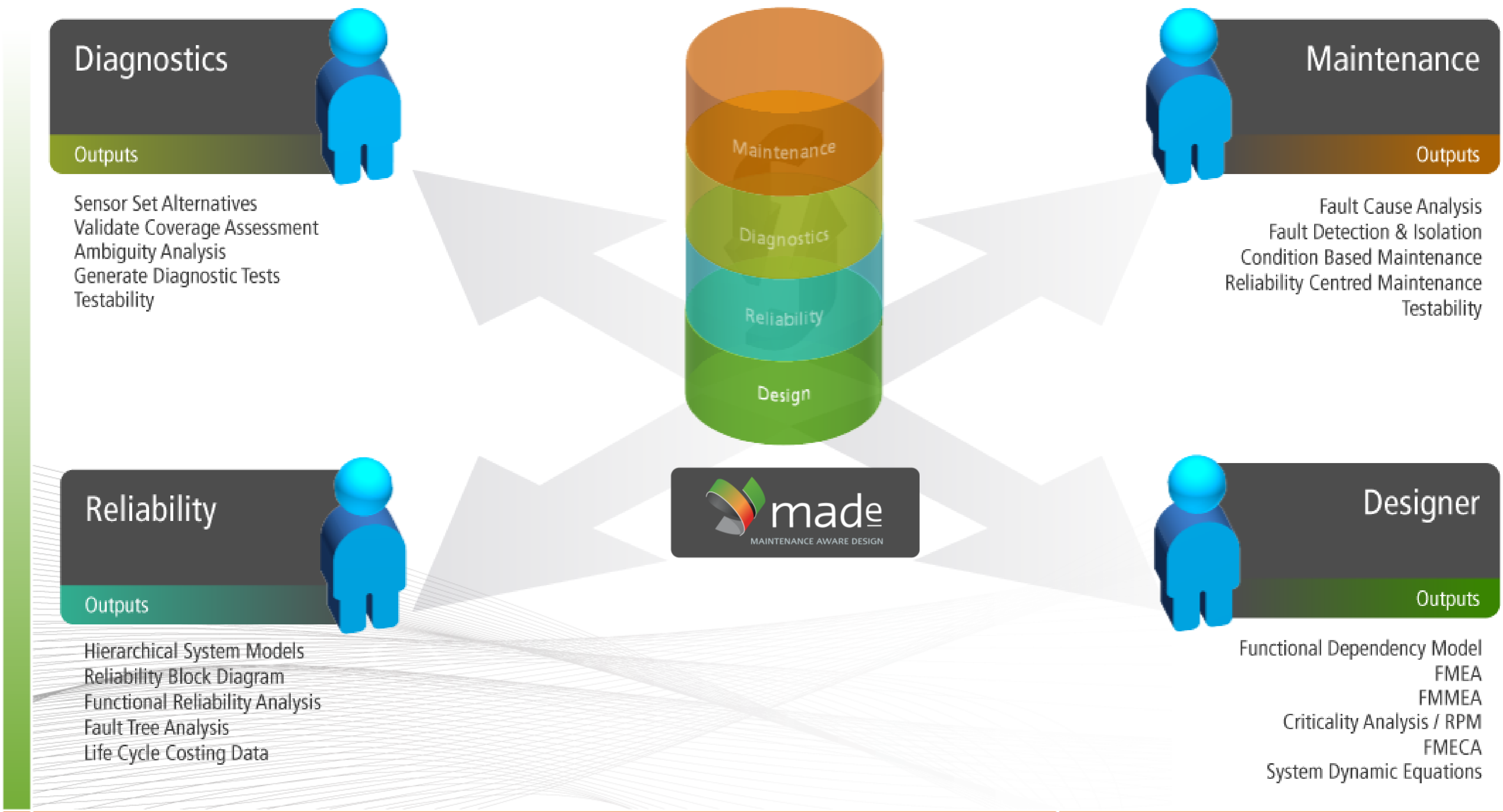
MADe software



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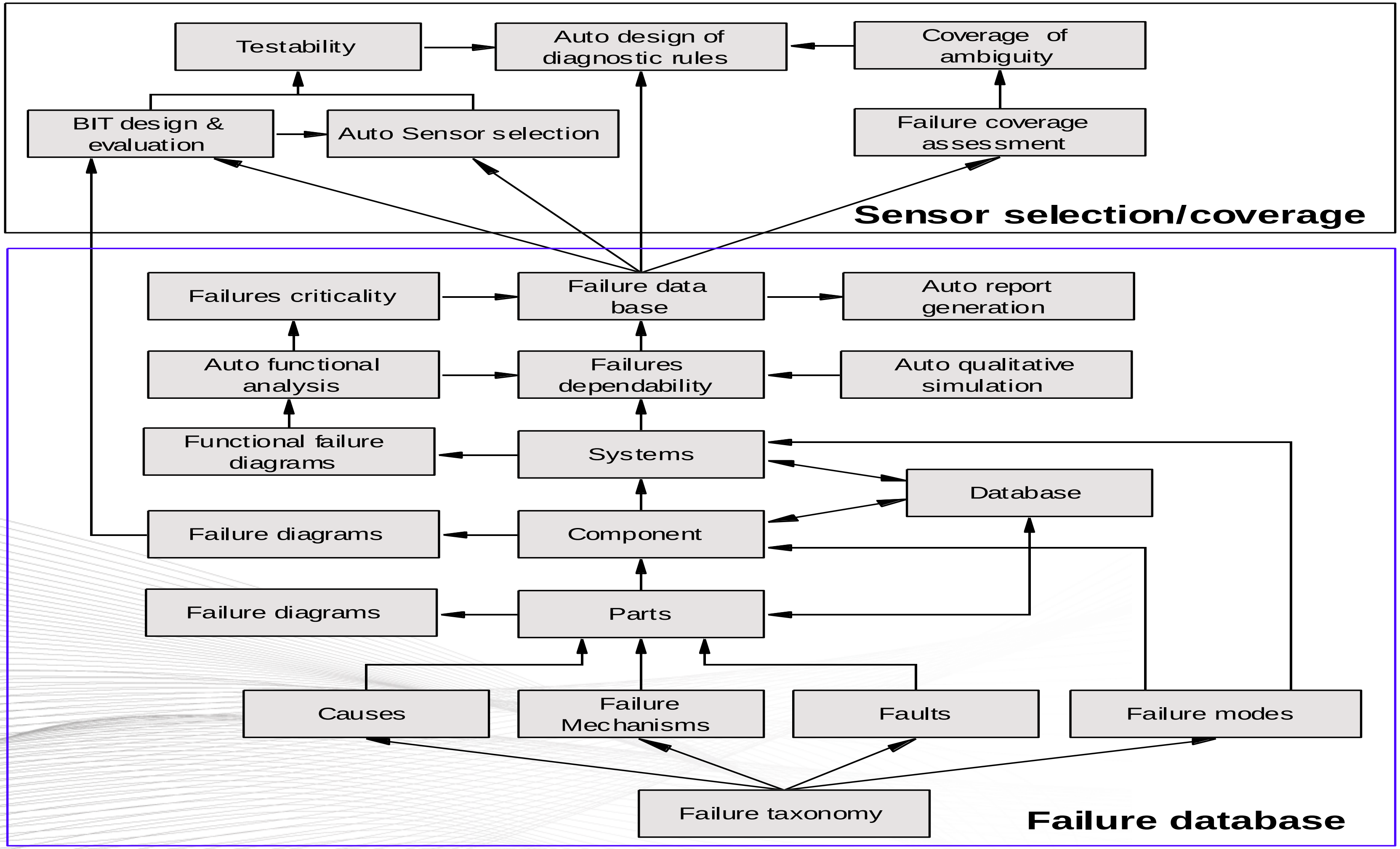
MADe software



