

What is supportability and how does it relate to reliability?

You can't sprinkle it on later ...



WORKBOOK

Presented by

Dr Chris Jackson

Reliability engineer

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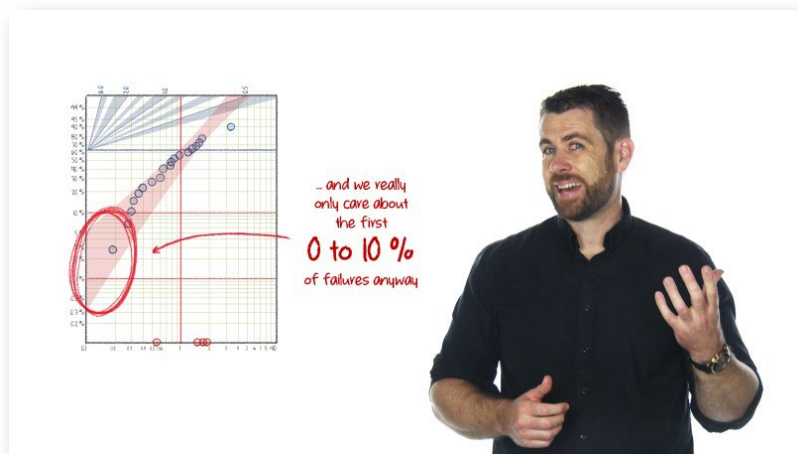
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Who is your teacher? ... Dr Chris Jackson

Dr Jackson holds a Ph.D. and MSc in Reliability Engineering from the University of Maryland's Center of Risk and Reliability. He also holds a BE in Mechanical Engineering, a Masters of Military Science from the Australian National University (ANU) and has substantial experience in the field of leadership, management, risk, reliability and maintainability. He is a Certified Reliability Engineer (CRE) through the American Society of Quality (ASQ) and a Chartered Professional Engineer (CPEng) through Engineers Australia.

Dr Jackson is the cofounder of is4 online learning, was the inaugural director of the University of California, Los Angeles (UCLA's) Center of Reliability and Resilience Engineering and the founder of its Center for the Safety and Reliability of Autonomous Systems (SARAS). He has had an extensive career as a Senior Reliability Engineer in the Australian Defence Force, and is the Director of Acuitas Reliability Pty Ltd.

He has supported many complex and material systems develop their reliability performance and assisted in providing reliability management frameworks that support business outcomes (that is, make more money). He has been a reliability management consultant to many companies across industries ranging from medical devices to small satellites. He has also led initiatives in complementary fields such as systems engineering and performance-based management frameworks (PBMFs). He is the author of two reliability engineering books, co-author of another, and has authored several journal articles and conference papers.



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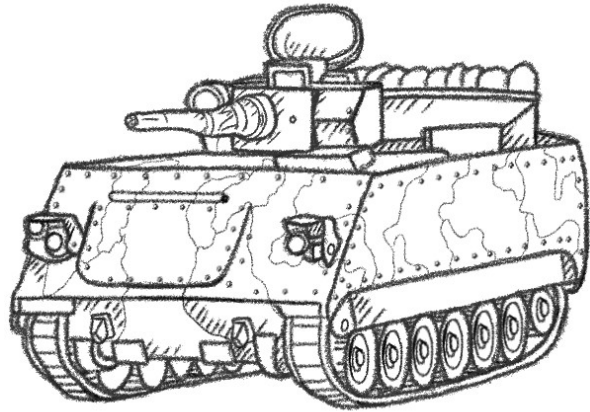
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There was once an armored vehicle (much like the one on the right) which underwent an upgrade. Several features were added. New weaponry was fitted. Engines were replaced.



And ... the 'belly plate' was welded shut to provide additional protection against chemical attack.

What is a 'belly plate?' It is a removable plate underneath the armored vehicle hull that allows maintainers to access the engine and transmission during maintenance.

This is really helpful for doing things like draining and changing oil. But of course, this was no longer possible after the belly plate was welded shut. Which now meant

The entire engine had to be removed to CHANGE THE OIL.

The team leading the upgrades forgot about *maintainability*. They missed an opportunity to install things like an 'oil pump' to allow oil to be drained AFTER the belly plate was welded shut. And every oil change meant untold amounts of damage being caused by having to remove the engine using a crane ... something it is not supposed to happen all the time.

But this was not the only opportunity missed. The military customer (in this case) was also unwilling to prioritize failure. They said that ...

... every failure is EQUALLY IMPORTANT.

