Development of an ontology supporting failure analysis of surface safety valves used in Oil & Gas applications

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Abstract

Purpose – The purpose of this paper is to provide a platform for development of an ontology supporting failure analysis of surface safety valves (SSVs) which will enable the technical dialogue between oil & gas operators, engineering companies and original equipment manufacturers (OEMs) when dealing with component failures.

Design/Methodology/Approach – The paper describes the use of a functional modelling based ontology in support of root cause analysis (RCA) which combined with the use of a defined definition for failure concepts and a complete database of these concepts relevant to surface safety valves can be applied to characterize degradation at the design stage. An examination of this new methodology was performed through the creation of a case study applying this new method on a hydraulically actuated surface safety valve.

Findings – The paper identifies a continuing problem with failure analysis; not just from a technical dimension, but it also encompasses elements related to organisational behaviour and culture and the stakeholders involved in dealing with failure of equipment in service. In today's digital operations and maintenance activities, addressing the challenge of failure analysis from only one dimension has proven to be unfeasible with significant downtime still occurring in many operations.

Originality/value – The overall value is a detailed picture of ontology capable of enabling the technical dialogue between operators, engineering companies and OEMs

Keywords Surface safety valves, Maintenance, Faults, Functional failures, Causes, Mechanisms, Symptoms, Through-life engineering services, Maintenance Effectiveness Reviews.

Paper type Research paper

Introduction

The oil and gas industry relies on a lot of different equipment when operating a well. One of the most vital components in these systems is the surface safety valve. This is a hydraulically or pneumatically actuated single acting swab-gate valve with the function to isolate the wellhead from further production equipment down the line. Surface safety valves are found in so called Xmas trees, which are situated on top of the wellhead and serve to route the flow of oil or gas to the different production systems (example shown in Figure 1). Surface safety valves function by monitoring the pressure in the main pipeline and triggering an automatic shutting of the valve mechanism in case of pressure readings which are outside of allowed norms. (EXPRO International Group , 2019)

Figure 1: A surface safety valve (red) on an Xmas tree

Typically, surface safety valves lasts for a long period, with life cycles up to 20 years (FMC Technologies, 2007) . Despite this, unanticipated breakdown of critical systems still occurs regularly. The reasons as to why are unclear however. Whilst some data is available on failure rates of valves, oil and gas operators are unwilling to share their information on causes of these failures due to the influence these databases could have on the stock prices of the company, or do not possess any database on this topic at all. From the little data that has been released to the public domain, such as OREDA – offshore and onshore reliability data, it has been found in previous research that valves contribute up to 52% of failures in Xmas tress (Stendebakken, 2014).

Current maintenance practises are fairly basic, with most components working on a run-to-failure principle with periodic visual inspections to determine if any leakages have occurred or if damage is visible, combined with quarterly valve shutting tests which are applied to determine whether the valve is still above the limit of safe operation. (David, 2014). Practices such as do not take into account why the valve no longer complies with the minimum requirements for safe operation, nor is this ever inspected.

Another problem the industry faces is the lack of commonly used, standardized set of taxonomy. Certain terms and concepts such as cause, mechanism, fault and symptoms are not universally defined with different standards being set (ISO-14224, ISO-20815, IEC-60812, etc.). Because of this, there is another barrier between oil and gas operators and OEMs in determining the true cause for failure in surface safety valves and characterizing the degradation that causes these failures.

All these factors contribute to an industry where there is a lot of room for improvement of maintenance practices, and a great opportunity to reduce total maintenance costs (Shaipov, 2018). Because of the high risk and crucial nature of surface safety valves, preventive maintenance actions are strongly recommended for implementation (Hooiveld, 2018).

With the goal in mind of lessening the issues described above plaguing the oil and gas industry the research that resulted in this paper was started with a number of objectives:

(I) To work towards the development of an ontology for failure analysis of surface safety valves which will enable the technical dialogue between oil and gas operators, engineering companies and original equipment manufacturers when dealing with component failures.

(II) To propose a proven methodology which, using the developed ontology, would improve the ability of oil and gas original equipment manufacturers in better identifying and characterizing degradation of surface safety valves at the design stage.

This paper proposes a methodology implementing failure mode, effect and criticality analysis (FMECA) with the use of functional modelling techniques and a common database of failure concepts, categorized in the four definitions of cause, mechanism, fault and symptom. Whilst FMECA is already a well-accepted method of risk assessment in many industries as well as oil and gas, the application of functional modelling to characterize these systems and their degradation at the design stage brings a unique opportunity to improve designs and implement better and more efficient preventive maintenance measures (Hawkins P. , 1998) with these techniques having been successfully implemented in the aerospace industry (Stecki, 2009) This paper concludes with a case study demonstrating the implementation of the proposed methodology with the aim of proving the ability for this methodology to produce FMECAs and the advantages that a model based approach gives, such as a high level of consistency and detail, and the ability to characterize and predict degradation without the need for a physical testing setup.

Findings: Surface safety valves (SSVs) are critical components of oil and gas wellheads that currently make use of fairly basic maintenance planning and reliability assessment which can result is a lot of unnecessary costs for oil and gas operators due to longer downtime and unexpected failures.

Background

The demand for Xmas trees is directly proportional to the demand for fossil fuels. In other words, the more wells are drilled, the more Xmas trees are required. During periods when oil suffers a significant price increase, fewer wells are drilled. This however, does not seriously affect Xmas trees manufacturers because they typically have significant backlogs of orders and limited production capacities.

The leaders of the surface equipment market are Cameroon, FMC and BHGE. These companies control more than 60% of the manufacturing of surface equipment. FMC has been the leader in the Middle East for many years, Cameroon has been working a lot in United Arab Emirates (UAE), and BHGE has been taking a significant lead in Qatar.

Companies like Cameroon have large distribution centres that enable them to react quickly when its customers need a critical spare. They also provide 365 days per year support. Whereas other companies do not have such stock and they manufacture the parts needed when they receive an order. Because of this, the lead time for a hydraulic valve can be as high as six months.

In a study done by The IHS Global Inc (IHS) in five onshore regions in the U.S, the total capital costs of onshore oil wells is calculated by using the values of the drilling and the installation, the land acquisition and the costs of the processing and the transportation. The total expenditure by adding all the factors is between $4.9 million and $8.3 million. This amount includes the completion costs that generally has a price from $2.9 million to $5.6 million per well.

The graphic in Figure 2 below shows the five essential cost for drilling and completing a typical onshore well in the U.S.

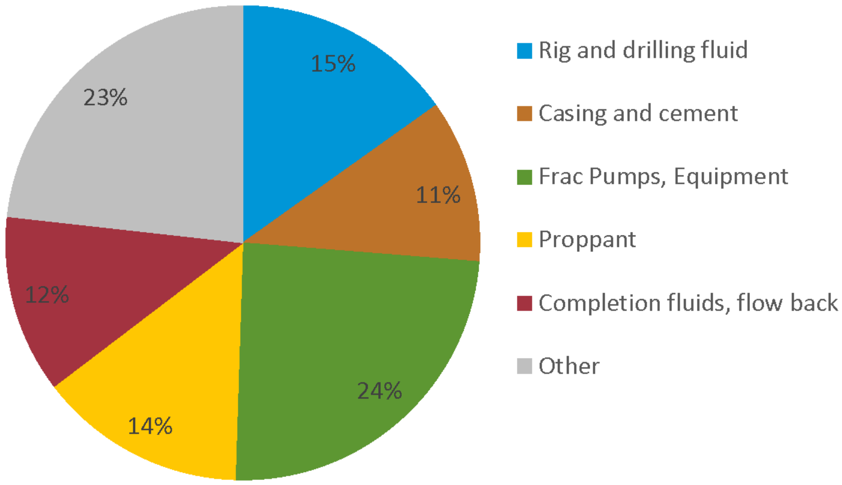

Figure 2: Pie chart of costs for operating a typical well in the US (Hartley, 2005).

If focus is put on the cost of the equipment which represents 24% of the total costs. it can be assumed that a standard configuration Xmas tree costs more or less $100k. This price can increase significantly by the non-standard size of the machine, the material and the size of the order. With bigger orders, it is possible to obtain better prices and shorter lead times because the order will be prioritised.

Findings: The oil and gas industry is a sector with high costs associated to all aspects of its business. This relates to the reluctance to divulge information as described in the introduction, with oil and gas stakeholders being reluctant to share information due to possibility of affecting share prices. These high costs also relate to the reluctance to perform tests on actual equipment, due to the high manufacturing costs.

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Definition of failure concepts

Failure concepts are situations, occurrences or phenomena that define the ways in which a system might experience potential failure. When investigating the standards used in the oil and gas industry, there appears to be a scattered and differentiating nature in the taxonomy used, with different definitions for the same concept, these concepts are catalogued below in Table 1 through the use of four categories: Causes, Mechanisms, Faults and Symptoms (CMFS). These categories were employed in the process to define clear terminology that could have a positive effect on the conversation between oil & gas operators and OEMs by having clear definitions that allow for a better understanding between companies.

An extensive literature review was performed where a number of industry standards, such as ISO – 14224 and other research papers were catalogued in these categories of CMFS to have a better understanding of the meaning of each concept and their use in this paper.

Table 1: Failure Concept definitions

Term	Definition	Source
Cause	The fundamental reason for a failure mode, which may see the physical degradation or process leading to a failure mode. A cause can relate to design, manufacture, environmental, operational or maintenance actions or an input flow that exceeds specified limits.	S.D. Rudov-Clark and J.Stecki. 2009
	Circumstances during design, manufacture or use which have led to a failure	ISO – 14224
	Failure Cause. Failure causes are the reasons "why" a failure event occurred. Failure causes may be quite obscure and not immediately apparent, and may require significant investigation, or root cause analysis for the underlying reasons to be revealed.	Allen S. B. Tam and Ian Gordon. 2009
	Set of circumstances that leads to a failure	ISO-20815
Mechanism	The chemical, electrical, mechanical or software processes which cause physical degradation of a system element and results in a fault.	S.D. Rudov-Clark and J.Stecki. 2009
	The failure mechanism is the physical, chemical or other process or combination of processes that leads to the failure. It is an attribute of the failure event that can be deduced technically, e.g. the apparent, observed cause of the failure.	ISO – 14224
	Failure Mechanism. This term describes "how" the equipment failed – and specifically refers to the physical, chemical or other process or mechanism that produced the failure event.	Allen S. B. Tam and Ian Gordon. 2009

	An attribute of the failure event that can be easily deduced technically. The failure mechanism is the apparent, immediate cause of the failure and is related to the lowest level in the hierarchy where it can be identified.	OREDA – Offshore & Onshore Reliability Data Volume I. 2015
Fault	Commonly used as a synonym for failure mode, however in MADe the term fault refers specifically to the physically degraded state of a system element (static) or a change in behaviour (dynamic) that which will result in a failure mode.	S.D. Rudov-Clark and J.Stecki. 2009
	State of an item characterized by inability to perform a required function, excluding such inability during preventive maintenance or other planned actions, or due to lack of external resources	ISO – 14224
	A state resulting from failure.	Rausand, M & Øien, K. 1996.
	Failure Effect. Failure effect is the immediate outcome that a failure event had upon the operation, function or status of the equipment. This failure effect is something that would be observable by a human operator, or detectable by instrumentation. This Information indicates that the equipment is not functioning as expected, or according to its specifications.	Allen S. B. Tam and Ian Gordon. 2009
	The termination or degradation of the ability of an item to perform its required functions, it includes: • Complete failure of the item • Failure of parts of the item that causes unavailability of the item for corrective action. • Failure discovered during inspection, testing or preventive maintenance that requires repair. Failure in safety devices or control/monitoring devices that necessitates shutdown or reduction of the item's capability below a specified limit.	OREDA – Offshore & Onshore Reliability Data Volume I. 2015
	State of an item characterized by the inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources.	IEC 60812
	inability of an item to perform as required, due to an internal state.	ISO-20815
Symptom	Failure symptoms are indicators or signs of a failure event. These indicators or signs may manifest before the event occurs, or after the event occurs.	Allen S. B. Tam and Ian Goron. 2009

	The response of a failed system element that can be used to detect a failure mode, or a loss generated by a failure process that can be used to detect a failure mode.	S.D. Rudov-Clark and J.Stecki. 2009

After reviewing these definitions, the concepts as defined by S.D. Rudov-Clark and J. Stecki. 2009, are selected for use. Mainly due to their use in the software package used during the case study that was performed for this paper, the fact that this standard defines all four of the failure concepts unlike most other sources and their clear, precice and relevant description of these concepts.

Findings: The taxonomy used in the oil & gas industry lacks standardization, which makes straight comparisons of datasets from different operators difficult. By taking these different definitions, compiling and comparing them, a platform is provided to allow for technical dialogue between operators and OEMs by allowing them to bridge the gap in different standards that are used by different companies.

A brief history of standards, recommended practices and guidelines addressing the technical risk, reliability and asset integrity

Preventive maintenance programs help to ensure that the well remains viable, which means that it continues producing viable quantities of oil past its expected lifetime. These systems with a lack of maintenance, may stop working or even worse, have catastrophic consequences due to a failure of the equipment.

To complete a certification of a wellhead and a Xmas tree, there are reliability assessment methods that the system need to pass:

In order to verify the design of a valve of 20-year life the OEMs do an endurance cycle test. This test for the standard valves requires pressure/temperature testing with a total of 200 cycles, and for the gate valves it test beyond the 300 cycles, arriving to a test of 500 cycles.

OEMs confirm that with proper maintenance, valves are designed to work 20 years under the most extreme conditions. (FMC Technologies, 2007)

The next inspection, which is for the well, serves to ensure that the installed equipment complies with the established safety and environmental standards. This survey includes:

- Part numbers and serial numbers, size, pressure rating, materials
- Condition of the well
- Configuration of Xmas tree and wellhead
- Well location
- Manufacturer
- Annulus pressure
- Seal isolation tests
- Pictures of the equipment
  (CAMERON, Schlumberger, 2019)

This field survey allows the operators to identify the critical maintenance items. By a visual inspection and well bore and annulus pressure and temperature readings operators know if the wellhead is affected by leaks, component deterioration, breakage or a missing part. This critical items are reported on a review with recommendations of how to proceed to repair them. The least problematic instances are when a component can be repaired without removing it. A skilled maintenance technician can quickly perform reparation of the annulus pressure or flushing a stuck gate, and obtain good results. Whereas, instances that require a replacement have problems in finding the same component, because some of them are obsolete and consequently are not available any more. In this situation, there are two options: find a pattern part manufacturer or reverse engineer the part from scratch.