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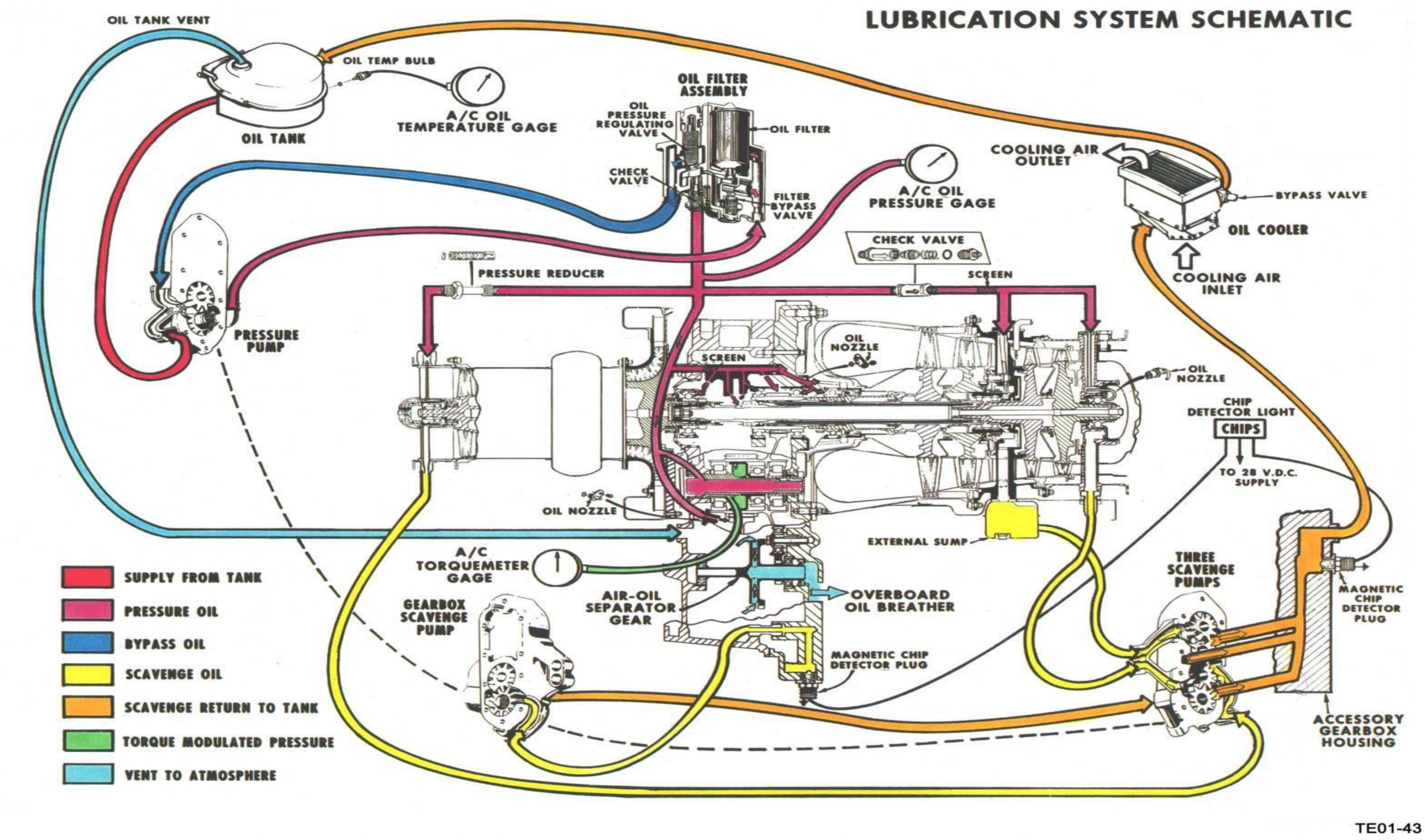
RR250 Engine Lubrication System



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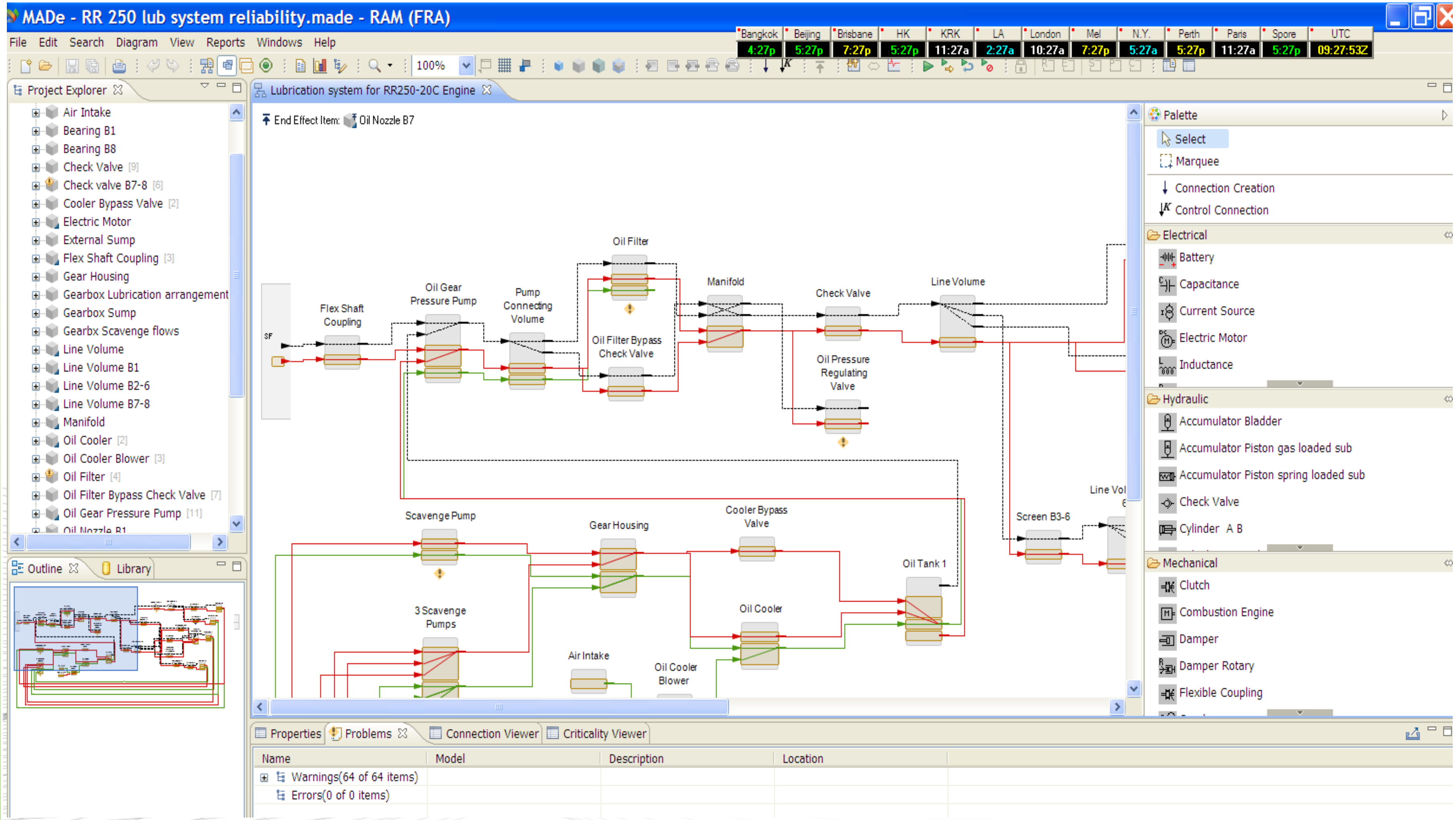
Engine Lubrication System Model