The problem with this is that if each failure es equally important,

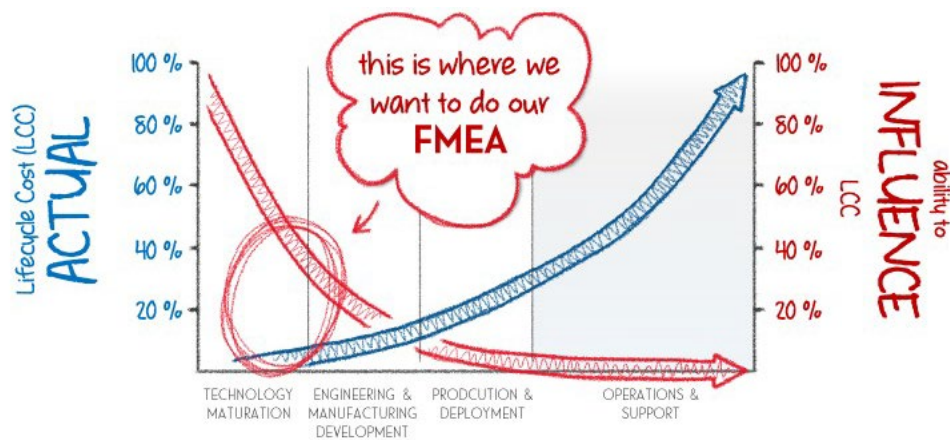
... then NO FAILURE IS IMPORTANT.

This meant that the (re)design team considered and then rejected a 'derating device' that would automatically limit the engine RPM should it detect things like radiator damage (which often happens in battle). Derating would limit top speed - BUT allow the mission to be completed. Instead, small amounts of radiator damage could lead to complete engine failure.

This is because the military customer said 'engine failure' is just as bad as 'reduced top speed.'

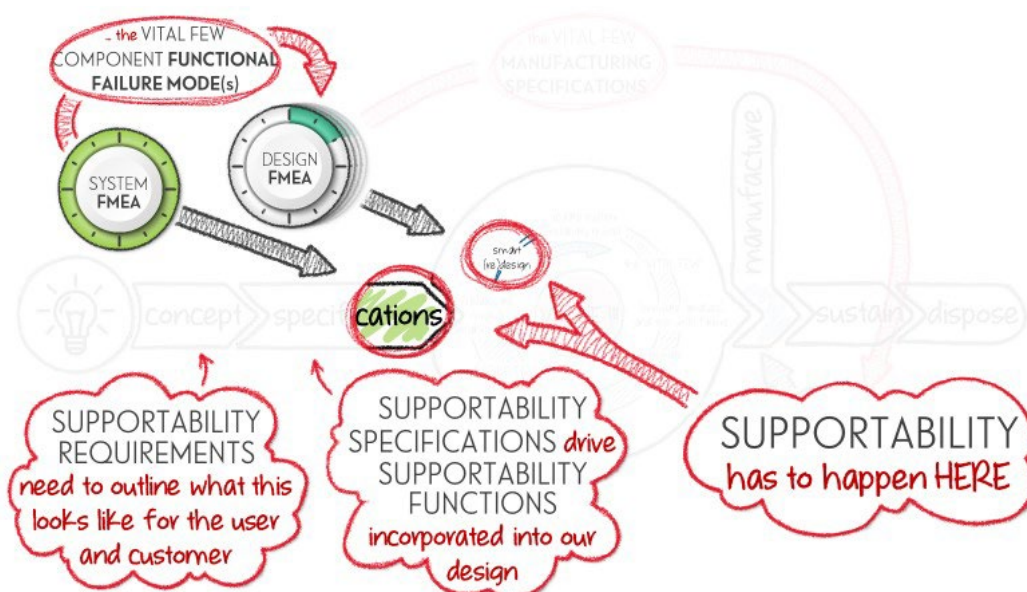
*SUPPORTABILITY is a design characteristic.
Therefore, it only happens if we design it into the system.*

We know that **Lifecycle Costs (LCCs)** are largely determined during design. For example, 90 % of future LCC of military equipment will be determined (and unable to be changed) by the time we have completed Engineering & Manufacturing Development (EMD).¹



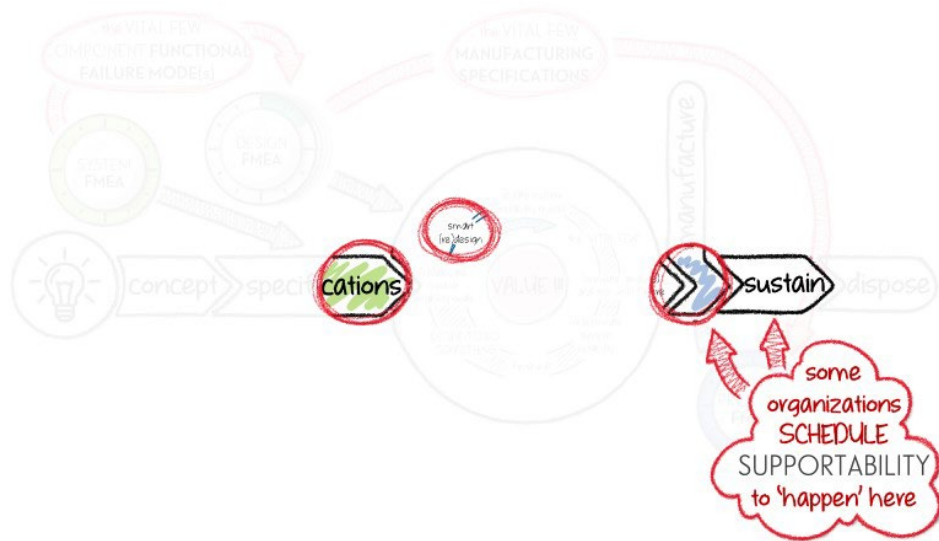
Conversely, only 20 – 40 % of all our **LCC** are spent before Operations and Support (O&S). Because **FMEAs** and **FMECAs** are design tools that influence design characteristics like **supportability**, we need to do them when we can actually implement their **corrective actions**.