At the end of the survey, OEMs will develop a well database with the information captured and a well schematic. Depending on the results obtained, OEMs will provide a maintenance plan to ensure a proper functioning of the system. A few examples of the typical variables that are recorded and monitored in each inspection are as follows:

- Functional testing of wellhead and tree gate valves (number of turns to open/close the valve)
- Pressure testing of tubing hanger and all casing hanger voids
- Pressure testing of the tree valves
- Actuator closure times and function testing (reaction time)

(Dale, Heskins, & Bolton, 2010)

An example of an inspection routine as described in this section is shown in Figure 3 and Figure 4. It is important to collect all the information into a report to maintain a record of these periodic readings. These data will allow the company to monitor the gradual deterioration of the parts or avoid an increase in a particular location of the pressure.

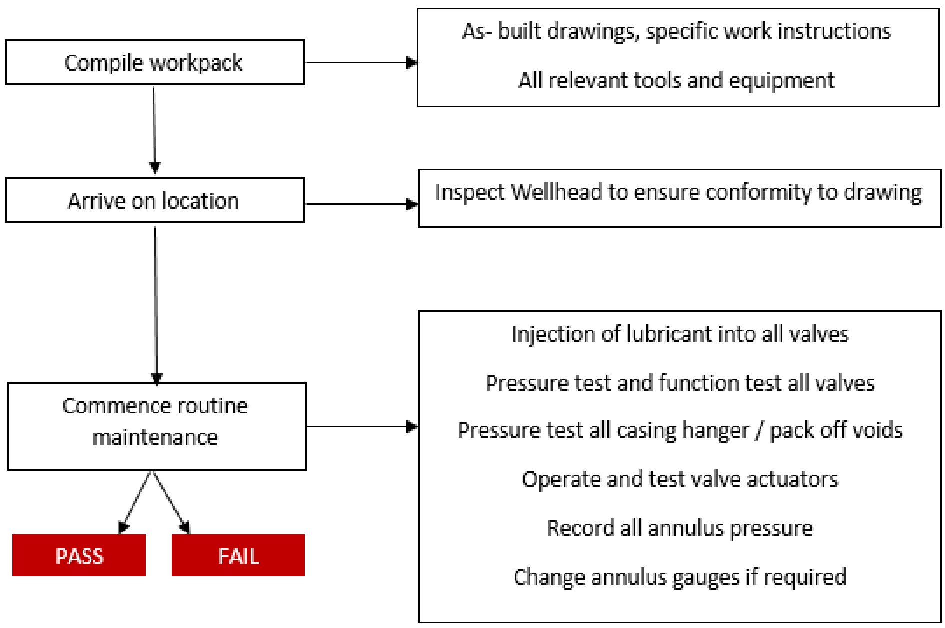


Figure 3: Flowchart for a routine maintenance inspection

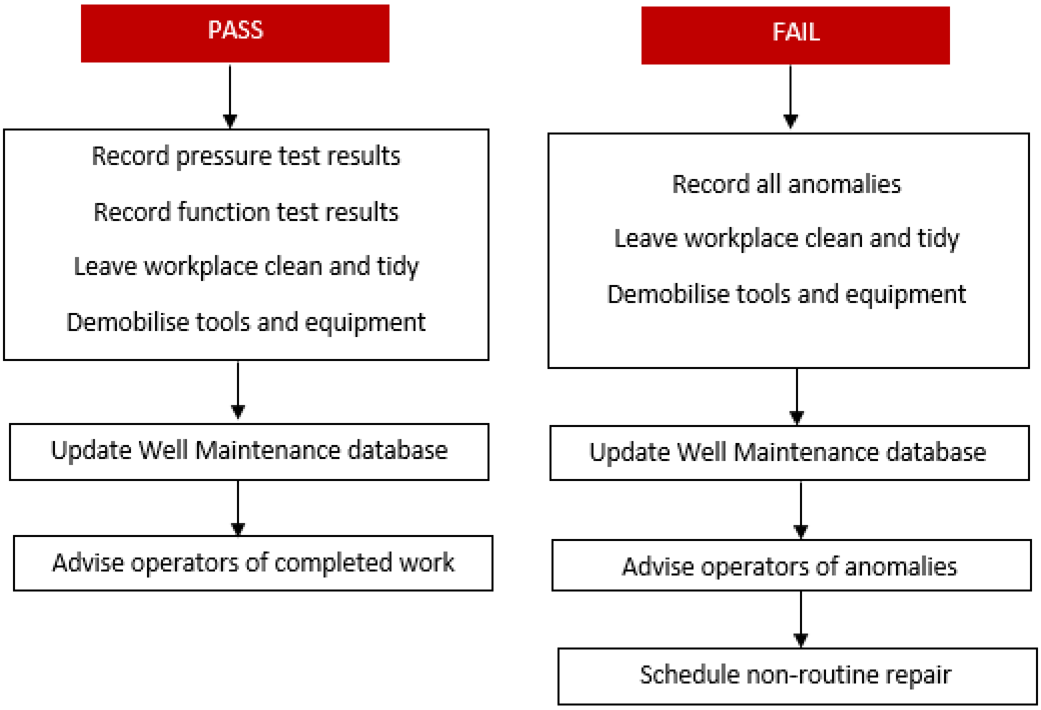


Figure 4: Flowchart of remedial actions to be taken depending on pass or fail of inspection (Dale, Heskins, & Bolton, 2010)

The next wellhead certification program is the Certification of Fitness for Service for Wellheads and Xmas Trees Under Flowing Conditions. This evaluates the condition of the wellhead and the Xmas tree and inspects if there are any external leaks. The inspection is done without disrupting the regular operation. All the data like the part numbers, the annulus pressure or the configuration of the wellhead and the Xmas tree is recorded in a file to provide traceability. If the evaluation of the system does not indicate pressure release or mechanical damage, the company delivers a certificate of conformance that contains the condition of the wellhead and the Xmas tree, and that certifies the "Fitness for Service, No Pressure Release to Atmosphere". This certification includes the annulus pressure recording, the greasing of the annulus valves and an evaluation of the system with a picture, the service life of the equipment, the established age and the components.

(CAMERON, Schlumberger, 2019)

The last certification can only be done after the well is secured and shut in. Its name is Certification of Wellhead and Xmas Tree Integrity Under Shut-In Conditions. It tests the integrity of the tubing hanger seals and includes:

- A wellhead inspection
- Full greasing of all valves
- Check the pressure integrity on all voids
- Test of wellhead seals
- Rectification of pressure integrity and mechanical issues

(CAMERON, Schlumberger, 2019)

There are a lot of possible failures in a Xmas tree, If any component of the Xmas tree has an unexpected failure, the performance will decrease, or even worse, the production could come to a halt. Other problems associated with a fault would be that the repair time of a component is between 80 and 100 hours((Faichnie, 2019) . If this part cannot be repaired, the new component lead time is six months. Finally, the last factor is the high cost that the company need to pay for a replacement part. (Faichnie, 2019)

Findings: Current maintenance practices and standards are numerous and can be quite extensive. Whilst these methods might detect an obvious failure as it is about to occur, or after it has occurred, they fall short when it comes to preventive maintenance. Failures are only recorded and tracked when the component needs repair, nor is the cause determined. As such, a lot of room for improvement is available to take more preventative measures by characterizing the degradation of components and implementing more efficient downtime and maintenance times.

Proposed methodology for analysing technical risk, reliability and asset integrity

This paper proposes a functional modelling methodology that allows for characterization of degradation at the design stage. Through this, better preventive maintenance measures can be taken and degradation anticipated to reduce issues such as lead time and allow for implementation of countermeasures such as Condition and Performance Monitoring (CPM) measures. These measure will allow the company to increase the production and anticipate possible failures that will help them to avoid unexpected operational problems. This method already has a current popular application in the aerospace industry (Scheuren, Caldwell, Goodman, & Wegman, 1998) and has the potential to improve the oil & gas industry as well.

Functional level modelling is a methodology where each component of a system or subsystem is described purely in terms of the function(s) that it performs to ensure the operation of the system. Such a methodology is key in the design stage to clearly define the architecture used in the system that is being modelled and is an asset in further steps of the design process, such as concepting, designing or selecting components and requirements of the system. The definitions of these basic functions may vary between designers, for this reason, catalogues and definitions such as those by Stone and Wood (Stone & Wood, Development of a Functional Basis for Design, 2000) are used that employ a functional decomposition, generalizing them to a set of terms that can apply to any system on a functional level, regardless of context. An example set of definitions, as given in (Stone & Wood, Development of a Functional Basis for Design, 2000) is given in Figure 5.

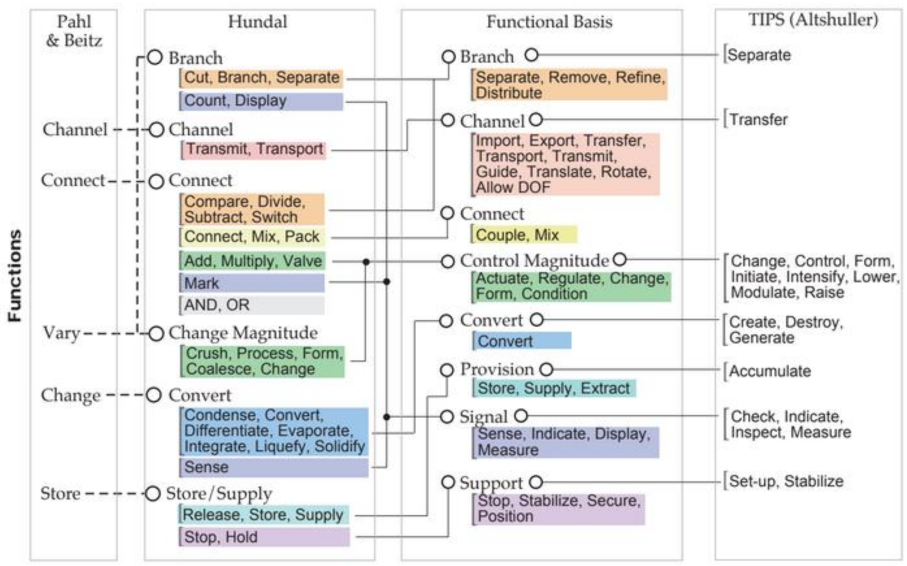


Figure 5: Functions definitions for functional modelling (Stone & Wood, Development of a Functional Basis for Design, 2000)

To create a complete functional model, defining the input and output relations between components is also necessary, this is done through the use of flows. These represent the dynamic interaction between components, but have been described as a representation of bonds between components as well (Stone & Wood, Development of a Functional Basis for Design, 2000). In their most raw form, flows represent the transfer of energy, matter or information between components, as well as the transformation or other changes a flow experiences when interacting with a component, e.g. An electric motor converts the flow from electrical energy into mechanical energy. These flows can have both a positive and negative effect on the output flows. An example of flow definitions is given in Figure 6 and an example of a functional flow diagram is shown in Figure 7.

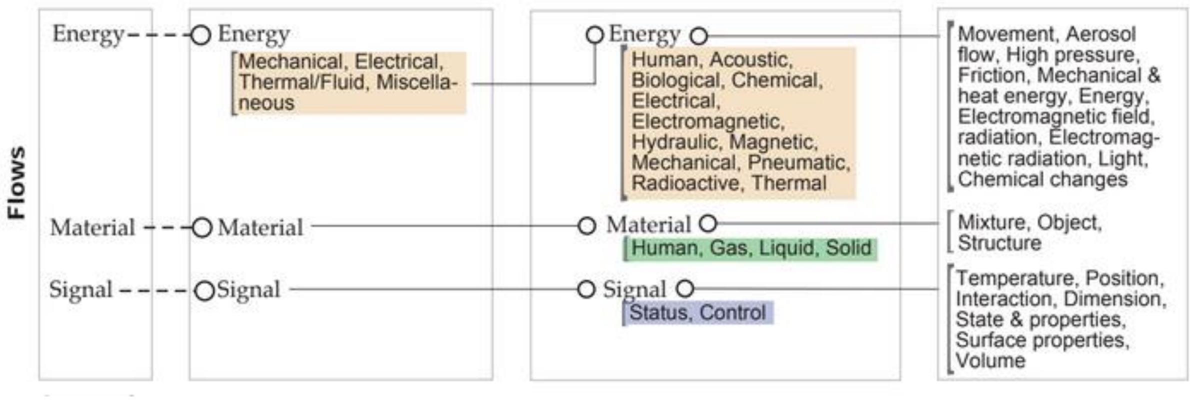


Figure 6: Flow definitions for functional modelling (Stone & Wood, Development of a Functional Basis for Design, 2000)

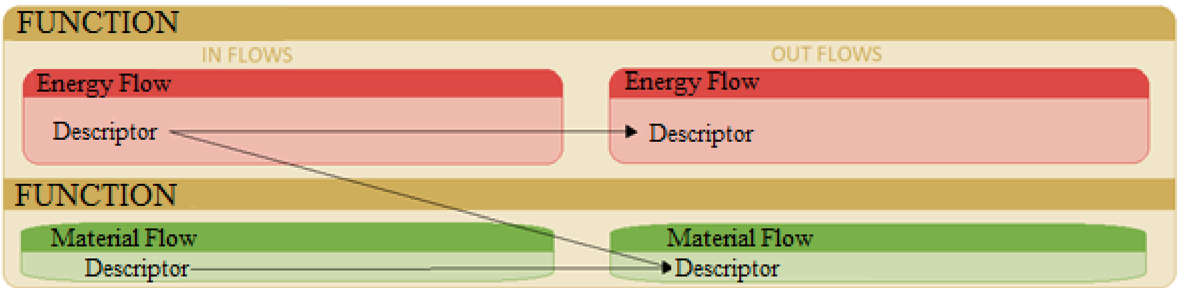


Figure 7: Functions and flows used together to define a component

Using the methodologies of functions and flows to break down a system to its most basic level gives engineers the opportunity to clarify the capabilities and limits of the system at the design stage through the use of a Functional Block Diagram. An example of such a functional block diagram is given in Figure 8, With the use of function and flow definitions as used by Stone and Wood, this breakdown shows the functionality of a manual pump using the terms of the generalized catalogue shown in Figure 5 and Figure 6, and demonstrates how this methodology combined with proper terminology allows for a consistent level of detail in system modelling and functional description.