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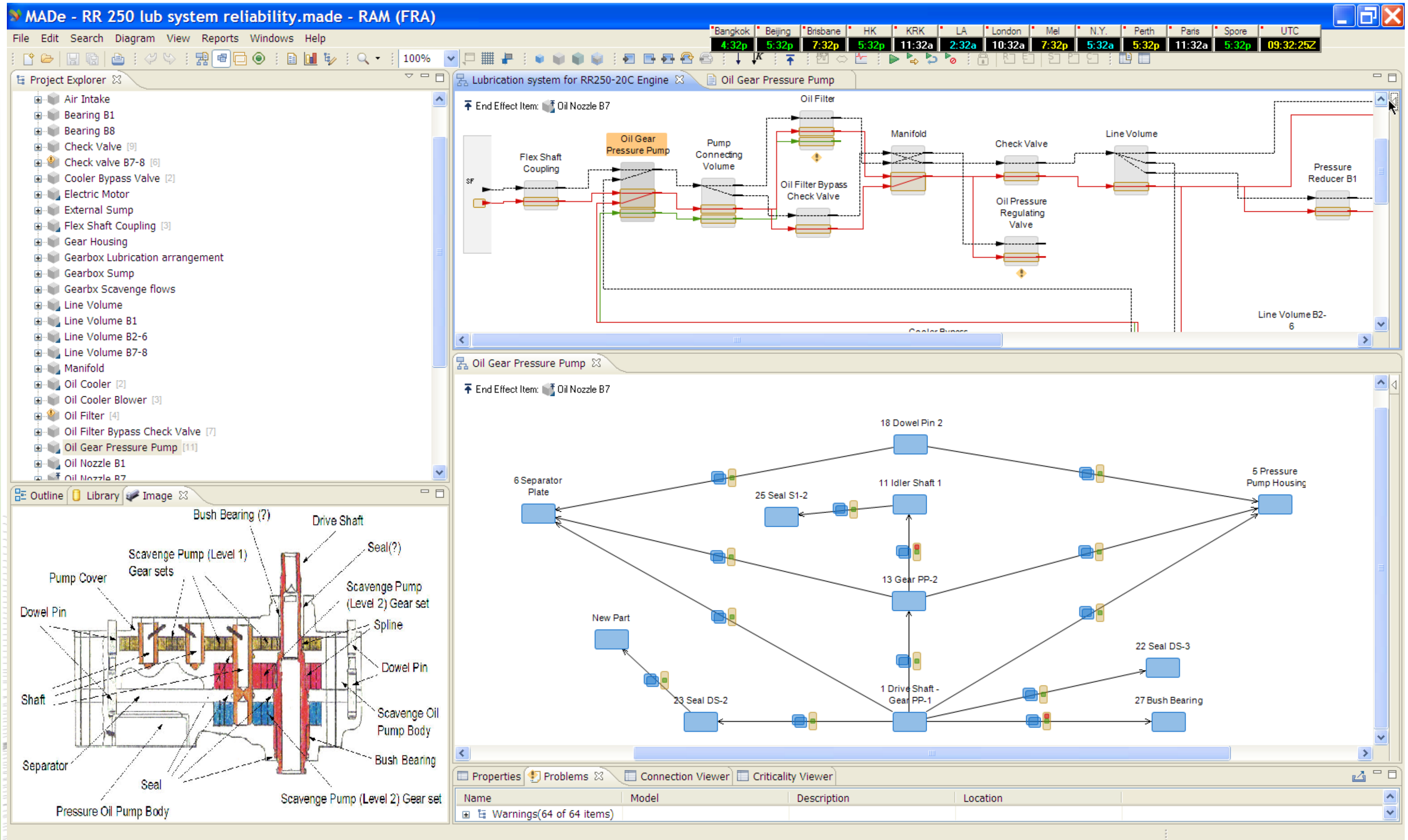
Define Component Structure