Remember that system **FMEAs** and **FMECAs** can help us prioritize effort (reliability and other design stuff), design **FMEAs** and **FMECAs** help us improve the design, and process **FMEAs** and **FMECAs** make sure we manufacture parts with high quality so that we don't lose all that hard earned **reliability**. This means that **supportability** needs to be baked into our **requirements**, which means we have **supportability functions** included in our **specifications**. This allows our **FMEA** and **FMECA** teams to 'bake' supportability into our system by firstly examining the **supportability functions** AND (perhaps most importantly) ensuring that **corrective actions** align with the 'supportability strategy.'

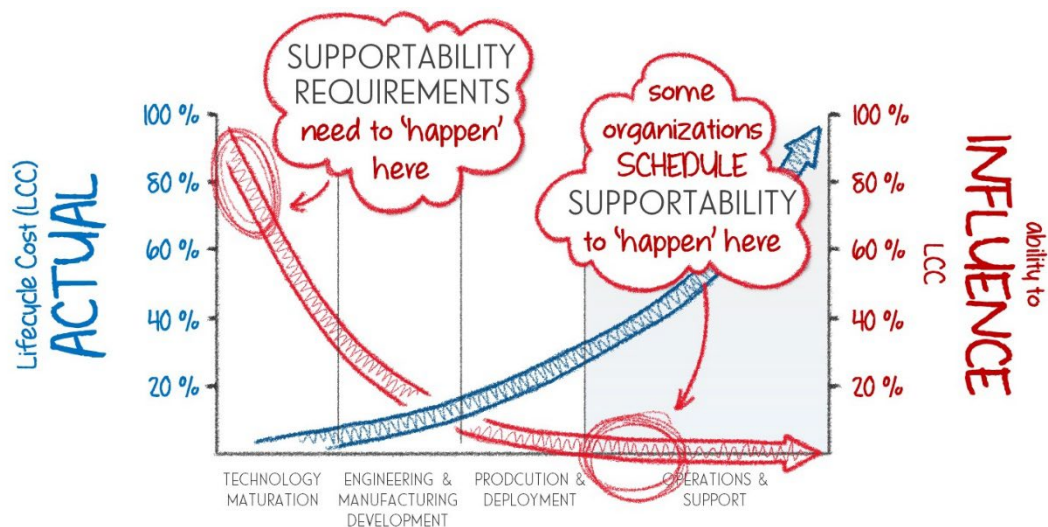


¹ Kathy Carnell – Defense Acquisition University (18 June 2020)

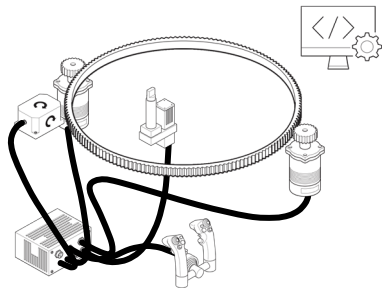
Many organizations only start considering things like **supportability** when it is too late, perhaps by thinking that a **Reliability Centered Maintenance (RCM)** activity is the only thing that needs to be done to 'bake' **supportability** into our product, system or service.



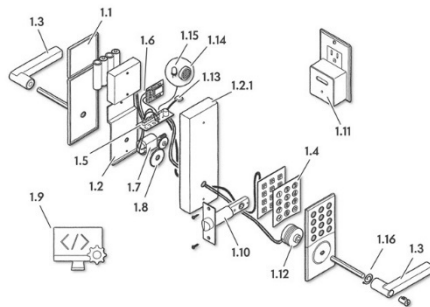
In most cases it is not possible to (for example) incorporate **RCM** recommendations like creating a **Built in Test (BIT)** to help identify engine and transmission faults ... after the design of a military armoured vehicle has been finalized. Even if it is 'technically' possible, it might not be economically (or bureaucratically) possible.



EXERCISE



Describe a 'high-level' SUPPORTABILITY requirement for the TPS.



Describe a 'high-level' SUPPORTABILITY requirement for the smart lock.

so what is SUPPORTABILITY?

Supportability ... is not well defined. It is often seen as a 'militaristic' concept and therefore not relevant to many commercial applications. *This is not the case.* Think of **customer support**. Virtually every product, system or service needs to be able to help users or customers resolve issues – often remotely or virtually. This means **supportability** (or however your organization defines it) needs to be a consideration at every step of the design and manufacture process.

Supportability refers to the inherent characteristics of a product, system or service and the enabling system elements that allow effective and efficient sustainment (including maintenance and other support functions) throughout the system's life cycle.² **Supportability** obviously helps drive down LCC, reduce logistics infrastructure (and footprints) and increases **Operational Availability (Ao)** by minimizing downtime. Most militaries consider supportability to have nine key elements which offer a good framework for most applications:³

Manpower and Personnel. Specifically support personnel for installation, checkout sustaining support and maintenance.

Training and Training Support. For the system operators and maintenance personnel.

Supply Support. Including repairable and non-repairable spares, consumables and special supplies.