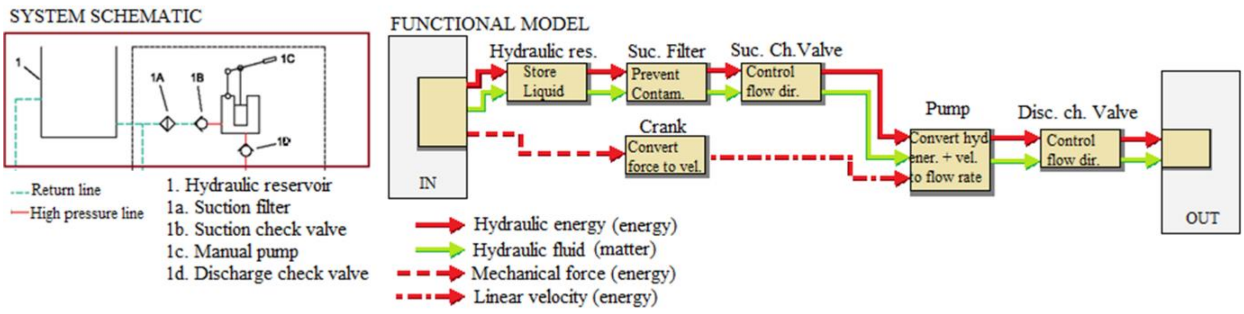


Figure 8: Example of a functional block diagram

A different approach to modelling components is through the use of part level modelling, where the component is not described only through the use of functions and flows, but also in terms of the parts that a component contains. These parts are defined by describing their characteristics in terms of the features it has (e.g. a hole, a thread, etc.), and the connections that this part has to other parts. These connections are further defined through the use of the same functional definitions shown in Figure 5 and Figure 6, with an example of part level modelling shown in Figure 9.The use of part level modelling comes into play when analysing the overall effect each part and their connections has on the component that it is in. An example of this is how failure of the connection between a rubber seal ring and the component it is connected to in a pipeline might cause leakage, which would hamper the function of the pipeline to transport its designated material.

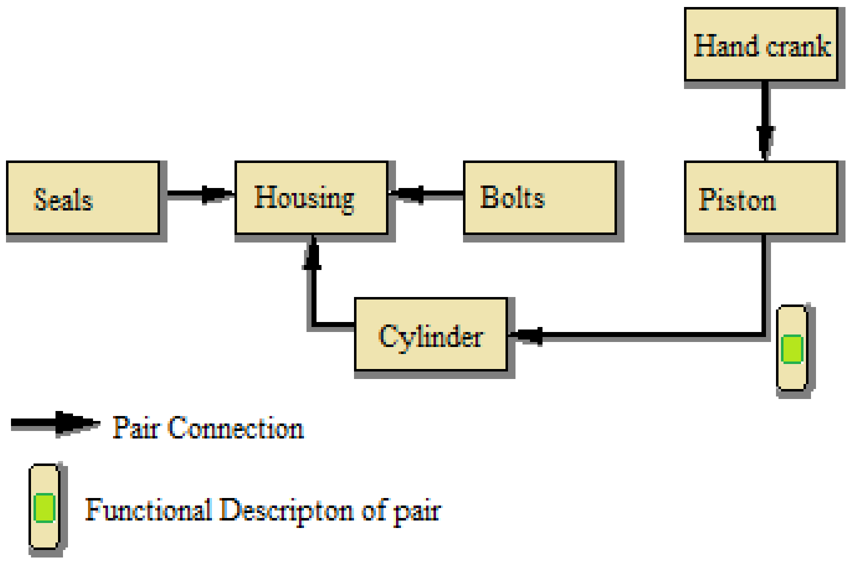


Figure 9: Part level modelling example

To create these part level models and ensure that the connections, features and functions are defined as accurately to the component being modelled, typically a part pair breakdown is created. This is breakdown very similar in function to the part level model itself, where each part is given features and connections. Showing how each part interacts with each other part in the system. This is usually summed up in a table. This method exists mainly as a preparatory step for creating a part level model, and to streamline the part level modelling process. An example of a part pair breakdown, as used in the case study in this paper, is shown in Appendix A.

The final aspect of the proposed methodology is the addition of Fault Tree Diagrams (FTD), which show the relation between Causes, Mechanisms, Faults and Symptoms (CMFS) as defined in Chapter II and the component that it is being applied to. In a functional model, each component has a separate FTD which shows these (CMFS) along with the probability that they will occur, as well as the progression rate it occurs at and how they might affect the component, or in the case of symptoms, show what is affecting the component. An example of a FTD is shown in Figure 10.

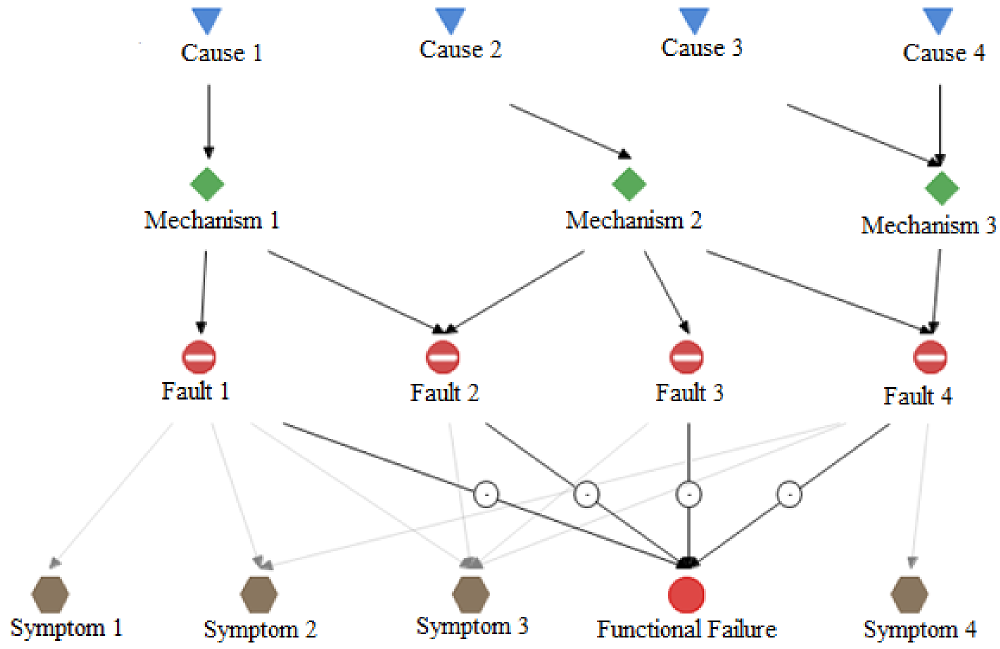


Figure 10: Fault Tree Diagram example

When implementing FTDs on a part level model, a slightly different approach is taken, where the diagram is broken up into different sub-trees for each part in a component. These sub-diagrams are related to the functional failure of connections between different part pairs, with variables such as probability defining the chance of failure occurrence. This is further subdivided to relate functional failure of part connections to the functional failure of the component as a whole. This difference means that a functional failure on the part pair connection level may not necessarily lead to a functional failure in the entire component. Through this method, the true use of part level modelling is shown, as it allows for the indication of the most critical and fragile parts in a component, which will need the most immediate measures taken. An example of a part level FTD is shown in Figure 11.

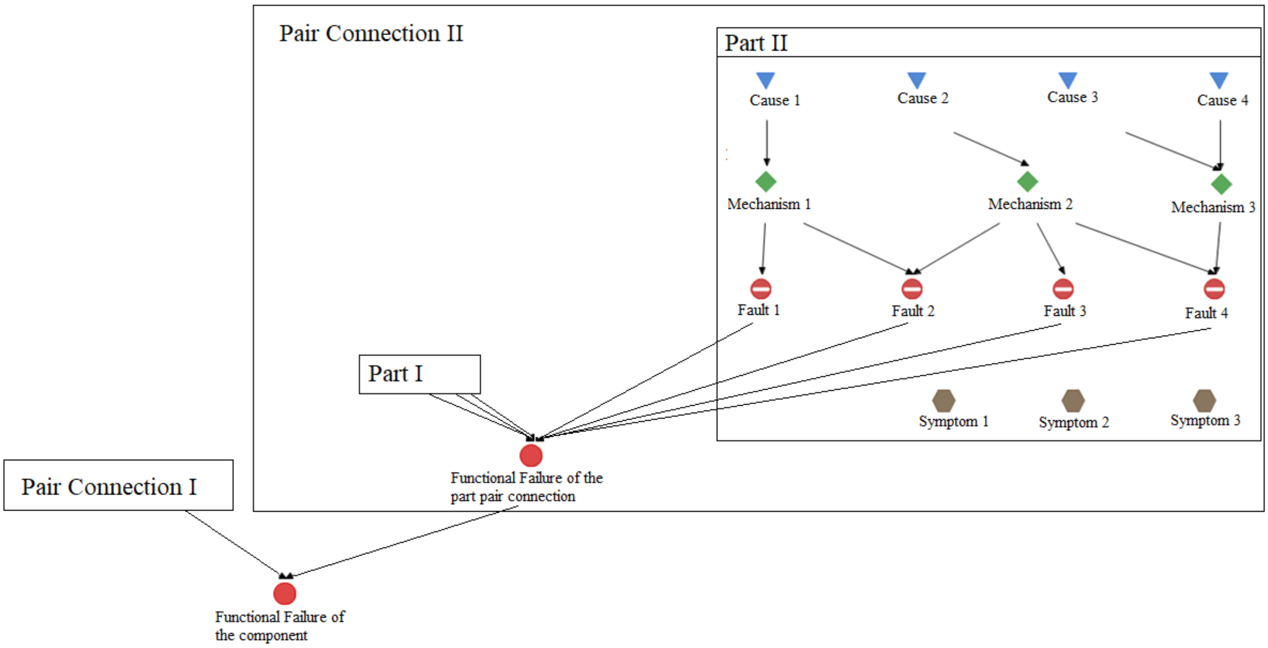


Figure 11: Fault Tree Diagram at the part level

Using FTDs in a functional model also allows, through the use of functional flows, to show how a failure in one component in the system will propagate throughout the system. Being able to predict how faults might propagate is one of the key components of fault isolation efficiency, and gives mechanics the ability to determine the cause of a failure much faster.

To analyse these CMFS, their effects and criticality on a system Root Cause Analysis is proposed as a following step when the functional modelling process is completed.

The tool that is used to do the root cause analysis is the Failure mode, effects, and critically analysis (FMECA). FMECA is a methodology to identify and analyse:

- All potential failure modes of the various components of the system
- The effects that these failures may have on the system
- How to avoid the failures or/and mitigate the impact of the failures

The steps to follow to create a FMECA report are determine the potential failure modes to consequently determine the effects and the causes of each failure. Then, with data obtained throughout use or by research, the Risk Priority number can be calculated. The RPN is a variable to evaluate the risks associated with the failure modes that a system contains. To determine the overall RPN for each issue we need to multiply:

- Severity of each failure
- Likelihood of occurrence for each failure
- Likelihood of detecting the problem before it arrives at the customer

Calculating the RPN is done by obtaining the three previous ratings is:

$$\boxed{\text{RPN= Severity x Occurrence x Detection.}}$$

In the RPN, each item is measured on a scale from 1 to 10. Consequently, the maximum value for the RPN is one thousand. Depending on the number obtained in the equation, it can be determined if the problem needs to be corrected or not. If the problem does not need a correction, the FMECA report is finalized. But if the problem needs a correction, the company needs to take appropriate corrective actions to mitigate the issue before writing the FMECA report. Examples of the processes that FMECA is typically used for, and that describe how these processes apply FMECA are shown in Figure 12and Figure 13 respectively.