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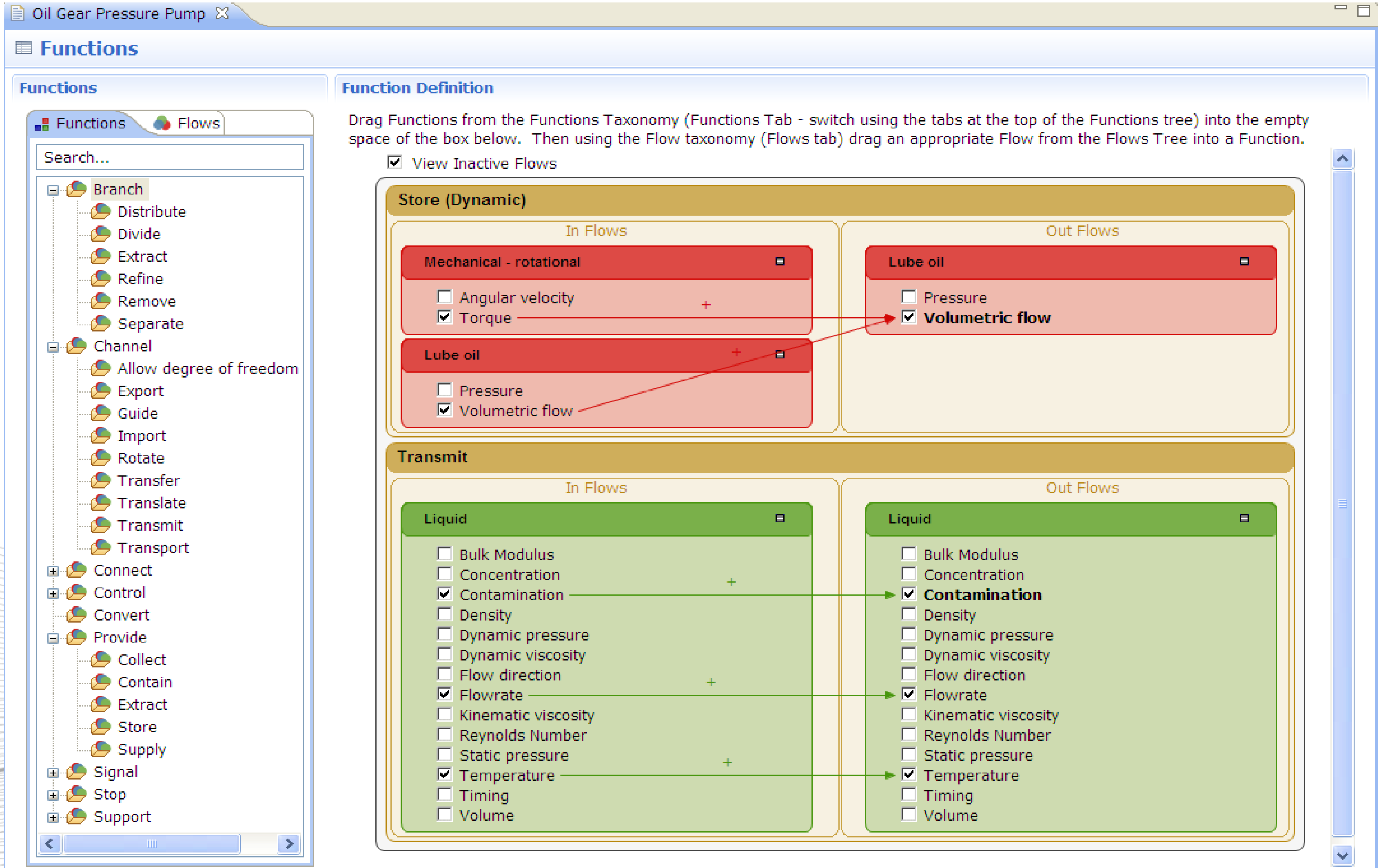
Define Component Functions



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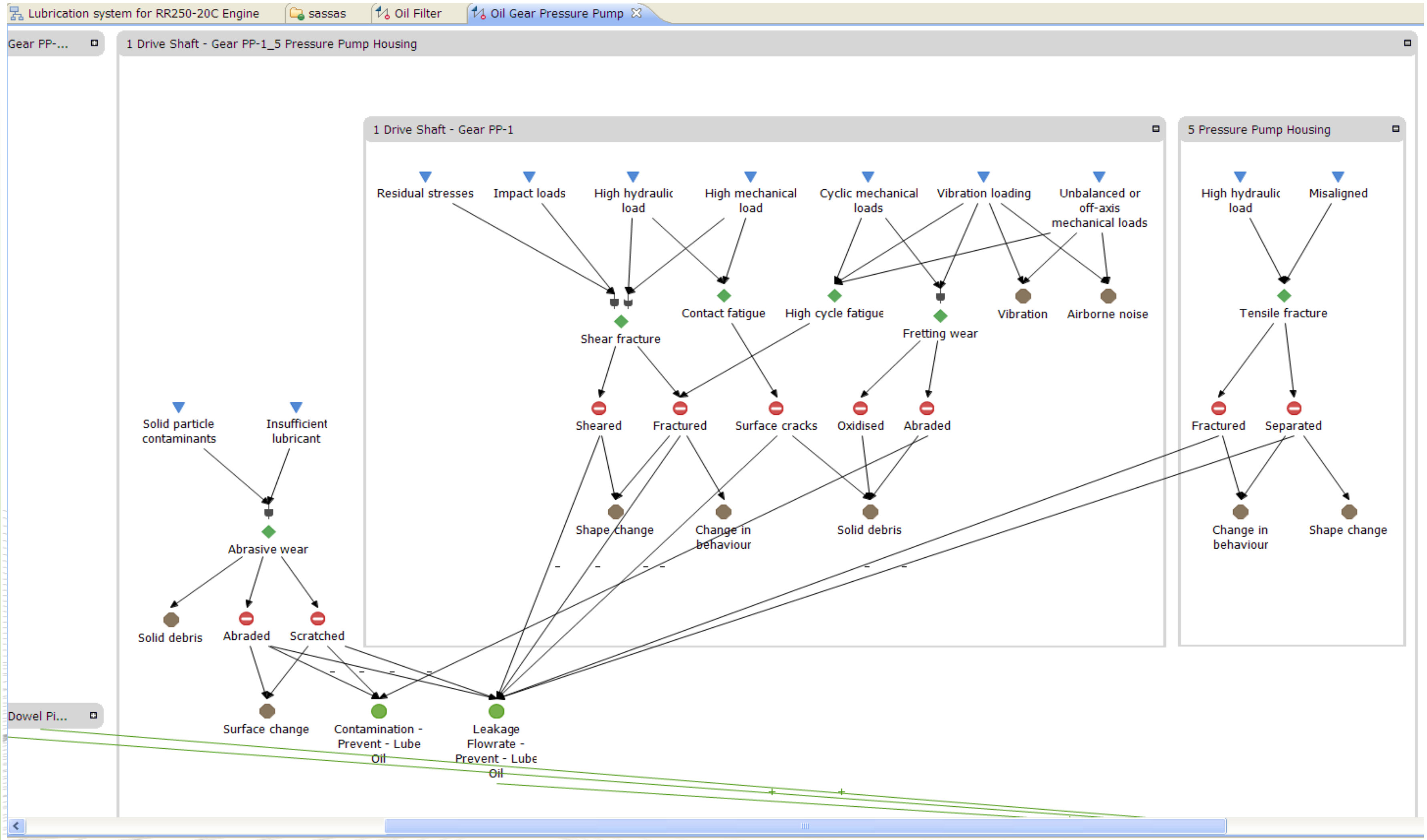
Define Physical Failures