Support Equipment. Including tools, condition and state monitoring, diagnostic and checkout special test and calibration equipment.

Computer Resources. Operating systems and software supporting logistics functions and associated infrastructure.

Packaging, Handling, Storage and Transportation. Special provisions, containers and transportation needs.

Facilities and Infrastructure. Including facilities to support logistics and sustainment actions at all levels.

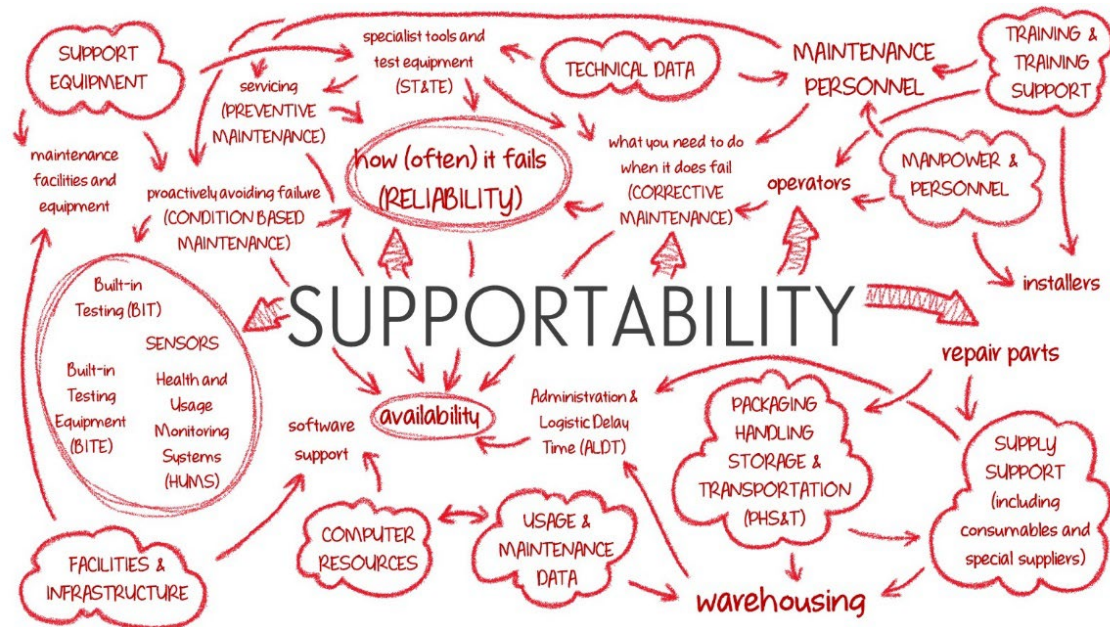
Technical Data. Including system installation and checkout procedures; operating and maintenance instructions and records; alteration and modification instructions, etc.

Usage and Maintenance Data. Including data acquisition, movement, storage and analytic capability to support life-cycle support decisions.

² Defense Acquisition University (DAU) Systems Engineering (SE) Brainbook, <https://www.dau.edu/tools/se-brainbook/Pages/Design%20Considerations/Supportability.aspx> (accessed 4th June 2021)

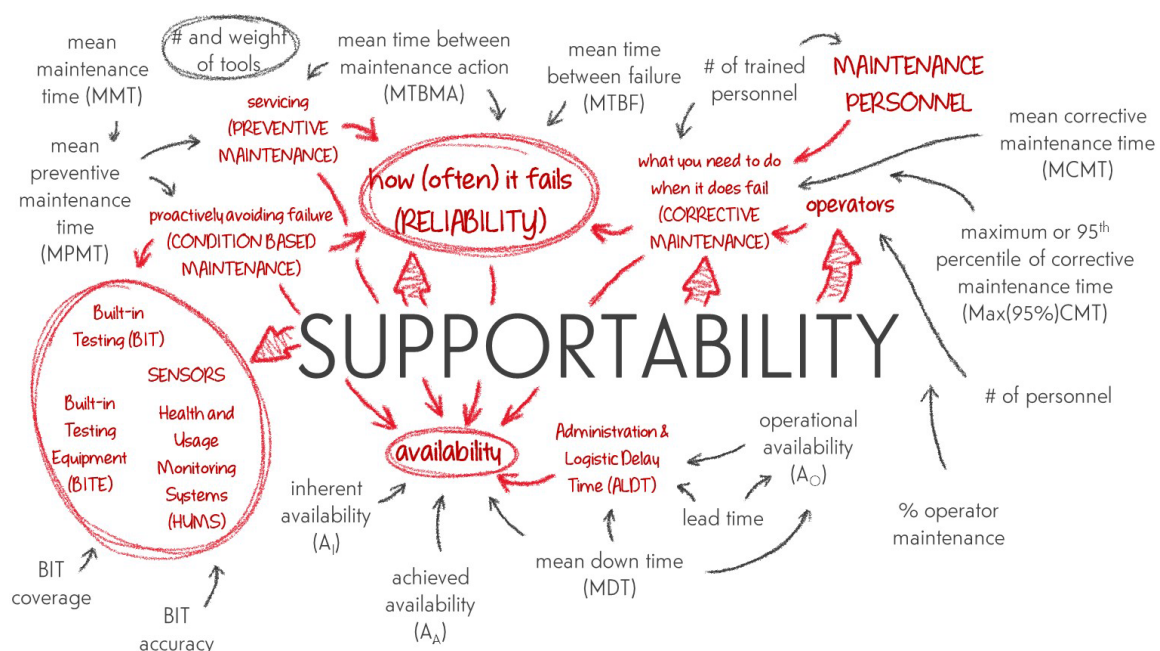
³ Defense Acquisition University (DAU) Systems Engineering (SE) Brainbook, <https://www.dau.edu/tools/se-brainbook/Pages/Design%20Considerations/Supportability.aspx> (accessed 4th June 2021)