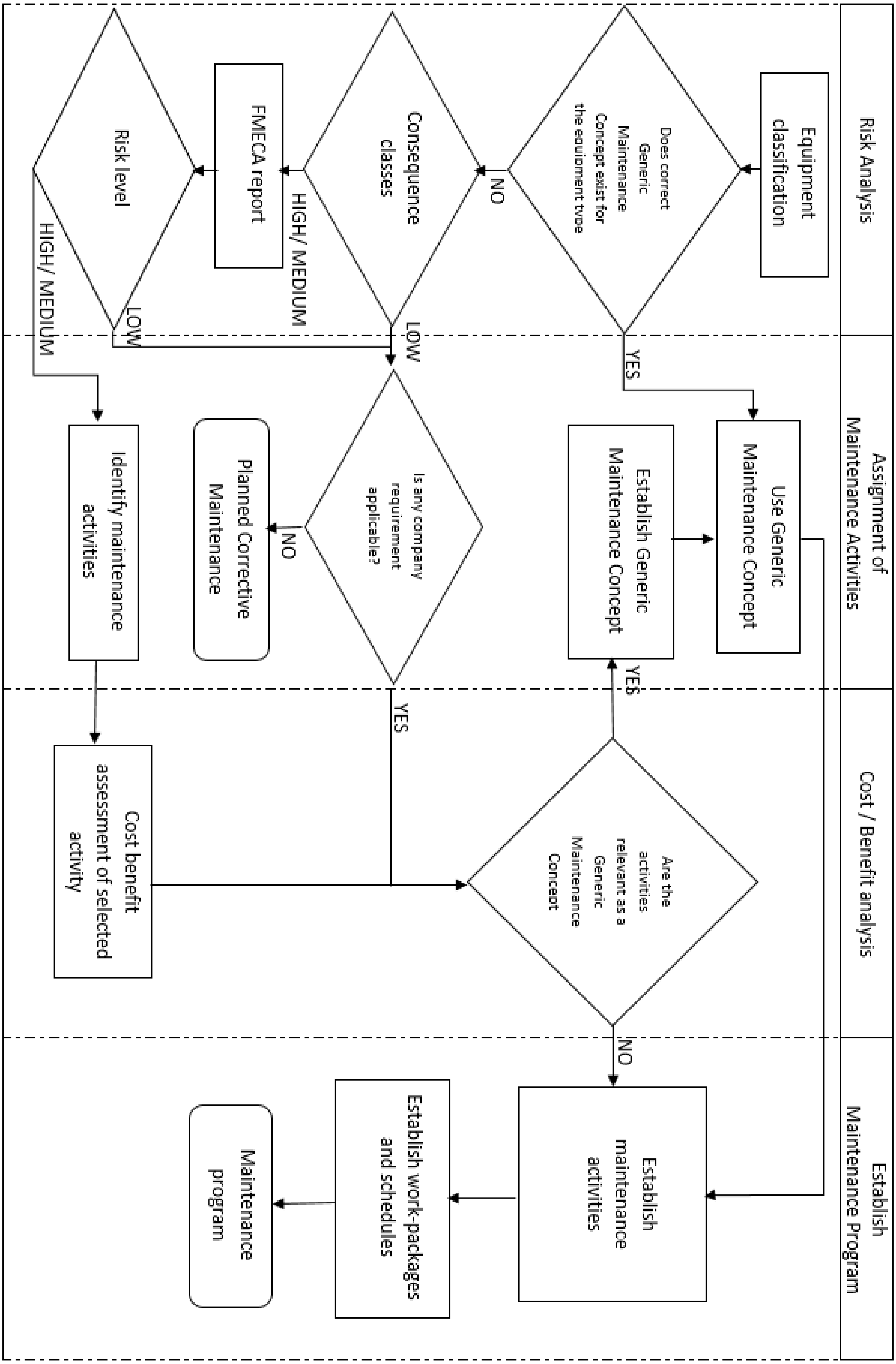


Figure 12: Breakdown of the situations that require a FMECA

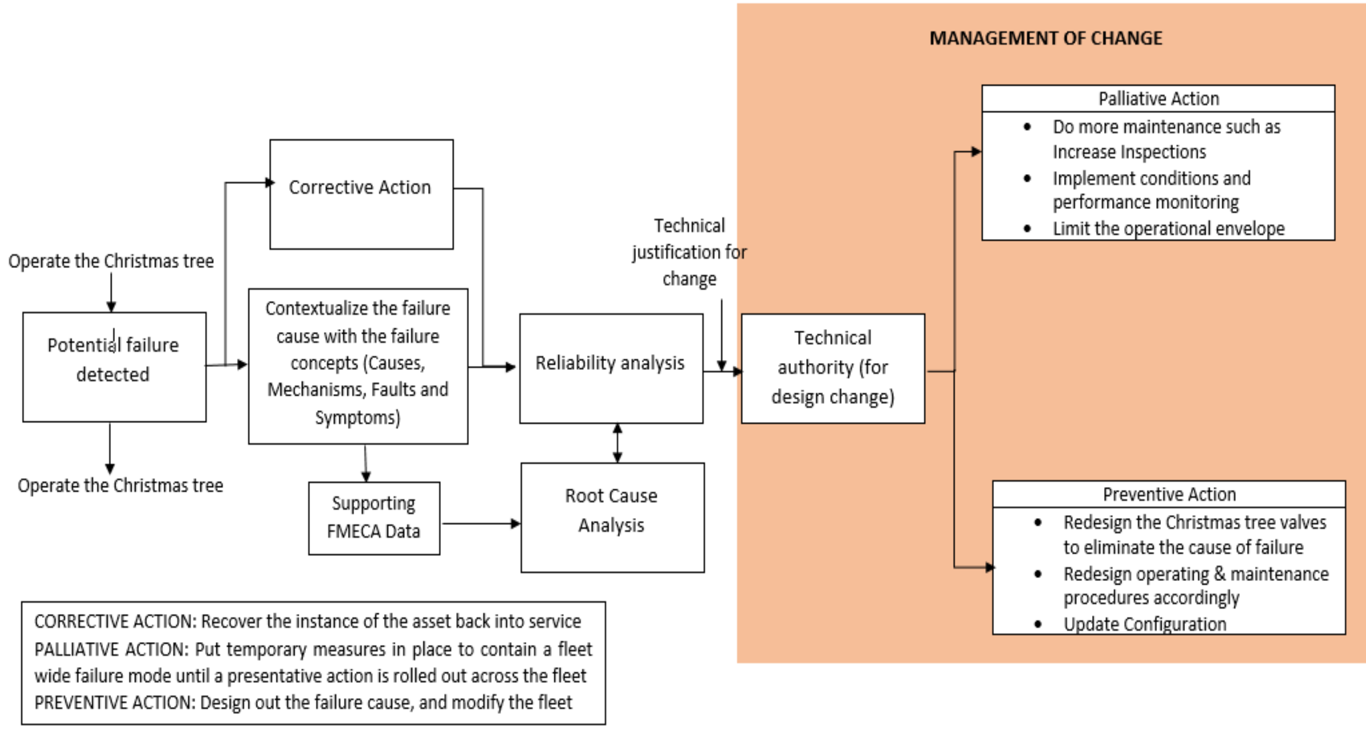


Figure 13: Breakdown of the applications of a FMECA

SWOT analysis is a technique that helps to develop business strategy by identifying strengths, weaknesses, opportunities and threats. Strengths and weaknesses are internal sources, and as such are variable to an extent within the context of the subject of the SWOT. Whereas opportunities and threats are external sources and cannot be adjusted by internal means.

The following SWOT analysis, shown in Figure 14, examines the advantages of using a model based FMECA instead of a traditional template:

Strengths

- Integrates the FMECA into the functional modelling process, which is widely used in creating new designs.
- Allows for a consistent level of detail in the reliability analysis
- Allows for integration of field data post-creation of the model to keep the FMECA for each component relevant.
- Characterization of degradation will allow OEMs to increase the amount of prediced cylces that components will last for.
- The model based nature allows for easier adjustment of and more easy and consistent upkeep of FMECA data over traditional methods (such as a spreadsheet).

Weaknesses

- Requires deep understanding of functional modelling techniques/software or the extra time and costs of learning these skills.
- The model is only as accurate as the person that makes it, therefore there is a margin for error.

Opportunities

- Has the potential to seriously reduce downtime and maintenance costs for oil and gas operators due to their ability to predict failure.
- The methodology can be integrated into the design process for new components from the start to allow engineers to more fundamentaly understand the system that is being worked on and integrate the functional modelling phase of the design process to generate a FMECA for their, saving time.

Threats

- Whilst better characterisation of degradation is usefull in terms of predicatbility and condition and performance monitoring, implementing counter measures to mitigate failures might not be useful for oil and gas operators, due to the need for all components to be EX-rated (allowed for aplication in an explosive hazard enviroment). The added costs of rating new equipment for this enviroment might make it more finanically viable to maintain the current course and not improve maintenance practices.
- The reluctance to share information might still be too much of hindering factor to allow for the creation of more reliable and detailed models of these components and their degradation.

Figure 14: SWOT analysis comparing the proposed methodology to current maintenance practices

Findings: The proposed methodology is comprised of a number of proven techniques employed primarily in the aerospace industry which, when used in conjunction with one another allow design engineers to be able to describe their to-be-designed system on a fundamental functional level. And assist them in assessing the highest risks within their system, further conceptualisation prototyping, as well as implementing preventative measures to prevent high risk failure from occurring.

Proposed database of failure concepts

To assist in the usage of the proposed method and to enable dialogue to take place between oil & gas operators, OEMs and other related engineering companies, a list of failure concepts was compiled. The list is divided into the Causes, Mechanisms, Faults and Symptoms (CMFS) categories as described in chapter II, and is further sub-categorized to allow these different CMFS to be contextualised to specific situations, i.e. distinguishing between causes originating during either assembly, transport or operation. An excerpt of all four categories (CMFS) is shown in Table 2, the complete database is shown in Appendix B.

This database has been reviewed and validated by TechnipFMC, an OEM of hydraulically actuated surface safety valves.

Table 2: Excerpts of failure concept database

Causes

Assembly and reassembly

Contamination

Biological contamination	A living organism that can degrade or consume a substance or component
Corrosive contaminant	An impurity that can degrade or consume a substance or component
Exposure to acid	The introduction of an item to a substance or gas that can cause corrosion.
Liquid contaminant	A liquid impurity that causes a substance or component to alter.
Saline contaminant	An impurity consisting of salt that causes a substance or component to alter.
Solid particle contaminant	A solid proportion of matter that causes a substance or component to alter.

Mechanisms

Corrosion

Cavitation corrosion	Acceleration of the corrosion process by cavitation-induced surface damage which continuously exposes unprotected material to a corrosive medium.
Corrosive attack	Degradation caused by the chemical reaction between two items, particularly metals and corrosive contaminants.
Corrosive fatigue	Accelerated corrosion of material due to fatigue cracks exposing fresh material to the corrosive agent.
Corrosive wear	Accelerated corrosion and wear in which wear removes corrosion protection, and the hard abrasive corrosion by-product that is removed acts as an abrasive agent.
Crevice corrosion	Localized corrosive attack by stagnant solution trapped between two surfaces and depleted of oxygen.

Erosion corrosion	Corrosion that is accelerated by an abrasive or viscid flow which removes surface materials and continuously exposes unprotected material to the corrosive medium.
Pitting corrosion	Localized corrosive attack that leads to the development of an array of holes or pits that penetrate the metal.
Stress corrosion cracking	Degradation process due to applied stress on a part in a corrosive environment, generating a field of localized surface cracks, usually along the grain boundaries.

Faults

Bulk change

Cracked	A crack propagated part way through the item
Fractured	A crack has entirely traversed an item and the item is completely separated into parts or fragmented
Voids	Empty spaces in the bulk of material

Symptoms

Appearance

Shape change	A change in the item geometry or shape
Surface change	A change in material surface characteristics

Behaviour

Change in behaviour	A change of the component or system due to a fault

Case study

The importance of hydraulically actuated Surface Safety Valves to successful Xmas Tree operation presents a situation where detailed characterization of the degradation of components and parts is extremely important. To that end, the SSV is used in the validation of the proposed methodology to characterize these degradation phenomena and allow for comparison to currently used reliability assessment methods.

Hydraulically actuated SSVs consist of three separate systems: The valve, the actuator and the Safety Instrumented System(SIS). These systems perform different functions but their cooperation is key to allowing a SSV to perform its function. As such, all three systems have to be taken into account when assessing degradation that can lead to SSV failure.

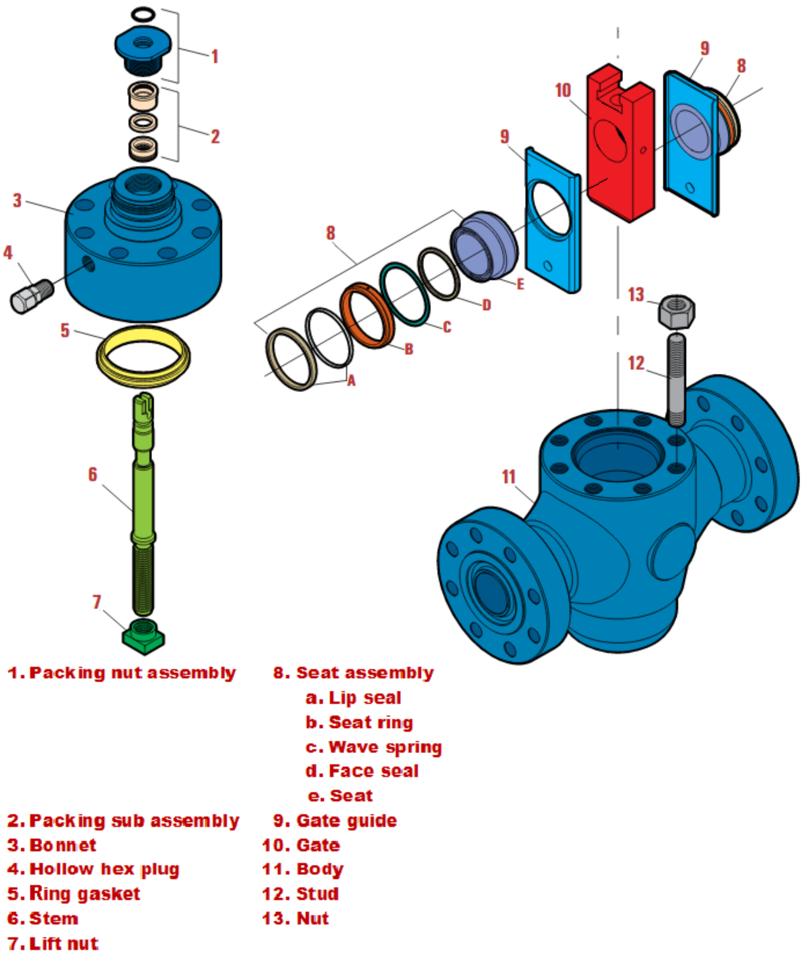


Figure 15: Valve body exploded view (Dril-Quip, 2014)

The valve is defined as the subsystem that regulates the flow of hydrocarbons from the wellhead. For SSVs a swab-gate valve is used, as the mechanism for opening and closing the valve needs to be able to be actuated linearly when using a hydraulic actuator. This gate combined with a number of seal rings, seats and retainers, as shown in Figure 15, is used to regulate, and if need be stop the flow to systems that are connected to the valve.