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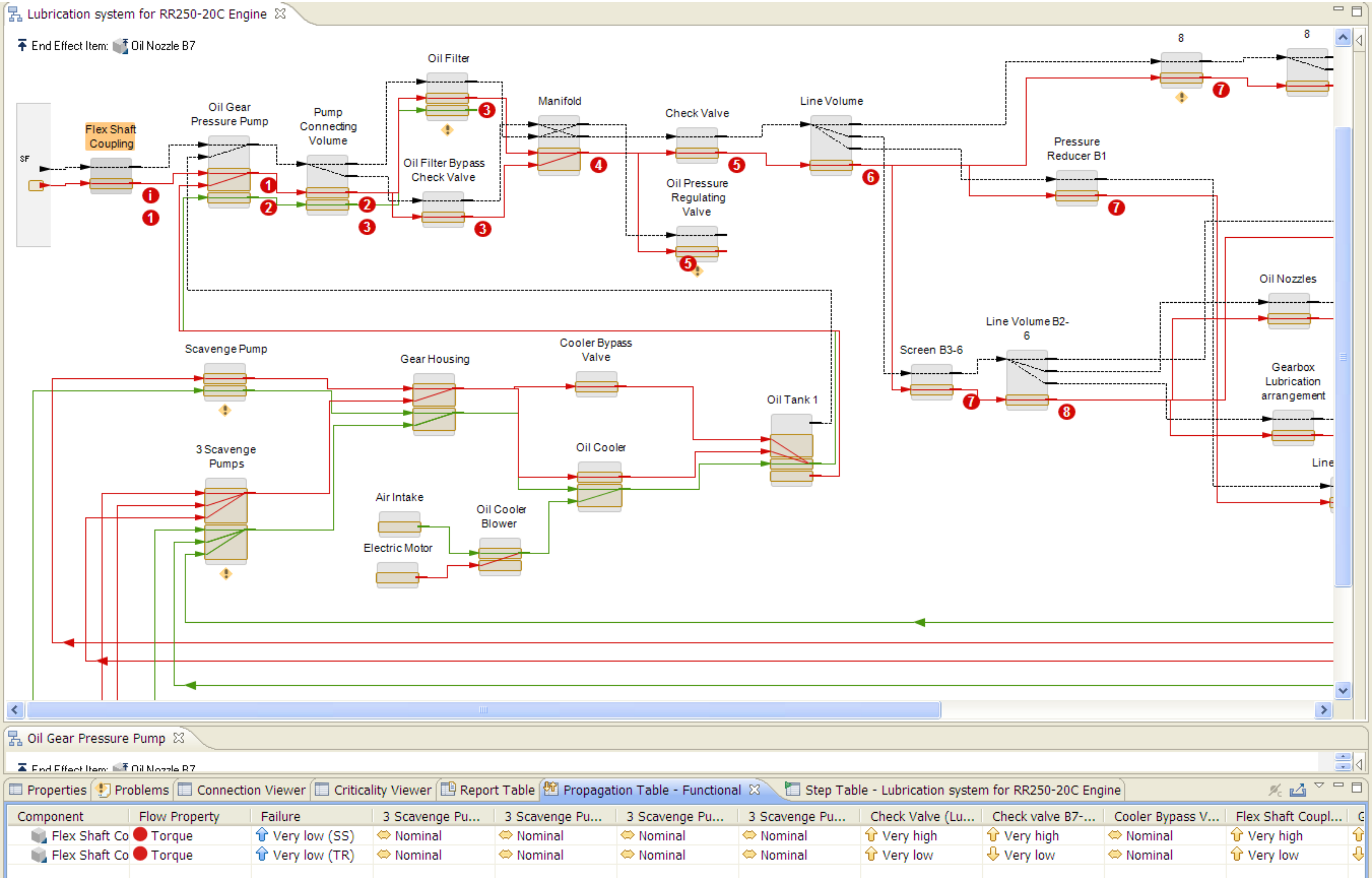
Propagate Functional Failures >> Dependency



Component	Flow Property	Failure	3 Scavenge Pu...	3 Scavenge Pu...	3 Scavenge Pu...	3 Scavenge Pu...	Check Valve (Lu...	Check valve B7-...	Cooler Bypass V...	Flex Shaft Coupl...
Flex Shaft Co	Torque	Very low (SS)	Nominal	Nominal	Nominal	Nominal	Very high	Very high	Nominal	Very high
Flex Shaft Co	Torque	Very low (TR)	Nominal	Nominal	Nominal	Nominal	Very low	Very low	Nominal	Very low

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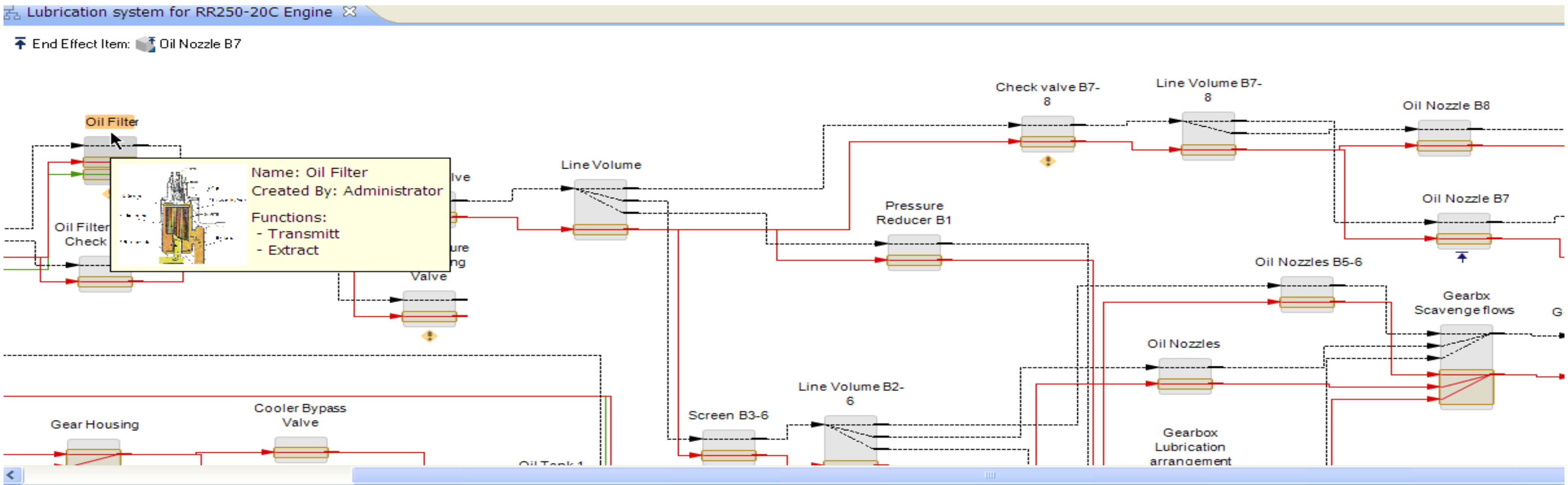
Assess Criticality



Step Table - Lubrication system for RR250-20C Engine | Criticality Viewer - Oil Filter