While not explicitly stated in these nine key elements, **Reliability, availability and maintainability (RAM)** are perhaps the most important underlying design characteristics for **supportability**. The reality is that supportability means completely different things depending on context, technologies involved, criticality of spare parts, the qualifications required from those supporting the product, system or service, and lots of other factors.



Reliability dictates how often our 'thing' will fail (and require us to do something about it). **Maintainability** dictates how long our 'thing' will be non-operational for each failure event. And **availability** takes into consideration, reliability, maintainability, and in many cases the **Administration and Logistic Delay Time (ALDT)** it takes for things like the resupply of spare parts.

So the **RAM metrics** that matter depend on which aspects of supportability matter to your organization.



So why are these RAM metrics so important?

*Because they help you define the SUPPORTABILITY FUNCTIONS
in your SPECIFICATIONS.*

There are different types of functions that make supportability happen. Examples are listed below.

1. The ability to **predict failure by advising the operator the Residual Useful Life (RUL)** of specific components and parts. This allows us to proactively schedule maintenance action to both prevent failure but also ensure we don't discard components and parts that will still operate for a considerable amount of time.

The ability to **warn about failure** that allows us to prevent failure. Early warning is not as useful as prediction based on RUL as we do not have as much lead time for failure, but warning certainly allows us to not have to endure failure.

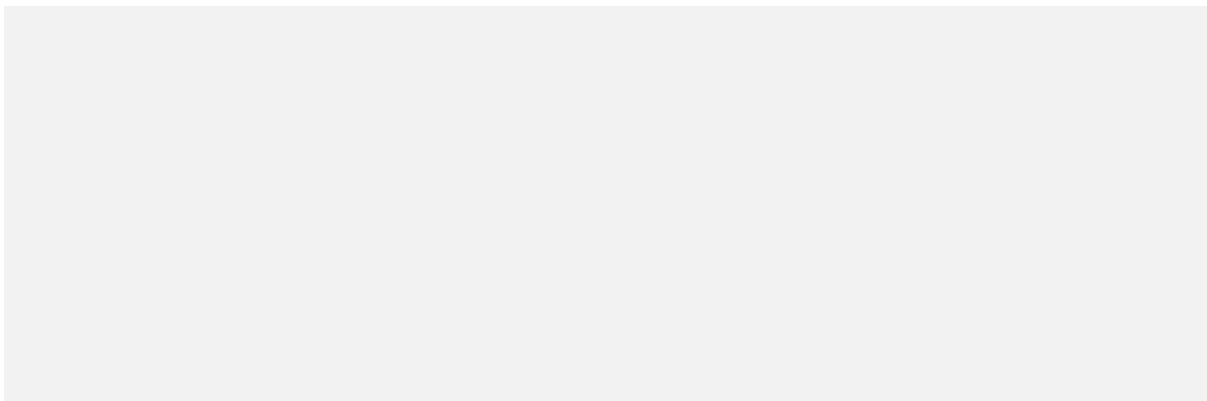
The ability to **prevent failure** through understanding the typical useful life of components and parts and creating servicing intervals that will likely allow us to remove or reconstitute these components and parts before failure. Because we are conducting maintenance based on intervals of usage (like 10 000 miles, 6 months et cetera) there are substantial uncertainties involved. This means we may conservatively underestimate intervals to minimize the probability of failure, but at the price of us discarding components and parts that might not fail immediately.

The ability to **diagnose failure** using things like Built in Test Equipment (BITE) to immediately inform maintenance personnel what parts, tools, and supporting equipment is needed to quickly conduct maintenance.

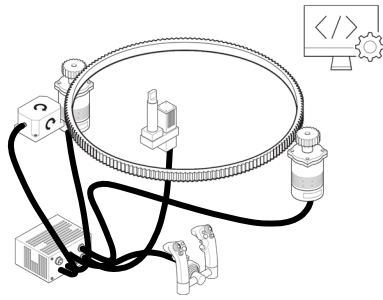
The ability to **mitigate faults** by using things like 'derating devices' to automatically modify operation to ensure that faults do not propagate further or allow additional damage to occur.

The ability to **easily rectify failure** by making sure that the components and parts that are most likely to fail are the easiest to access and remove (along with many other design ideas that make maintenance easier).

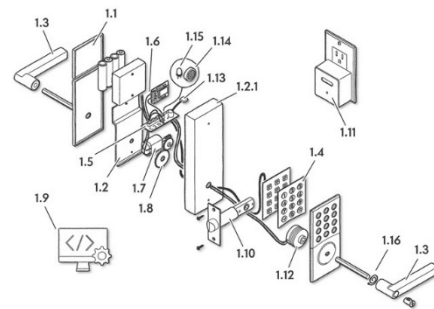
The ability to **communicate maintenance information** and materiel states to maintenance personnel to allow them to manage maintenance resources more easily.