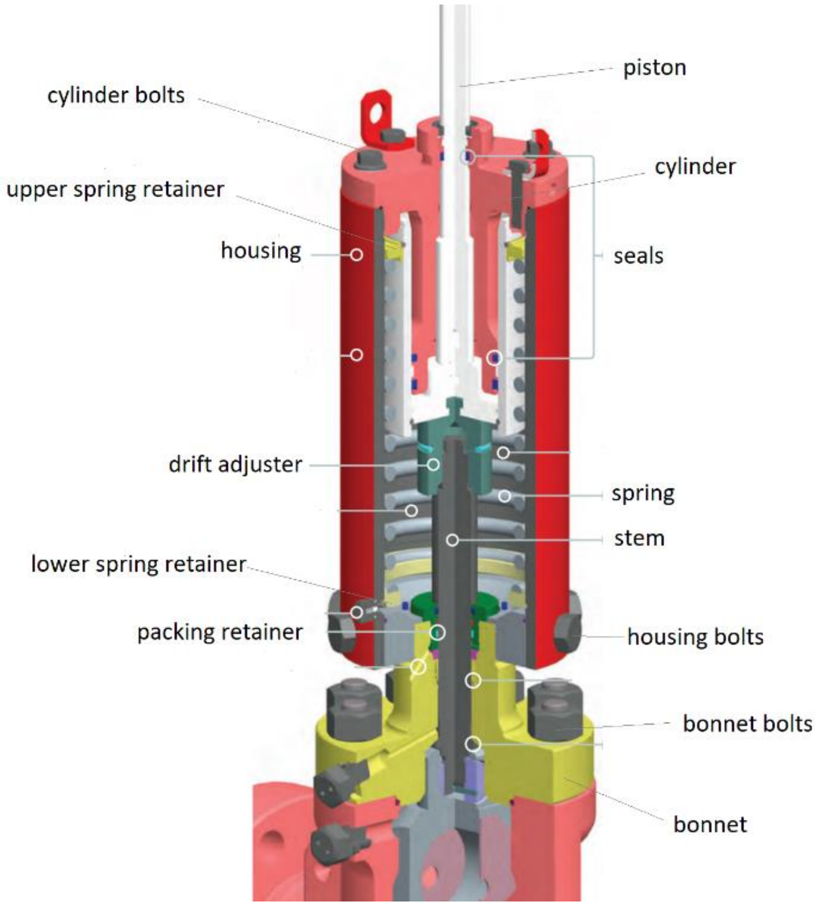
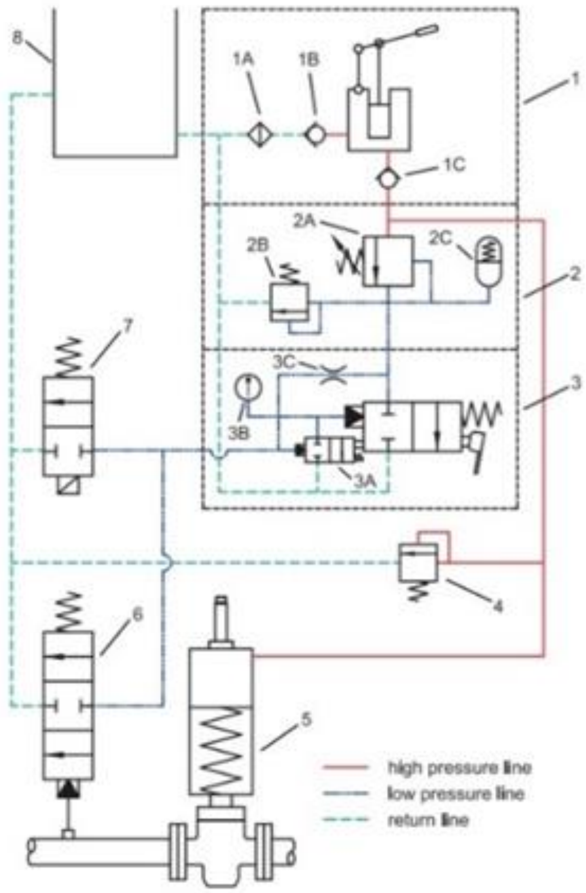


Figure 16: Hydraulic actuator section view (FMC Technologies, 2007)

The actuator is defined as the subsystem that controls the linear movement of the gate valve mechanism. It is composed of a single-acting hydraulic cylinder with a spring to return the system to a closed position, shown in Figure 16. The use of a single acting cylinder with spring adds an inherent safety feature where any loss of hydraulic pressure in the actuator automatically closes the valve.

The SIS is the subsystem that controls the hydraulic pressure and flow in the entire system. It consists of a manually operated pump to increase system pressure, with a number of relief valves and other safety measures to keep hydraulic pressure within the allowed margin, shown in Figure 17. This system also monitors hydrocarbon pressure to be able to shut the valve in case any situation arises where this pressure could pose a hazard to the production systems downstream.



Component	Function	Operational conditions
1 Manual Pump	Control pressure in the system	Boosting pressure
1a Suction Filter	Reduce hydraulic fluid contamination	Collecting contaminations
1b Suction Check Valve	Prevent reverse flow	Open during positive flowrate, closed during negative flowrate
1c Discharge Check Valve	Prevent reverse flow	Open during positive flowrate, closed during negative flowrate
2/ 2a Pressure Reducing Valve	Lower pressure for lower pressure components	Reduces pressure
2b LP Pressure Relief Valve	Protect from over pressurization	Closed – normal pressure Open – high pressure
2c LP Accumulator	Compensate pressure for temperature changes	Storing hydraulic pressure
3 Manual Override Valve	Override safety systems	Closed – safety systems engaged Open – safety systems ignored
3a Trip Valve	Lower pressure when triggered	Closed – normal operation Open – valve closed
3b Fusible Element	Cause intentional leakage in case of fire	Normal operation – end cap function In case of fire – melt to allow for pressure compensation
3c Flow Restrictor	Control hydraulic flow rate	Restricting flow to return line
4 HP Pressure Relief Valve	Protect from over pressurization	Closed – normal pressure Open – high pressure
5 Hydraulic Actuator	Actuate the valve gate	Open – valve open Closed – valve closed
6 High/Low Pressure Pilot	Detect high/low pressure in the hydrocarbon line	Detecting pressure anomalies
7 Solenoid Valve	Allow for manual closing of the valve	Closed – valve open Open – valve closed
8 Hydraulic Reservoir	Provide the system with hydraulic fluid	Providing hydraulic fluid

Figure 17: Safety Instrumented System breakdown (FMC Technologies, 2007)

Because of the easy distinction between the three subsystems of an SSV this breakdown is used when adapting this design into a model to allow for a detailed look into the root causes for different failures, where failures in one subsystem can propagate throughout the others and affect the entire SSV. This ‘closed loop’ nature of the SSV in a functional sense is also why further Xmas tree components are not taken into account in this breakdown.

Applying the methodology described in this paper to this system requires a number of different approaches depending on the subsystem being modelled. For the SIS, a component level approach is used when modelling the SIS in a Functional Block Diagram (FBD), shown in Figure 18, with each component performing a separate function that contributes to the functionality of the SIS as a whole, e.g. the hydraulic reservoir supplies fluid, and the pump regulates pressure.

The valve and the actuator make use part level modelling to define how each part of these subsystems contribute to the required function and how the failure of each part can contribute to overall functional failure of the system. The valve and the actuator are taken into account in the complete model separately by two functional component blocks in the FBD as shown in Figure 19. To define this part level model, the subsystems are described through the use of part pair breakdowns, shown in Table 3.

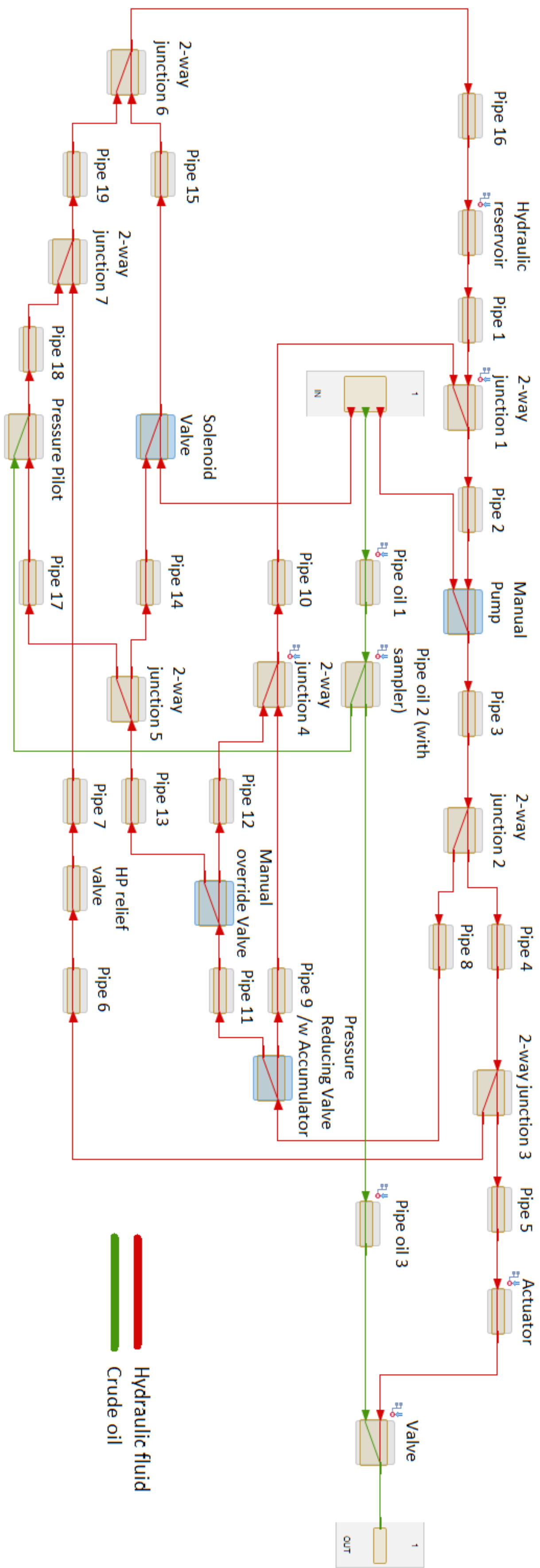


Figure 18: Functional Block Diagram of the complete system

Table 3: Part pair breakdown for the valve

ID NO.	PART NAME	FEATURES	NAME IN TAXONOMY
1	Packing nut assembly	Thread Seal ring	Seal Seat
2	Packing sub assembly	Thread	Seat Retainer
3	Bonnet	Thread	Fitting
4	Hollow hex plug	Thread	Plug
5	Ring gasket		Washer
6	Stem	Thread, notch	Stem
7	Lift nut	Thread	Retainer
8	Seat assembly	a. Lip seal b. Seat ring c. Wave spring d. Face seal e. Seat	Seal Seat Tension spring Seal Seat
9	Gate guide		Guide
10	Gate		Block
11	Body	Holes	Housing
12	Stud	Thread	Stud
13	Nut	Thread	Nut

ID NO	FIRST PART NAME	FIRST PART FEATURE	SECOND PART NAME	SECOND PART FEATURE
1	Bonnet	Thread	Packing nut assembly	Thread
2	Bonnet	Hole	Packing sub assembly	
3	Bonnet	Thread	Hollow hex plug	
4	Bonnet	Hole	Ring gasket	
5	Bonnet	Thread	Stud	
6	Stem		Packing nut assembly	Hole
7	Stem	Notch	Packing sub assembly	Hole
8	Stem	Thread	Lift nut	Thread
9	Stem		Gate	Hole
10	Gate		Gate guide	
11	Seat assembly		Gate guide	Hole
12	Body	Hole	Seat assembly	
13	Body	Thread	Stud	Thread
14	Body		Bonnet	
15	Body		Ring gasket	
16	Stud	Thread	Nut	Thread

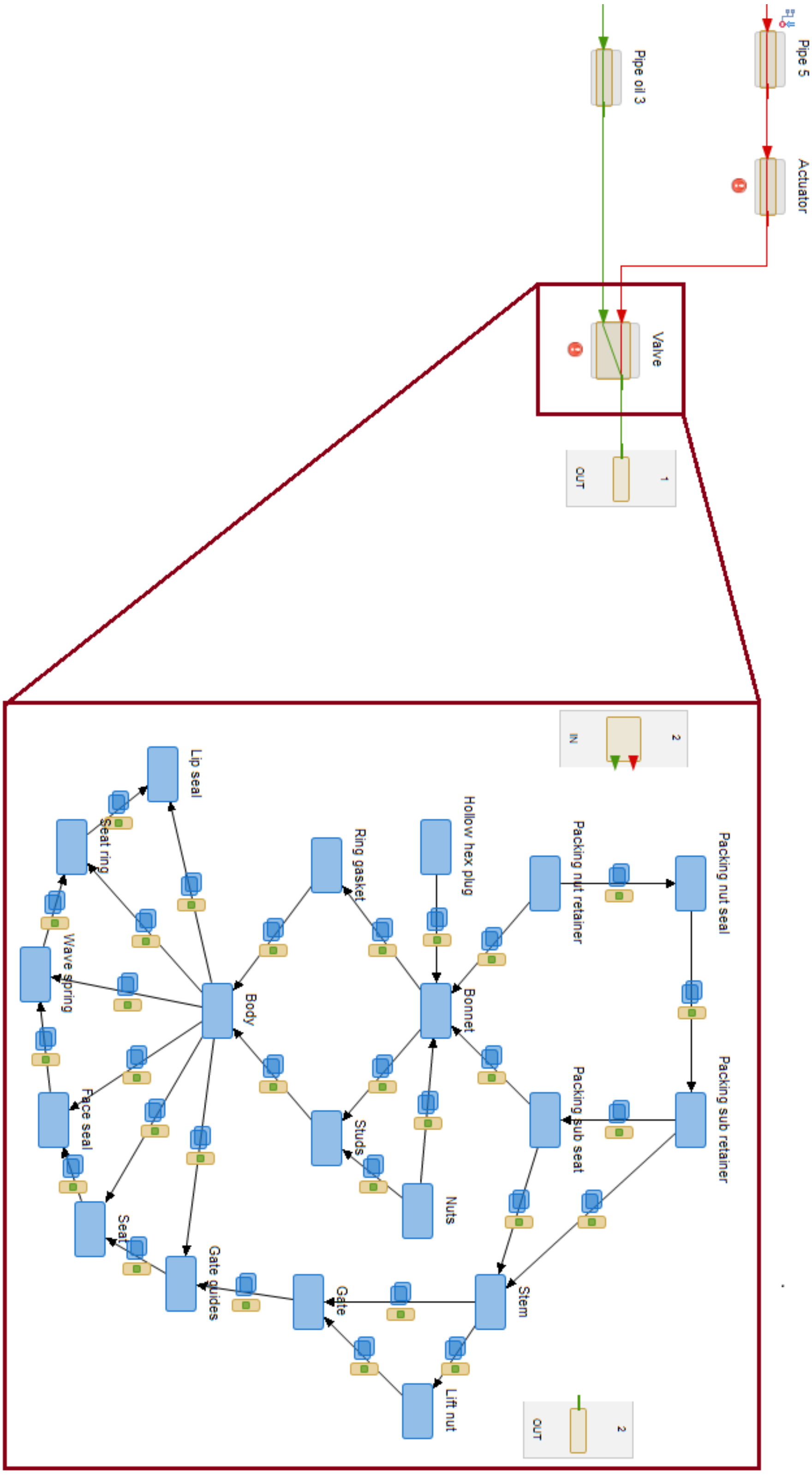


Figure 19: Part level model of the valve component

The use of functions and flows is done purely on the component level. For this system the use of flows comes down mainly in the form om hydraulic energy. The function that each component performs in relation to these flows is also defined, as shown in Figure 20.