Type	Function	Flow	Flow Property	Mode	Detectability	Occurrence	Severity	Trivalent	Failure Mod...	End Effect Pr...	System Failure
Effect	Transmit	Hydraulic	Volumetric flow	Very high	10.0	10.0	10.0	N/A	0.01	0.01	Yes
Effect	Transmit	Hydraulic	Volumetric flow	High	10.0	10.0	10.0	1	0.01	0.01	Yes
Effect	Transmit	Hydraulic	Volumetric flow	Low	10.0	10.0	10.0	-1	0.01	0.01	Yes
Effect	Transmit	Hydraulic	Volumetric flow	Very low	10.0	10.0	10.0	N/A	0.01	0.01	Yes
Effect	Extract	Liquid	Contamination	Very high	10.0	10.0	10.0	N/A	0.01	0.01	Yes
Effect	Extract	Liquid	Contamination	High	10.0	10.0	10.0	1	0.01	0.01	Yes
Effect	Extract	Liquid	Flowrate	Very high	10.0	10.0	10.0	N/A	0.01	0.01	Yes
Effect	Extract	Liquid	Flowrate	High	10.0	10.0	10.0	1	0.01	0.01	Yes
Effect	Extract	Liquid	Flowrate	Low	10.0	10.0	10.0	-1	0.01	0.01	Yes
Effect	Extract	Liquid	Flowrate	Very low	10.0	10.0	10.0	N/A	0.01	0.01	Yes
Effect	Extract	Liquid	Temperature	Very high	10.0	10.0	10.0	N/A	0.01	0.01	Yes
Effect	Extract	Liquid	Temperature	High	10.0	10.0	10.0	1	0.01	0.01	Yes
Effect	Extract	Liquid	Temperature	Low	10.0	10.0	10.0	-1	0.01	0.01	Yes
Effect	Extract	Liquid	Temperature	Very low	10.0	10.0	10.0	N/A	0.01	0.01	Yes
Cause	Transmit	Lube oil	Pressure	Very high	10.0	10.0	10.0	1	0.01	0.01	
Cause	Transmit	Lube oil	Pressure	High	10.0	10.0	10.0	N/A	0.01	0.01	
Cause	Transmit	Lube oil	Pressure	Low	10.0	10.0	10.0	N/A	0.01	0.01	
Cause	Transmit	Lube oil	Pressure	Very low	10.0	10.0	10.0	-1	0.01	0.01	
Cause	Extract	Liquid	Contamination	Very high	10.0	10.0	10.0	N/A	0.01	0.01	
Cause	Extract	Liquid	Contamination	High	10.0	10.0	10.0	1	0.01	0.01	

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Produce FMEA/FMECA Report

Oil Gear Pressure Pump | Lubrication system for RR250-20C Engine Report

	Input Shaft		N/A	Vibration loading	High cycle fatigue	Fractured	Very low (Input Shaft_Coupling)	Low (Oil Nozzle B7)		10.0	10.0	2.3	230	

ITEM INDENTURE LEVEL: 1 Drive Shaft
NEXT INDENTURE LEVEL: Flex Shaft Coupling
SYSTEM NAME: Lubrication system for RR250-20C Engine
REFERENCE DRAWING:

LOADING TYPES: Torsion
LOAD CHARACTERISTIC: Constant load
LOADING TIME: Low - Less or equal to mission time.

Item ID	Item Name	Operation Mode	Function	Cause	Failure Mechanism	Effects			Detection Method	Criticality				Remarks
						Local	Next	End		O	S	D	RPN	
	1 Drive Shaft		N/A	Cyclic mechanical loads	High cycle fatigue	Fractured	Very low (Coupling_1 Drive Shaft)	Low (Oil Nozzle B7)		10.0	10.0	2.3	230	
	1 Drive Shaft		N/A	Vibration loading	High cycle fatigue	Fractured	Very low (Coupling_1 Drive Shaft)	Low (Oil Nozzle B7)		10.0	10.0	2.3	230	

ITEM INDENTURE LEVEL: Coupling
NEXT INDENTURE LEVEL: Flex Shaft Coupling
SYSTEM NAME: Lubrication system for RR250-20C Engine
REFERENCE DRAWING:

LOADING TYPES: None
LOAD CHARACTERISTIC: Constant load
LOADING TIME: High - Multiple missions.

Item ID	Item Name	Operation Mode	Function	Cause	Failure Mechanism	Effects			Detection Method	Criticality				Remarks
						Local	Next	End		O	S	D	RPN	
	Coupling		N/A	Vibration loading	High cycle fatigue	Fractured	Very low (Input Shaft_Coupling)	Low (Oil Nozzle B7)		1.0	10.0	2.3	23	
	Coupling		N/A	Cyclic mechanical loads	High cycle fatigue	Fractured	Very low (Input Shaft_Coupling)	Low (Oil Nozzle B7)		5.0	10.0	2.3	115	
	Coupling		N/A	Random or transient mechanical loads	Compression fracture	Fractured	Very low (Input Shaft_Coupling)	Low (Oil Nozzle B7)		7.5	10.0	2.3	173	
	Coupling		N/A	High mechanical load	Compression fracture	Fractured	Very low (Input Shaft_Coupling)	Low (Oil Nozzle B7)		10.0	10.0	2.3	230	
	Coupling		N/A	Vibration loading	High cycle fatigue	Fractured	Very low (Coupling_1 Drive Shaft)	Low (Oil Nozzle B7)		1.0	10.0	2.3	23	
	Coupling		N/A	Cyclic mechanical loads	High cycle fatigue	Fractured	Very low (Coupling_1 Drive Shaft)	Low (Oil Nozzle B7)		5.0	10.0	2.3	115	
	Coupling		N/A	Random or transient mechanical loads	Compression fracture	Fractured	Very low (Coupling_1 Drive Shaft)	Low (Oil Nozzle B7)		7.5	10.0	2.3	173	