EXERCISE



What sort of **SUPPORTABILITY FUNCTIONS** support your **TPS SUPPORTABILITY REQUIREMENT(S)** (... remembering that these can be measured in terms of **RAM metrics**)?



What sort of **SUPPORTABILITY FUNCTIONS** support your **smart lock SUPPORTABILITY REQUIREMENT(S)** (... remembering that these can be measured in terms of **RAM metrics**)?

so how do we make SUPPORTABILITY happen?

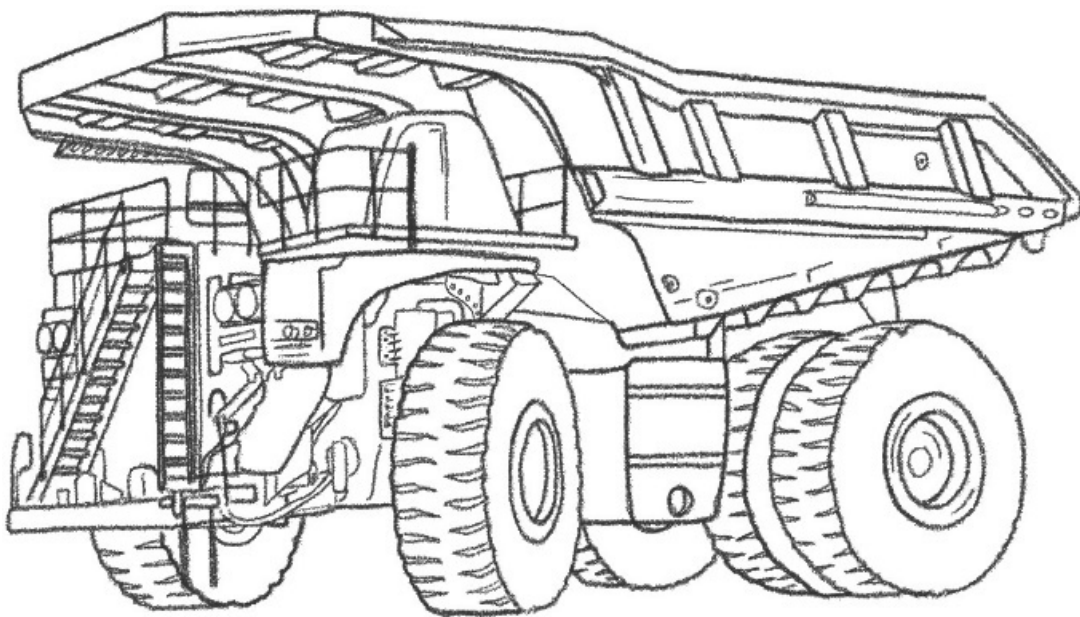
*Supportability MUST be a SYSTEM PERFORMANCE REQUIREMENT.*⁴

*Supportability requirements will define SUPPORTABILITY FUNCTIONS
(remembering that functions are behaviors, processes, actions or tasks).*

FMEAs and **FMECAs** are fantastic design tools. They are also fantastic for designing in **supportability** through **corrective actions**. **Supportability** is often 'principally' based on dealing with failures. This can be through activities that prevent failures like scheduled servicing or **preventive maintenance (PM)** and **Condition Based Maintenance (CBM)**. And of course, **supportability** is also based on dealing with failures by virtue of how many people we need, how many spare parts we need to have in stock and so on.

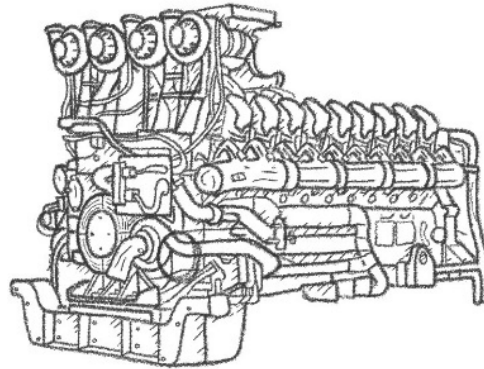
Which mean we need to know HOW something fails to be able to work out how to support it. We can only prevent 'wear out' failures – because these are the only ones that involve **failure mechanisms** that **accumulate damage**. If we want to place sensors on an engine to try and predict **RUL**, we need to know the physics of that **failure mechanism**. **FMEAs** and **FMECAs** can identify which **failure mechanism** applies to which **failure mode**. Meaning we can create a tailored **supportability function**.

This mining truck is REALLY big. It has a 400-tonne payload. It will likely be driven 'non-stop' with driver shifts making sure as much mineral ore as possible can be processed every hour. And because of the value of this processing, mining companies are willing to spend \$ USD 5 – 6 million on each truck. They are *incredibly* important.



⁴ Military Handbook (MIL-HDBK) 502A Product Support Analysis (PSA) requires for all military equipment that *supportability needs to be included as a system performance requirement*.