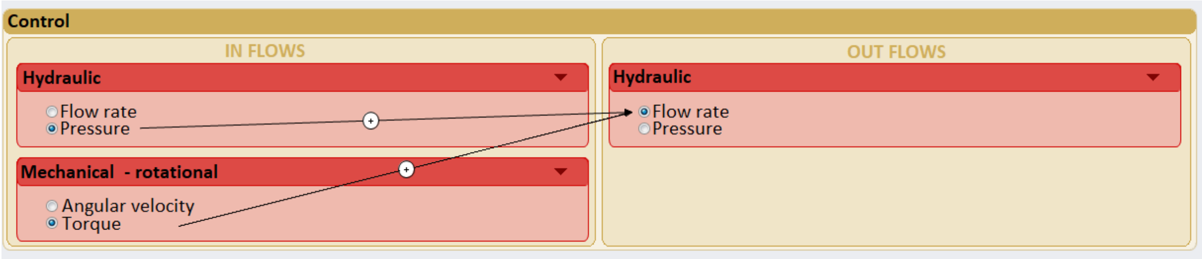


Figure 20: Functional flow breakdown for the pump in the SIS

The application of Failure Tree Diagrams (FTD) also differs between the SIS and the valve and actuator, due to the difference in modelling technique. The SIS makes use of separate FTDs, shown in Figure 21, for each component where the connections between components are defined through the propagation of the effect of a failure in a component, e.g. If a leakage occurs in a component, hydraulic pressure will typically drop, causing a loss of pressure throughout the entire system.

Create accurate FTDs that are applicable to the different components, the database in Appendix B is used.

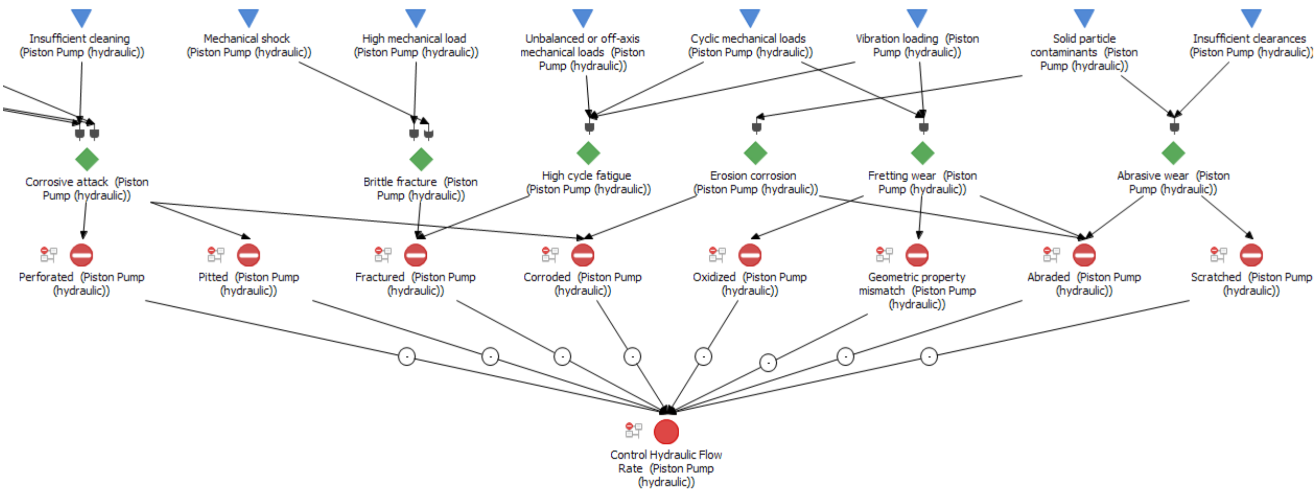


Figure 21: Failure Tree Diagram for the pump in the SIS

The valve and actuator make use of a different form of FTD, where the diagrams created for the different parts of the subsystem are interconnected through their interaction with other components where failure is defined as the failure of the function of the particular connection. This functional failure is then related through the use of probability and progression rates to the functional failure of the entire system as shown in Figure 22. This allows for the analysis of the relationship between failure in a specific part of the valve or actuator component, and functional failure throughout the entire system.

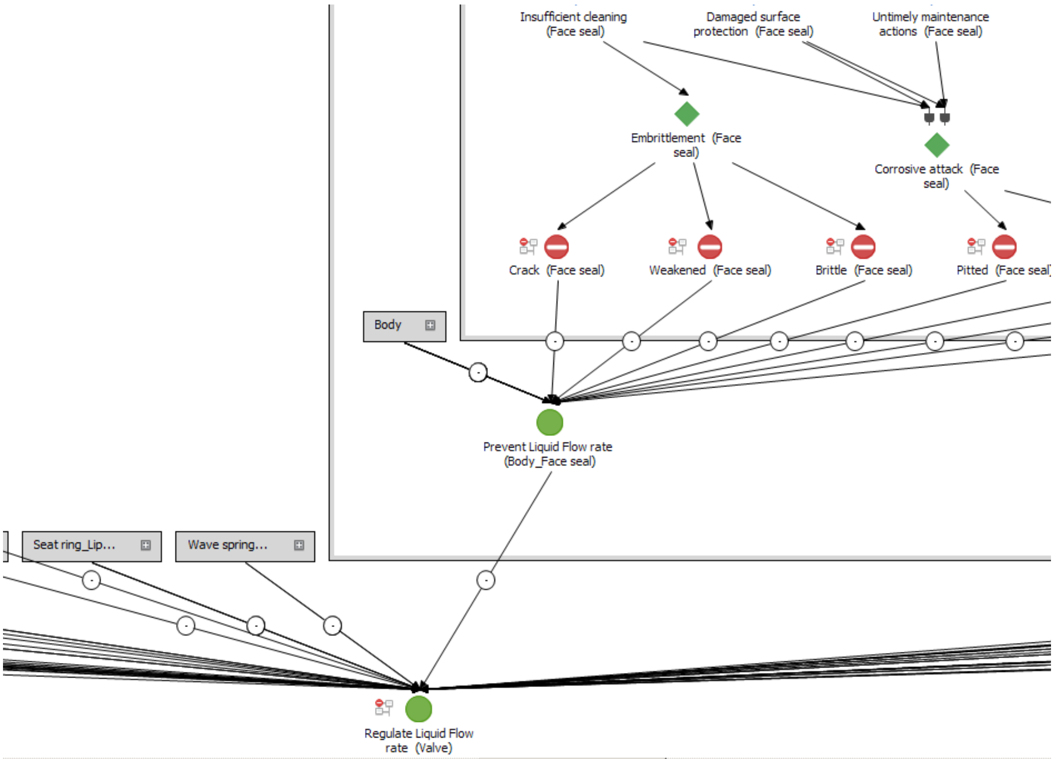


Figure 22: Failure Tree Diagram for the valve

In order to create an accurate FTD for all components in the model, the proposed database was used and all possible CMFSs selected that can affect different components. In order to assure the accuracy of these assumptions, this selection was verified by David Faichnie of TechnipFMC.

To validate the accuracy of this functional model of the SSV, the model was validated by PHM Technology, the company responsible for the software package used in this case study. After validation,

Using this model, a FMECA was created in accordance with the RPN criticality method in SAE and AIAG standards. The FMECA report lists the failure mode for each item in the system model that leads to functional failure for the valve, using the values for severity, detectability and occurrence set in the FTD for each component combined with probability and progression rates to show the probability that different faults and failures in a component or part cause a total system failure.

This FMECA allows for assessment of the SSV to determine where further action needs to be taken. i.e. which components have the highest risk of failure and need counter measures, such as periodic inspection or active sensors, to ensure that failure does not occur. An excerpt of the FMECA is shown in Figure 23.

Using data from actual oil & gas operations will allow for the assessment of the accuracy of the FMECA, a large advantage in using this method shows in the ability to adjust the different rankings (severity, detectability and occurrence) in accordance with the assessment to perpetually increase the accuracy of the report and optimize any maintenance strategies, sensor placement and other preventative measurements that are available.

Comparing the results shown in this FMECA to previously made analyses throughout the industry proved difficult however, due to the lack of available information pertaining to SSVs. This, coupled with the lack of failure analysis data in general, due to the industry being unwilling to share this information or no data being available at all. As such, this case study serves more as an example of the application of this new method.

Findings: Applying the new methodology as described in this paper assists in the creation of a detailed and adaptable functional model of a Surface Safety Valve at both the component and part level. Modelling techniques like this can be used for constantly updating reliability assessments, FMECA generation and characterization of degradation at the design stage to insure the safe operation of the system.

ITEM NO.	ITEM / PHYSICAL DESCRIPTION	FUNCTION/ FUNCTIONAL NARRATIVE	FAILURE MODE		CAUSES OF FAILURE		FAILURE EFFECTS		DETECTION METHODS	COMPENSATING PROVISIONS	CRITICALITY			
			FUNCTIONAL FAILURE	FAULT	MECHANISM	CAUSE	NEXT HIGHER LEVEL	END EFFECTS			O	S	D	RPN
	Valve	Regulate Liquid Flow rate	Regulate Liquid Flow rate High Degraded output or Failure to cease operation or Failure to operate or Loss of output or Premature Operation			Connect Solid Position Displaced - (Face seal_Ware spring) Degraded output or Failure to cease operation or Failure to operate or Loss of output or Premature Operation	Degraded output or Failure to cease operation or Failure to operate or Loss of output or Premature Operation	Regulate Liquid Flow rate High			2.7	10.0	8.4	227
						Connect Solid Fatigue life Low (Face seal_Ware spring) Degraded output or Failure to cease operation or Failure to operate or Loss of output or Premature Operation	Degraded output or Failure to cease operation or Failure to operate or Loss of output or Premature Operation	Regulate Liquid Flow rate High			2.7	10.0	8.4	227
						Prevent Liquid Flow rate Low (Seat_Face seal) Degraded output or Failure to cease operation or Failure to operate or Loss of output or Premature Operation	Degraded output or Failure to cease operation or Failure to operate or Loss of output or Premature Operation	Regulate Liquid Flow rate High			4.3	10.0	5.3	228
						Connect Solid Shape Misshapen - (Seat_Face seal) Degraded output or Failure to cease operation or Failure to operate or Loss of output or Premature Operation	Degraded output or Failure to cease operation or Failure to operate or Loss of output or Premature Operation	Regulate Liquid Flow rate High			4.3	10.0	5.3	228
						Connect Solid Position Displaced - (Seat_Face seal) Degraded output or Failure to cease operation or Failure to operate or Loss of output or Premature Operation	Degraded output or Failure to cease operation or Failure to operate or Loss of output or Premature Operation	Regulate Liquid Flow rate High			4.3	10.0	5.3	228
						Prevent Solid Position Displaced - (Packing nut retainer_Packing nut seal) Degraded output or Failure to cease operation or Failure to operate or Loss of output or Premature Operation	Degraded output or Failure to cease operation or Failure to operate or Loss of output or Premature Operation	Regulate Liquid Flow rate High			4.0	10.0	7.9	316

Figure 23: Excerpt from the FMECA of the system

Concluding remarks

The oil & gas industry contains a lot of opportunities for improvement in the field of failure analysis. Whilst reliability assessment methodologies such as FMECA are widespread throughout the oil and gas sector, there are still a lot of unknowns when it comes to failure of components and understanding the degradation that causes them to fail.

The high costs of equipment and the reluctance to share information due to the nature of publicly traded companies are a major obstacles to overcome, with purposefully running equipment to failure to characterize their degradation not being viable to OEMs due to the cost of producing this equipment and operators unwilling to share the information they have or not having this information in the first place, discourse and cooperation between these companies will need to be encouraged and developed to allow for optimal implementation of the methodology proposed in this paper.

In unifying the multiple industry definitions for Causes, Mechanisms, Faults and Symptoms, this paper hopes to improve dialogue between oil & gas operators and Original Equipment Manufacturers about failure rates, causes maintenance concepts and overall reliability and safety.

Current maintenance practises are adequate for safety standards. They do, however, leave much to be desired in the optimisation of wellhead use and minimalizing the costs related to downtime and replacement parts. Current reporting methods are very surface level, leaving OEMs with little information as to the degradation of their components.

The proposed method to implement these new definitions, along with the compiled database hopes to improve the ability of the industry to characterize and predict degradation at the design stage. Using well known techniques such as Functional Block Diagrams, part level modelling and Fault Tree Diagrams gives engineers a versatile selection of tools to analyse a system and simulate degradation without the added costs that in the field run-to-failure testing would bring. The validation of this method through its popular current use in the aerospace industry in such projects such as the F-35 Joint Strike Fighter also bodes well for the implementation of this method in other sectors.

From the SWOT analysis it can be seen that the proposed methodology offers a number of advantages over traditional methods, particularly in the field of long term reliability analysis. The ability to more easily and reliably adjust FMECA reports over time through the use of the same model, and the advantages that a consistent level of detail of a report offers will hopefully entice OEMs to embrace the proposed methodology in the future.

Current issues that the proposed method will have to overcome mainly pertain to the current reluctance of oil & gas companies to share data, this is understandable given that making such data publicly available can influence stock prices negatively. Any data that is currently available, such as OREDA and the database released by Equinor are either fairly limited or difficult to interpret due to the scattered nature of this raw dataset. The further interpretation and cataloguing of this dataset might significantly improve the ability of the oil & gas industry to characterize degradation in their systems over longer periods of time. Convincing the industry to adopt the database of failure concepts and then applying it to the different components in the industry will require time and effort on the part of both OEMs and operators.

This lack of data also had a great influence in the validation of the FMECA that was generated as a result of the case study, with the case study resulting more so in a worked example of the proposed method and to prove the ability of this method to generate a FMECA, instead of validation of the FMECA generated through this method. However, due to the popular application of this method in the aerospace industry, validation of the method is achieved nonetheless outside of the scope of this paper.

Further research will be done on this subject to provide a proper oil & gas industry validation of this method and to hopefully incite the oil & gas industry to adopt new techniques and technologies to improve the efficiency, safety and reliability of their systems.