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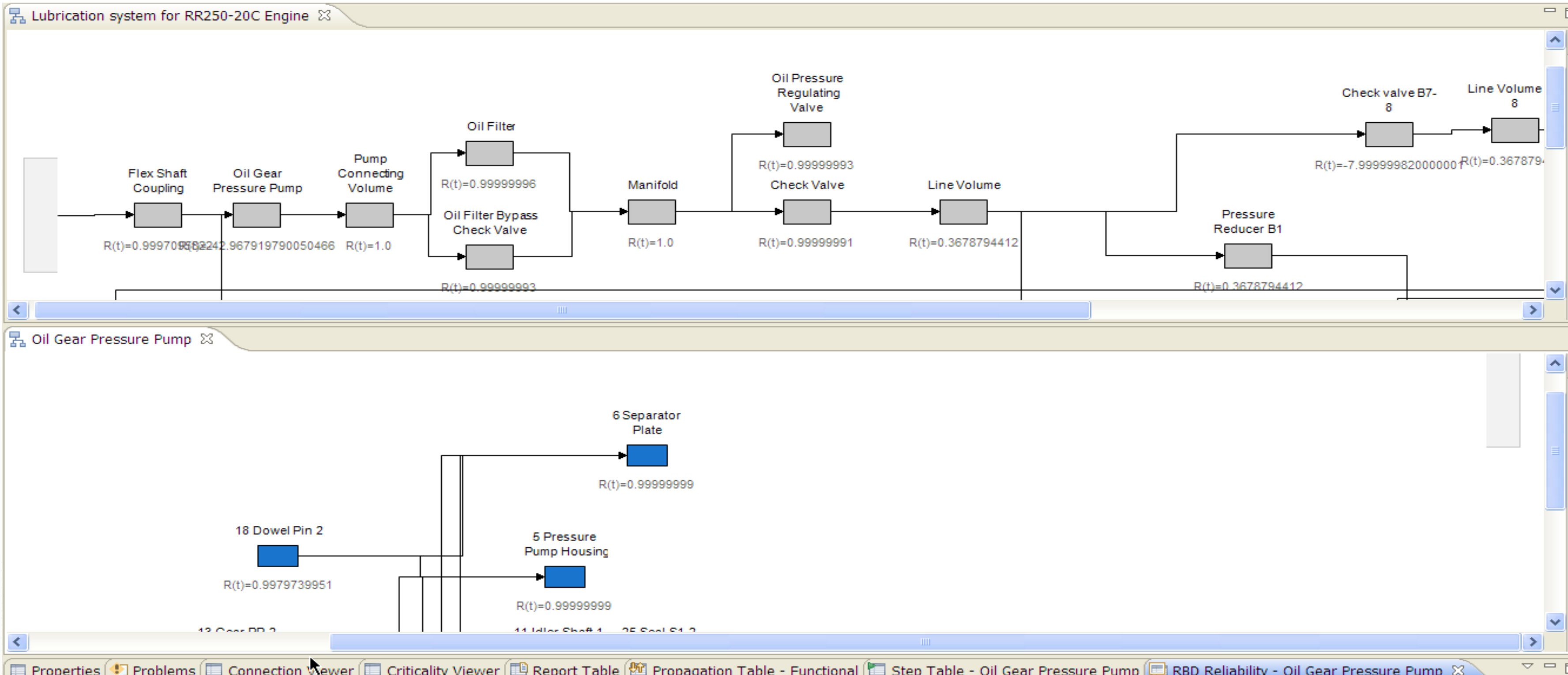
Assess hardware Reliability



Item	Reliability	Failure Distribution Type	Duration of operation	Failure Rate	Mean Failure Rate	Standard Deviation (Failure Rate)	Characteristic Life	Mean Characteristic Life
Oil Gear Pressure Pump	[Insufficient data]	Weibull	1.0				[Insufficient data]	0.0
11 Idler Shaft 1	0.99999999	Exponential	1.0	0.01	1.0	1.0		
18 Dowel Pin 2	0.9979739951	Exponential	1.0	2028.06	1.0	1.0		
5 Pressure Pump Hous	0.99999999	Exponential	1.0	0.01	1.0	1.0		
27 Bush Bearing	0.99999999	Exponential	1.0	0.01	1.0	1.0		
1 Drive Shaft - Gear PI	0.99999999	Exponential	1.0	0.01	1.0	1.0		
13 Gear PP-2	0.99999999	Exponential	1.0	0.01	1.0	1.0		
22 Seal DS-3	0.99999999	Exponential	1.0	0.01	1.0	1.0		
6 Separator Plate	0.99999999	Exponential	1.0	0.01	1.0	1.0		
23 Seal DS-2	0.99999999	Exponential	1.0	0.01	1.0	1.0		
25 Seal S1-2	0.9980170586	Exponential	1.0	1984.91	1.0	1.0		

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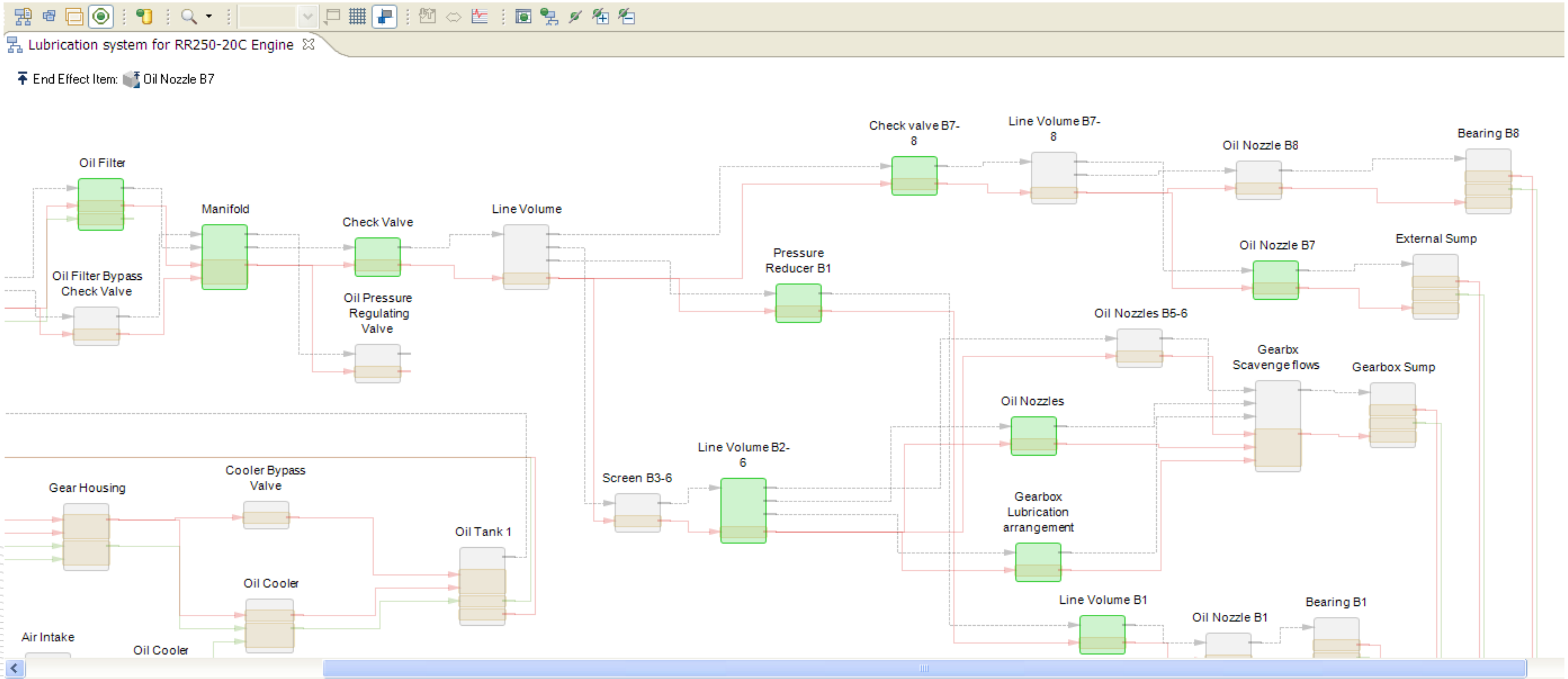
Define Sensors Locations