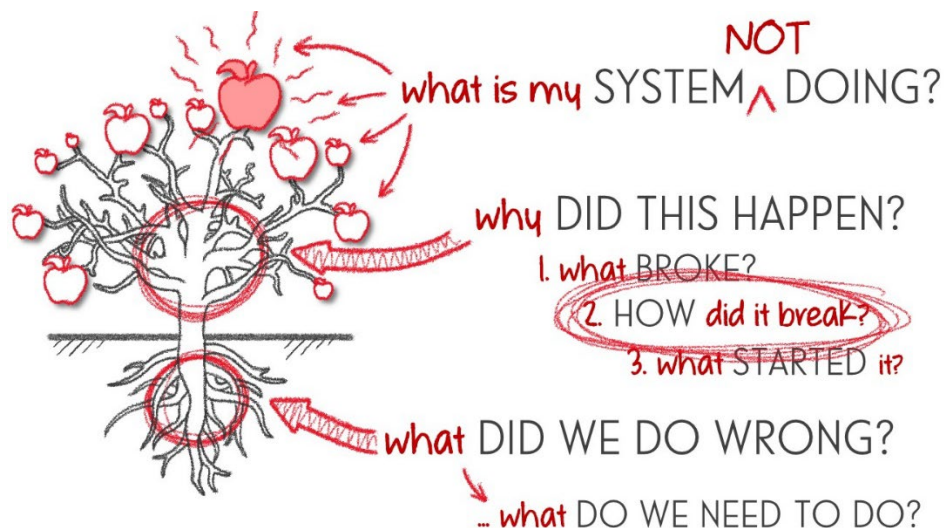
Mining can occur in very remote regions across the world. This means that it can be very difficult to ship repair parts to mine sites. They will often need to be transported 'en masse' using infrequent but large resupply runs. We might need to always have several spare 20-cylinder engines for our mining truck on site. But these engines have their own challenges. They can cost \$ USD 700 – 800 thousand each. They can also deteriorate if they are left 'on the shelf' for a long time.



So how many spare engines do I need. Specifically ...

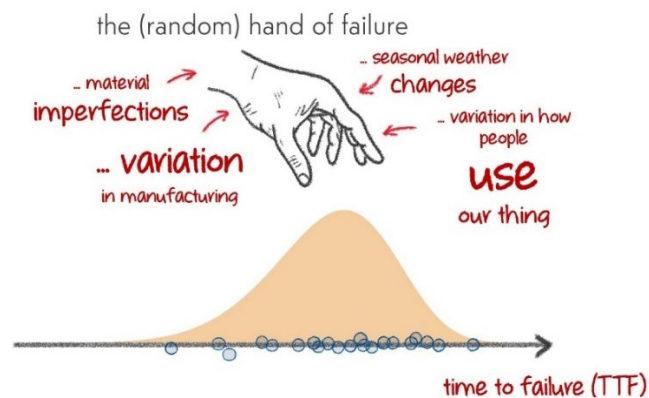
... how many spare engines do I need to support a single truck for 3 years?

To answer this question, we need to go through our TREE OF FAILURE for the engine to understand 'how it will break.'

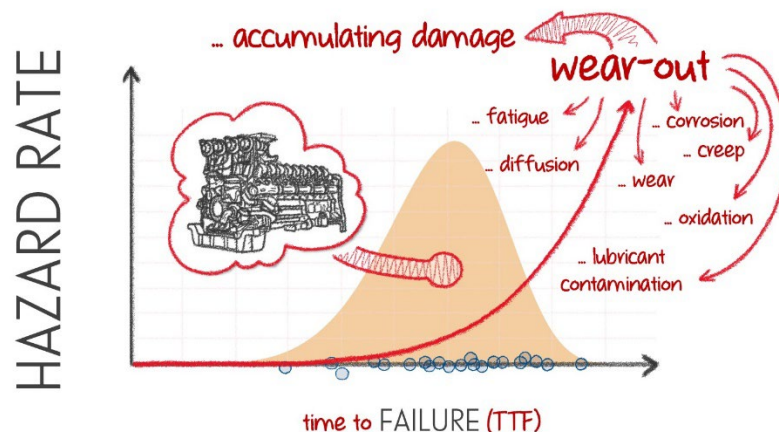


The answer to this question will be a number of FAILURE MECHANISMS (... the physical, chemical, electrical, thermal or other processes which results in failure.) Now the engine is very complex, meaning that there are lots of different FAILURE MECHANISMS. However, there will often be a small number of 'dominant' failure mechanisms that drive reliability characteristics. And – it is not uncommon for them to all behave in a similar way ... particularly if our engine WEARS OUT or accumulates damage.