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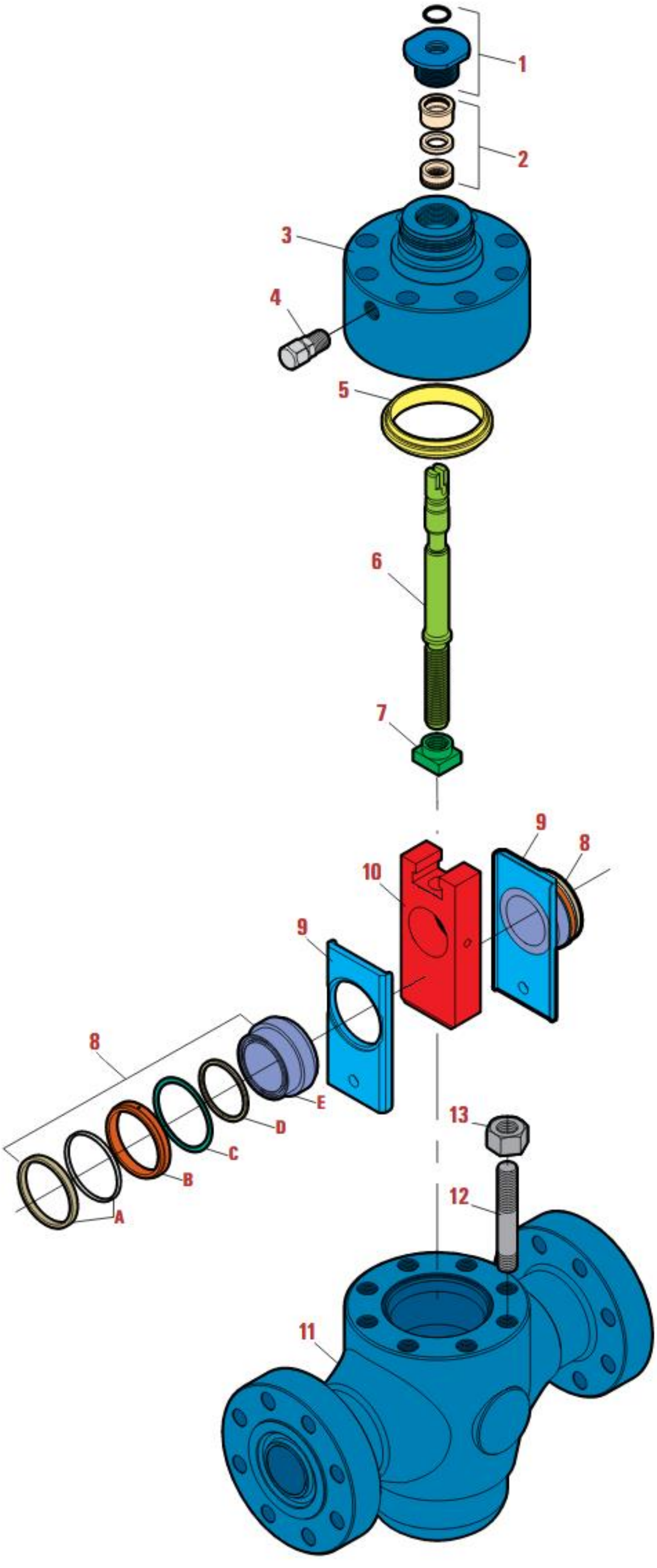
Appendix

Appendix A – Part Pair breakdown for the valve and actuator components of the Surface Safety Valve

Valve parts and part pairs

ID NO.	PART NAME	FEATURES	NAME IN TAXONOMY
1	Packing nut assembly	Thread Seal ring	Seal Seat
2	Packing sub assembly	Thread	Seat Retainer
3	Bonnet	Thread	Fitting
4	Hollow hex plug	Thread	Plug
5	Ring gasket		Washer
6	Stem	Thread, notch	Stem
7	Lift nut	Thread	Retainer
8	Seat assembly	f. Lip seal g. Seat ring h. Wave spring i. Face seal j. Seat	Seal Seat Tension spring Seal Seat
9	Gate guide		Guide
10	Gate		Block
11	Body	Holes	Housing
12	Stud	Thread	Stud
13	Nut	Thread	Nut

ID NO	FIRST PART NAME	FIRST PART FEATURE	SECOND PART NAME	SECOND PART FEATURE
1	Bonnet	Thread	Packing nut assembly	Thread
2	Bonnet	Hole	Packing sub assembly	
3	Bonnet	Thread	Hollow hex plug	
4	Bonnet	Hole	Ring gasket	
5	Bonnet	Thread	Stud	
6	Stem		Packing nut assembly	Hole
7	Stem	Notch	Packing sub assembly	Hole
8	Stem	Thread	Lift nut	Thread
9	Stem		Gate	Hole
10	Gate		Gate guide	
11	Seat assembly		Gate guide	Hole
12	Body	Hole	Seat assembly	
13	Body	Thread	Stud	Thread
14	Body		Bonnet	
15	Body		Ring gasket	
16	Stud	Thread	Nut	Thread

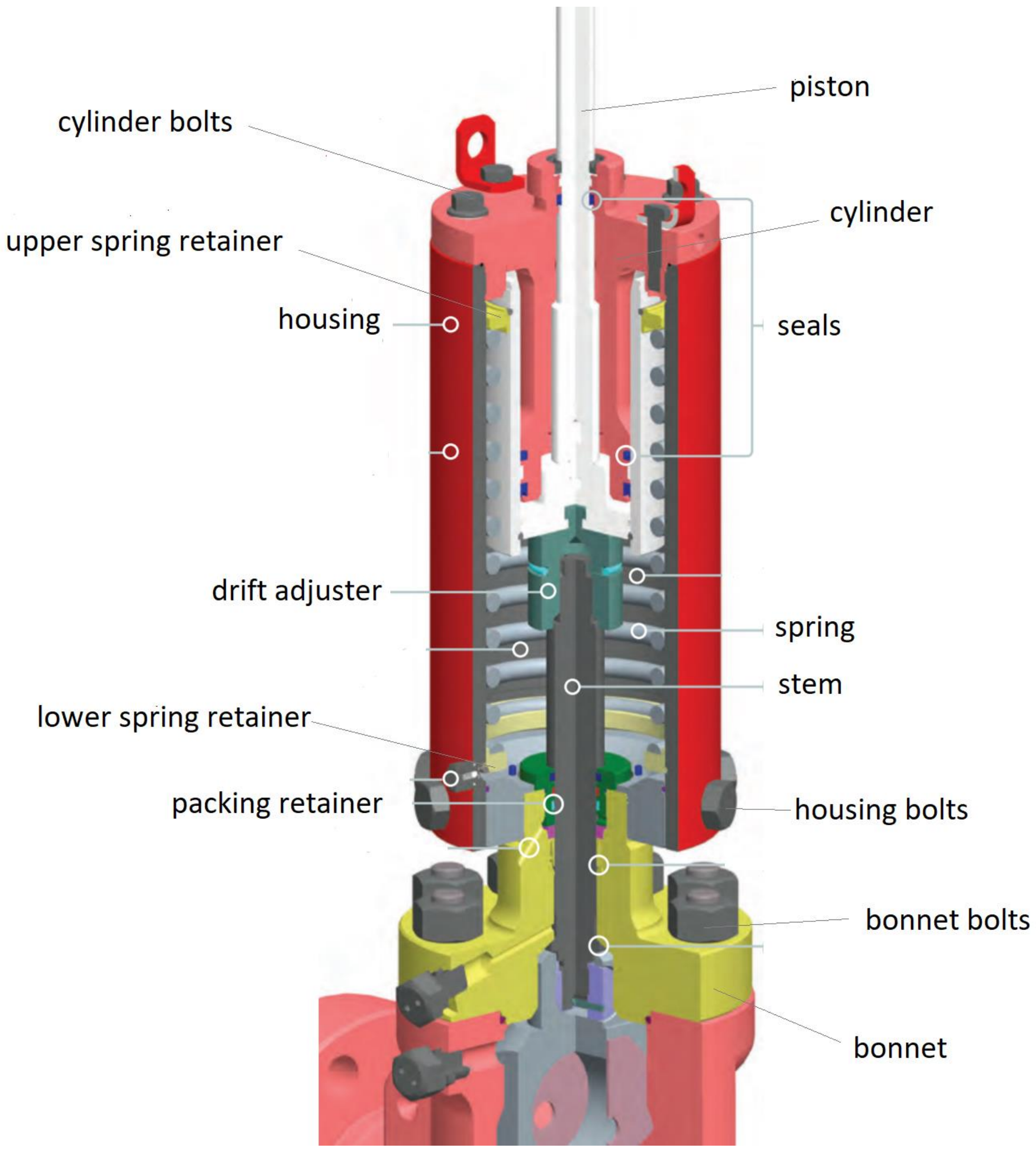


1. Packing nut assembly
2. Packing sub assembly
3. Bonnet
4. Hollow hex plug
5. Ring gasket
6. Stem
7. Lift nut
8. Seat assembly
   a. Lip seal
   b. Seat ring
   c. Wave spring
   d. Face seal
   e. Seat
9. Gate guide
10. Gate
11. Body
12. Stud
13. Nut

Hydraulic Actuator parts and part pairs

ID NO.	PART NAME	FEATURES	NAME IN TAXONOMY
1	Piston		Piston
2	Cylinder	Hole	Cylinder
3	Upper piston seal		Seal
4	Lower piston seal		Seal
5	Spring		Torsion spring
6	Upper spring retainer	Hole	Retainer
7	Lower spring retainer	Hole	Retainer
8	Drift adjuster	Notch	Guide
9	Housing	Thread	Housing
10	Cylinder bolts	Thread	Bolt
11	Housing bolts	Thread	Bolt

ID NO	FIRST PART NAME	FIRST PART FEATURE	SECOND PART NAME	SECOND PART FEATURE
1	Housing		Lower spring retainer	
2	Housing	Thread	Housing bolts	Thread
3	Housing		Spring	
4	Housing	Thread	Cylinder bolts	thread
5	Housing	Hole	Cylinder	
6	Spring		Upper spring retainer	
7	Spring		Lower spring retainer	
8	Piston		Drift adjuster	Notch
9	Piston		Upper piston seal	Hole
10	Piston		Lower piston seal	Hole
11	Cylinder		Upper piston seal	
12	Cylinder		Lower piston seal	
13	Cylinder	Thread	Cylinder bolts	thread


piston
cylinder bolts
cylinder
upper spring retainer
housing
seals
drift adjuster
spring
stem
lower spring retainer
packing retainer
housing bolts
bonnet bolts
bonnet

Appendix B – Complete database of failure concepts

Causes

Assembly and reassembly

Contamination

Corrosive contaminant	An impurity that can degrade or consume a substance or component
Exposure to acid	The introduction of an item to a substance or gas that can cause corrosion.
Liquid contaminant	A liquid impurity that causes a substance or component to alter.
Saline contaminant	An impurity consisting of salt that causes a substance or component to alter.
Solid particle contaminant	A solid proportion of matter that causes a substance or component to alter.

Environmental protection

Damaged surface protection	The outer preservation or layer of an item is comprised.

Geometry

Blocked opening	A congested inlet caused by incorrect assembly.
Disconnected	A separation of the connection between two or more items.
Dynamic imbalance	An imbalance caused by the center of mass being out of alignment with the center of rotation.
Excessive clearance	A gap that allows relative movement and is larger than needed.
Insufficient clearances	A gap that allows relative movement is too small for intended purpose.
Loose fit	An item that is unsecured or can move about freely.
Mechanical interference	A disruption between the connection of two mating physical items.
Misaligned	An item is having an incorrect position or orientation in an assembly.
Tight fit	An item that is overly secure or restricted movement.
Wrong part orientation	A part has been placed into an item with incorrect alignment.

Humidity

High humidity	An excessive amount of moisture.

Material quality

Surface damage	The exterior destruction of an item.

Mechanical loading

High mechanical load	A higher than expected mechanical force is exerted on an item.
Impact loads	A force exerted on an item that is generated by a moving object.

Mechanical property

Weak bond	The adhesive strength of a bond between items is lower than expected.

Design

Chemical property

Chemically reactive material	The tendency of a substance to undergo a chemical reaction.

Environmental protection

Insufficient environmental constraints	A lack of or inadequate sealing between internal environments.
Insufficient surface protection	A lack of or inadequate exterior preservation for an item.

Geometry

Blocked opening	A congested inlet caused by design errors.
Disconnected	A separation of the connection between two or more items.
Excessive clearances	A gap that allows movement and is larger than needed.
Inappropriate flow geometry	The geometric design of the system does not allow the ideal flow.
Incorrect size	The item sizing is to large or too small for intended purpose.
Insufficient clearances	A gap that allows relative movement is too small for intended purpose.
Loose fit	An item that is unsecured or can move about freely.
Misaligned	An item having an incorrect position or orientation in an assembly.
Possesses curvature	An item has been designed with more curvature than is necessary.
Stress concentrations	A localization and amplification of stress at a particular point of an item.
Tight fit	An item is overly secure or restricted in movement.
Wrong part orientation	A part has been placed into an item with incorrect alignment.

Material quality

Incorrect material composition	The materials selected have an inaccurate formation for intended purpose.

Mechanical loading

Residual stress	A stress present in an object that was caused by a previous loading or process.

Mechanical property

Brittle material	The tendency to break without significant deformation.
Hardness mismatch	The ability to restrict plastic deformation substantially differs between two connected items.
Insufficient stiffness	An item has inadequate or poor rigidity.
Soft material	An item is susceptible to being deformed by external loads.
Stiffness mismatch	The rigidity substantially differs between two connected items.
Thermal coefficient mismatch	The thermal resistance substantially differs between two connected items.
Weak material	The material has a lower yield strength than its operating load.
Wrong coefficient of thermal expansion	The incorrect correlation between geometry and thermal temperature of an item.

Operational capacity

Cannot withstand operational loads	The maximum load or force the item can endure is inadequate for usage.
Insufficient capacity	The maximum volume or weight the item can store is inadequate for usage.

Maintenance

Contamination

Chemically reactive contaminant	An impurity that results in a substance or components to undergo a chemical change.
Corrosive contaminant	An impurity that can degrade or consume a substance or component.
Exposure to acid	The introduction of an item to a substance or gas that can cause corrosion.
Gaseous contaminant	A vapour impurity that causes a substance or component to alter.
Ionic contaminant	A residue or harmful material that is left behind during a manufacturing process.
Liquid contaminant	A liquid impurity that causes a substance or component to alter.
Saline contaminant	An impurity consisting of salt that causes a substance or component to alter.
Solid particle contaminants	A solid portion of matter that causes a substance or component to alter.

Environmental protection

Damaged surface protection	The outer preservation or layer of an item is compromised.

Humidity

High humidity	An excessive amount of moisture.

Input

Incompatible input material	A substance or component used during maintenance is incorrect and will not function within the system.
Incorrect lubricant	The wrong type of coating was used to reduce surface friction.

Material quality

Surface damage	The exterior destruction of an item.

Mechanical loading

Impact loads	A force exerted on an item that is generated by a moving object.

Procedure

Insufficient cleaning	An inadequate amount of sanitation has been used.
Mishandling	Improper handling of a component, leading to damage.
Untimely inspections	The monitoring tasks performed to check health are not conducted frequently enough.
Untimely maintenance actions	The maintenance tasks performed to restore item health are not conducted frequently enough.