Ambiguity Groups | Sensor Sets - Lubrication system for RR250-20C Engine

Name	Location	Type	# of Sensors	Coverage	Possible Cov...	Cost	Weight (kg)	Description	Coverage Focuses	Analysis Focuses
sasasas	*Lubrication system for RR25...*	*Dynamic*	*15*	*100%*	*100%*	*$0.00*	*0.00*			
asasa	*Lubrication system for RR25...*	*Dynamic*	*12*	*91%*	*100%*	*$0.00*	*0.00*			
Dynamic Sensor Set	Lubrication system for RR25...	Dynamic	13	100%	100%	$0.00	0.00			
Dynamic Sensor Set	Lubrication system for RR25...	Dynamic	13	100%	100%	$0.00	0.00			
Dynamic Sensor Set	Lubrication system for RR25...	Dynamic	13	100%	100%	$0.00	0.00			
Dynamic Sensor Set	Lubrication system for RR25...	Dynamic	13	100%	100%	$0.00	0.00			
Dynamic Sensor Set	Lubrication system for RR25...	Dynamic	13	100%	100%	$0.00	0.00			
Dynamic Sensor Set	Lubrication system for RR25...	Dynamic	13	100%	100%	$0.00	0.00			

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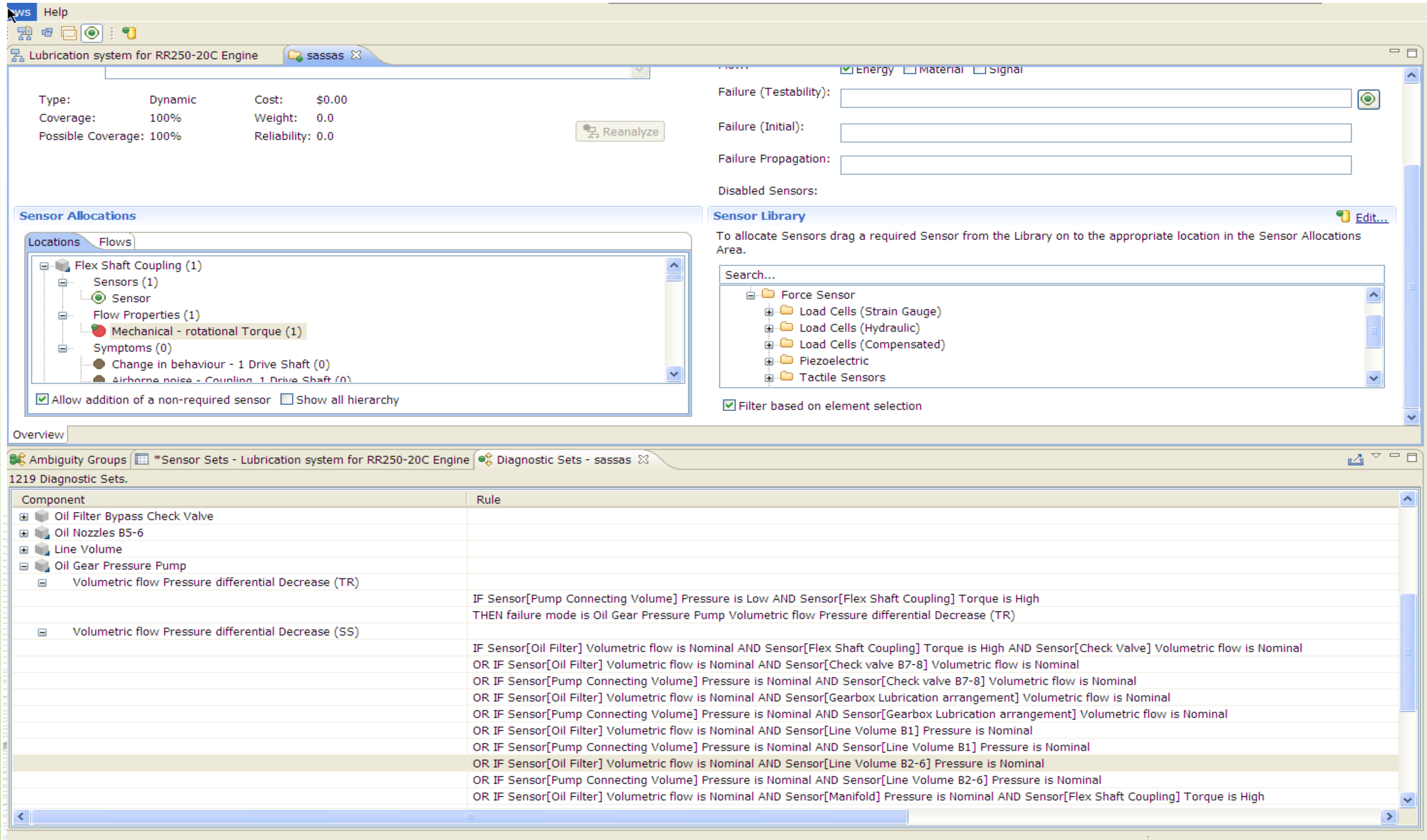
Select sensors and generate diagnostic rules



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PHM Design Cycle Deliverables

At the end of the risk assessment process, the user has knowledge of:

- → How the system can fail (failure modes)
- → How critical each failure is
- → What are the causes of functional failures
- → What are the interactions between functional failures
- → What physical failures are linked to functional failure
- → Where to place sensors – i.e sensor fusing
- → How to monitor physical failures
- → How to diagnose functional failure
- → What is the expected reliability of the sensing system
- → What is the expected functional and hardware reliability of the system

Concluding Remarks

Despite expectations the acceptance and effectiveness CBM is in question.
To be effective:

- CBM/PHM programs must be designed and executed with the knowledge of the risks to which a system is exposed, i.e. the knowledge of how the system fails
- Model-based failure analysis, defining failures dependencies and improving the completeness of risk identifications, should be adopted in preference to checklists and “spreadsheet” based FMECA methodology or tools
- Model-based failure analysis should be adopted to enhance knowledge retention, knowledge transfer and to facilitate integration of risk assessment through supply chains
- Standardised taxonomies of functions, failure concepts and components should be adopted to improve readability/portability of risk assessment results
- Diagnostic rules and Sensors sets should be selected on the basis of the identified dependencies between failure modes (symptoms >> syndrome)
- Clear hierarchy of failure concepts should be enforced in the risk assessment process (cause > failure mechanism > fault > failure mode)
- Physical failures (cause/failure mechanism/fault) and their symptoms should form the basis for BIT design

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