Manufacturing

Chemical property

Chemically reactive material	The tendency of a substance to undergo a chemical reaction.

Contamination

Chemically reactive contaminant	An impurity that results in a substance or components to undergo a chemical change.
Corrosive contaminant	An impurity that can degrade or consume a substance or component.
Exposure to acid	The introduction of an item to a substance or gas that can cause corrosion.
Gaseous contaminant	A vapour impurity that causes a substance or component to alter.
Ionic contaminant	A residue of a harmful material is left behind during a manufacturing process.
Liquid contaminant	A liquid impurity that causes a substance or component to alter.
Saline contaminant	An impurity consisting of salt that causes a substance of component to alter.
Solid particle contaminants	A solid portion of matter that causes a substance or component to alter.

Environmental protection

Insufficient surface protection	A lack of or inadequate exterior preservation for an item.

Geometry

Excessive clearances	A gap that allows relative movement and is larger than needed.
Inappropriate flow geometry	The geometric design of the system does not allow the ideal flow.
Incorrect size	The item sizing is to large or too small for intended purpose.
Insufficient clearances	An item is unsecured or can move about freely.
Possesses curvature	An item has been designed with more curvature than is necessary.
Stress concentrations	A localization of stress at a particular point of an item.

Humidity

High humidity	An excessive amount of moisture.

Material quality

Crystal defects	Issues with crystalline structure of an item, impacting on the properties of the material.
Excessive material defects	An unacceptable amount of deformities in an item.
Incorrect material defects	The materials selected have an inaccurate formation for intended purpose.
Material contains inclusion	The presence of small foreign items that alter the material quality.
Presence of voids	The occurrence of small interstices on the interior of an item, potentially altering them material properties.
Rough surface	The exterior of an item is coarse or ridged.
Smooth surface	The exterior of an item is continuous or invariable.

Mechanical loading

Residual stress	A stress present in an object that was caused by a previous loading or process.

Mechanical property

Brittle material	The tendency to break without significant deformation.
Hardness mismatch	The ability to resist plastic deformation substantially differs between two connected items.
Insufficient stiffness	- An item has inadequate or poor rigidity.
Soft material	An item is susceptible to being deformed by external loads.
Stiffness mismatch	The rigidity substantially differs between two connected items.
Weak material	The material has a lower yield strength than its operating load.
Wrong coefficient of thermal expansion	The incorrect correlation between geometry and thermal temperature of an item.

Metallization defect

Etching defects	A coating is performed leaving impression flaws on the item.
Inadequate step coverage	A coating is performed in poor vacuum resulting in non-uniform trends.
Incorrect alignment	A coating is performed at an incorrect angle or orientation.
Incorrect composition	A coating is performed with inaccurate material constituents.
Incorrect thickness	A coating is performed of inaccurate depth.
Line width	A coating is performed with inaccurate width.
Poor adhesion	A coating is performed with an insufficient bond strength.
Scratching	A coating is performed resulting in abrasive flaws on the item.
Thin oxide layer	A coating is performed with an inaccurate oxide layer depth.
Voids in oxides	The presence of gaps in the oxide layer of a coating.

Operation

Ambient pressure

High pressure	The ambient pressure is higher than expected.
Low pressure	The ambient pressure is lower than expected.
Pressure differential	The range between maximum and minimum pressure experienced is different to expected.
Pressure fluctuations	Variations in ambient pressure that effect an item.

Contamination

Chemically reactive contaminant	An impurity that results in a substance or components to undergo a chemical reaction.
Corrosive contaminant	An impurity that can degrade or consume a substance or component.
Exposure to acid	The introduction to an item to a substance or gas that can cause corrosion.
Gaseous contaminant	A vapour impurity that causes a substance or component to alter.
Liquid contaminant	A liquid impurity that causes a substance or component to alter.
Solid particle contaminants	A solid portion of matter that causes a substance or component to alter

Environmental protection

Damaged surface protection	The outer preservation or layer of an item is comprised.

Hydraulic loading

Transient hydraulic loads	Short lived bursts of random hydraulic loads.

Input

Aerated liquid input	A material inlet flow is made effervescent by being charged with carbon oxide or other gas.
Contaminated input flow	An incoming flow is comprised by impurity.
High pressure input flow	An incoming flow that is generating a higher than expected pressure.
Incorrect timing of input flow	An incoming flow has an incorrect or different pacing to what was expected.
Input flow too fast	An incoming flow has a higher than expected rate of flow.
Input flow too slow	An incoming flow has a lower than expected rate of flow.
Low pressure input flow	An incoming flow that is generating a lower than expected pressure.
Moist input flow	An incoming flow has a high humidity.

Mechanical loading

Acceleration	An increase in speed or rate.
Cyclic mechanical loads	A series of repeated forces or loadings.
High mechanical loads	A higher than expected mechanical force is exerted on an item.
Impact loads	A force exerted on an item that is generated by a moving object.
Mechanical shock	A sudden acceleration due to impact.
Transient mechanical loads	Short lived bursts of random mechanical loads.
Vibration loading	A continual and oscillating loading on an item.

Operating procedure

Dry start	An item is operated without proper priming or lubrication.
Shut-down procedures breached	The end of the operation process is performed incorrectly.
Start-up procedures breached	The beginning of operation process is performed incorrectly.

Operating speed

High operating speed	The operating speed of an item is higher than expected.
Low operating speed	The operating speed of an item is lower than expected.

Operating time

Item life-span exceeded	The long-term life expectancy has been surpassed.
Maximum continuous use time exceeded	The short-term usage for an item has been surpassed.

Pneumatic loading

Cyclic pneumatic loads	A series of repeated pressure changes in a pneumatic flow.
High pneumatic load	A gas is generating a higher than expected pressure or rate.
Low pneumatic loads	A gas that is generating a lower than expected pressure or rate.

Transportation

Contamination

Chemically reactive contaminant	An impurity that results in a substance or components to undergo chemical change.
Corrosive contaminant	An impurity that can degrade or consume a substance or component.
Exposure to acid	The introduction of an item to a substance or gas that can cause corrosion.
Gaseous contaminant	A vapour impurity that causes a substance or component to alter.
Ionic contaminant	Residue or harmful material that is left behind during a manufacturing process.
Liquid contaminant	A liquid that causes a substance or component to alter.
Saline contaminant	An impurity consisting salt that causes a substance or component to alter.
Solid particle contaminants	A solid portion of matter that causes a substance or component to alter.

Environmental protection

Damaged surface protection	The outer preservation or layer of an item is compromised.

Humidity

High humidity	An excessive amount of moisture.

Material quality

Surface damage	The exterior destruction of an item.

Mechanical loading

Impact loads	A force exerted on an item that is generated by a moving object.
Vibration loading	A continual and oscillating loading on an item.

Mechanisms

Corrosion

Cavitation corrosion	Acceleration of the corrosion process by cavitation-induced surface damage which continuously exposes unprotected material to a corrosive medium.
Corrosive attack	Degradation caused by the chemical reaction between two items, particularly metals and corrosive contaminants.
Corrosive fatigue	Accelerated corrosion of material due to fatigue cracks exposing fresh material to the corrosive agent.
Corrosive wear	Accelerated corrosion and wear in which wear removes corrosion protection, and the hard abrasive corrosion by-product that is removed acts as an abrasive agent.
Crevice corrosion	Localized corrosive attack by stagnant solution trapped between two surfaces and depleted of oxygen.
Erosion corrosion	Corrosion that is accelerated by an abrasive or viscid flow which removes surface materials and continuously exposes unprotected material to the corrosive medium.
Pitting corrosion	Localized corrosive attack that leads to the development of an array of holes or pits that penetrate the metal.
Stress corrosion cracking	Degradation process due to applied stress on a part in a corrosive environment, generating a field of localized surface cracks, usually along the grain boundaries.

Elastic deformation

Bending deformation	Deformation of a body under bending loading.
Buckling	A sudden collapse of a member under ‘column’ compression load due to elastic instability.
Compression deformation	Deformation of a body under compression loads, which results in contraction of the body in one dimension.
Shear deformation	Deformation of a body under shear loading, characterized by the relative sliding of planar sections of the material.
Tensile deformation	Elastic extension of a part under the action of a tensile load.

Fatigue

High cycle fatigue	Crack initiation and growth due to cyclic application of stresses or strains that extend mainly into elastic range, with failure occurring after 50,000 cycles.
Impact fatigue	Growth of cracks due to repetitive impact loading.
Low cycle fatigue	Crack initiation and progression caused by the cyclic application of stresses or strains that extend into plastic range of produce failure in about 10,000 cycles or less.

Fracture

Brittle fracture	Fracture characterized by no apparent plastic deformation prior to rupture.
Ductile fracture	Fracture characterized by extensive plastic deformation prior to complete rupture.
Impact fracture	High stresses and strains due to impact which cause separation of a part into two or more pieces.
Shear fracture	Fracture characterized by the relative sliding of planar surfaces of the material.
Tearing	A tensile failure in thin materials characterized by a fracture initiating at one edge and propagating across.
Tensile fracture	Fracture characterized by the axial extension of the material and separation of the broken parts.

Material decomposition

Coking	The thermal decomposition of a hydrocarbon liquid into a solid mass of impure carbon.

Material degradation

Embrittlement	Reduction of ductility/toughness in a metal or plastic with negligible change in other mechanical properties.
Oxidation	The reaction of a material with oxygen to form an oxide compound.

Material transfer

Build-up of debris	Deposition and accumulation of solid contaminants.
Silting	The deposition of particulate contaminants from a flowing liquid medium.

Plastic deformation

Creep	Accumulation of plastic deformation in a part over a period of time under the influence of stress and temperature, causing excessive deformation or rupture.
Creep buckling	Accumulation of plastic deformation due to a combination of compression loading and high temperatures over a period of time, that results in buckling instability of the material.
Stress relaxation	Non-linear material behaviour in which stress is relieved under constant strain.
Yielding	Plastic deformation of a part caused by the imposed operational loads or strains.

State change

Heat loss	Energy or power transmitted out of the system in the form of heat.
Micro-dieseling	Adiabatic compression of air bubbles in aerated oil under high pressure and temperature, resulting in very high localized temperatures and thermal degradation of the oil.

Wear

Abrasive wear	The loss of material from a solid surface due to abrasion by hard particles or protuberances.
Deformation wear	Growth of surface cracks, due to repeated plastic deformation, that coalesce to form wear particles.
Erosion	The wearing action of an abrasive or viscid fluid or gas on an exposed surface, which results in removal of material from exposed surface.
Fretting wear	Wear that occurs at the contact area between two materials under load and subject to minute relative motion by vibration or some other force.
Surface fatigue wear	Cyclic shear stress produced in the subsurface material leading to crack growth causing the loss of surface material.

Faults

Bulk change

Cracked	A crack propagated part way through the item
Fractured	A crack has entirely traversed an item and the item is completely separated into parts or fragmented
Voids	Empty spaces in the bulk of material

Fluid property change

Contaminated	A fluid contains undesirable, foreign liquid or solid materials

Mechanical connection

Blocked	The clearance between two items is filled by a foreign material, preventing the flow of material between them
Disconnected	The clearance between to items is increased, preventing mechanical interactions between them
Geometric property mismatch	The mechanical property of an item is changed, generating mechanical interactions between it and another item
Interference	The clearance between two items is decreased, enabling mechanical interactions between them
Loose	The clearance between two items is increased, allowing undesired relative motion between them
Misaligned	The relative position or attitude of an item has changed
Seized	The clearance between two items is decreased, preventing relative motion between them
Separated	The clearance between two items is increased, allowing the flow of material between them
Tight	The clearance between two items is decreased, generating excessive normal forces between them

Mechanical property

Brittle	The resistance of an item to brittle fractures is decreased
Plastic	The resistance of an item to irreversible mechanical deformation is decreased
Stiffness reduced	The resistance of an item to elastic deformation is decreased
Weakened	The resistance of an item to ductile fracture is decreased

Operator faults

Action fault	The operator’s actions were insufficient to bring about the desired consequences
Attention fault	The trigger information was presented to the operator but not noticed by him/her
Decision fault	The operator made a wrong choice in an undetermined situation
Intention fault	The operator knew what action to perform, but omitted to perform the action
Perception fault	The trigger information was presented but not noticed or understood by the operator
Reasoning fault	The operator falsely concluded what his/her action should be

Shape change

Bent	An initially straight item possesses curvature
Buckled	An initially straight item is permanently bent out of shape to the point of structural instability
Dimensions changed	Dimension change making item(s) unsuitable for its intended duty
Expanded	Item is deformed in more than one direction such that its volume is increased
Extruded	Item is deformed according to the shape of the opening through which it has been pushed
Sheared	The item is deformed such that parallel planes are translated with respect to each other
Stretched	Item is deformed such that its length is increased
Twisted	Item is deformed about on axis such that one end is rotated relative to the other

Surface change

Abraded	Outer layer of surface material has been removed, and lower layers of the same material have been exposed
Chipped	Loss of surface material leaving shallow, rounded voids
Corroded	The outer layer of an item has been chemically removed by a corrosive agent
Etched	Localized areas of the outer layer of an item have been chemically removed
Grooved	Surface material has been locally removed or deformed
Oxidized	The outer layer of an item has reacted with oxygen and is an oxide compound
Pitted	Loss of surface material leaving deep, rounded voids
Porous	Surface material contains voids
Rough	The outer layer is unevenly deformed and possesses peaks and valleys
Ruptured	A tear in the item, result of breaking open or bursting
Scratched	Surface material has been locally removed or deformed
Stripped	Generalized loss of surface material, exposing a surface layer to different material
Surface cracks	Surface layer of material is fractured

Symptoms

Appearance

Shape change	A change in the item geometry or shape
Surface change	A change in material surface characteristics

Behaviour

Change in behaviour	A change of the component or system due to a fault

Energy

Airborne noise	An acoustic emission that propagates through a fluid
Fluid borne noise	An acoustic emission that propagates through a fluid
Vibration	A change in vibration caused by normal or abnormal system operation

Environment

Change in environment	An emission or loss from the system that leads to an alteration of some aspect of the external environment

Material

Leakage	An accidental emission of a liquid or gas caused by a fault
Solid debris	And emission of debris that is formed by the act of erosion or wear

Other

Other	A generic change in emission from a fault or flow

Performance

Change in performance	A loss in the item that manifests by changing a measured performance variable