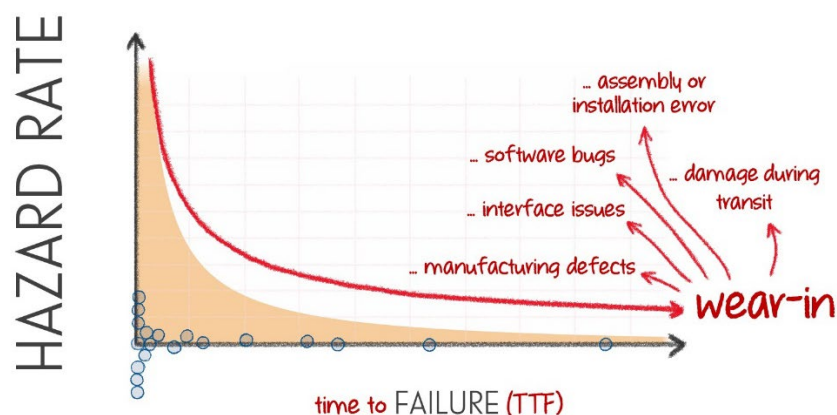
Even a rudimentary investigation into the reliability of our engine should be able to confirm some of its underlying **FAILURE MECHANISMS** and how they behave. In this case, our engine wears out with an increasing **HAZARD RATE**. And this means that the Time to Failure (TTF) for our engine will tend to cluster around a central or typical value. If we have enough TTF data points, we could (hypothetically) create a smooth 'bell curve' that represents the likelihood of specific TTFs for specific engines. So if you ever see a 'bell curve' describe the TTF of anything, we know that it is wearing out.



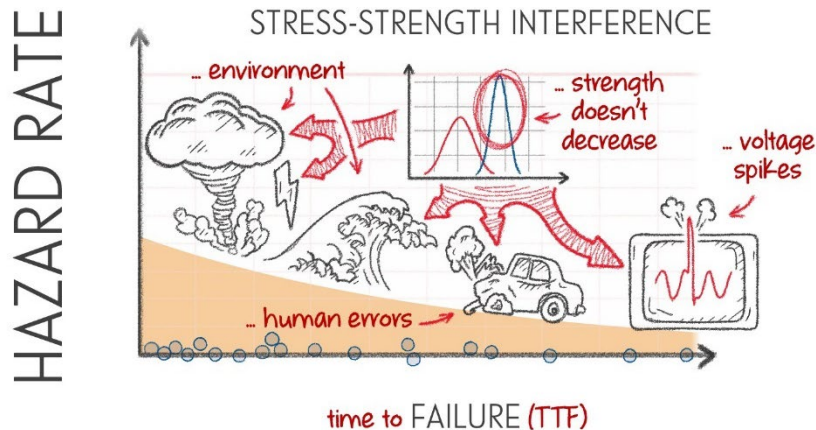
And so we know our engine has an increasing hazard rate based on the accumulation of damage.



The opposite of **WEAR OUT** is **WEAR IN**. This is **NOT** what is happening with our engine.



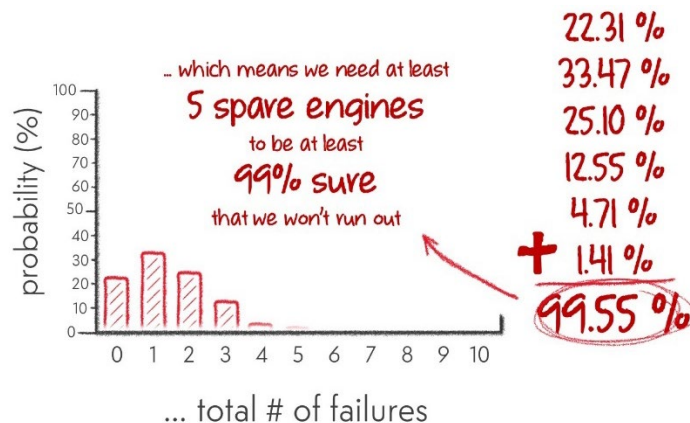
Then there are failures that occur at a **CONSTANT HAZARD RATE**.



These are based on external, randomly occurring external stresses that when they do occur, cause catastrophic failure. This essentially means our thing **NEVER GETS OLD** as age doesn't matter for these external stresses. **THIS IS NOW WHAT IS HAPPENING FOR OUR ENGINE.**

Even though our engine is not failing at a **CONSTANT HAZARD RATE**, many textbooks and standards will essentially require you to act as if it does. This is often because the **CONSTANT HAZARD RATE** model is mathematically simple ... and therefore more convenient

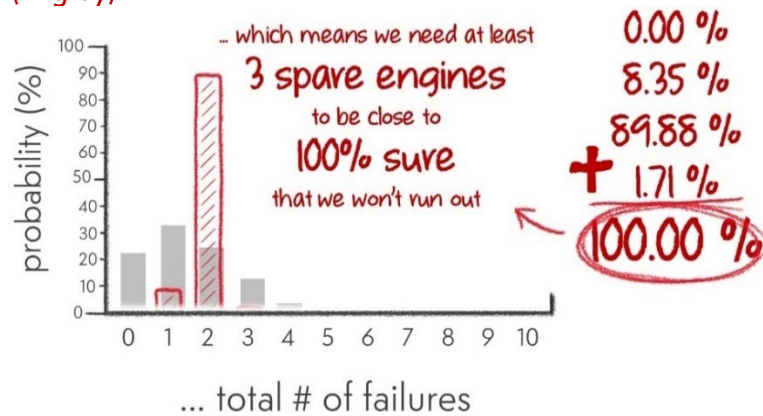
If we do assume a constant hazard rate, we can use what is called the 'Poisson distribution' to understand that probability of different numbers of engine failures occurring over a specific interval. For example, let's say that we know our engine has a 2 year Mean Time Between Failure (MTBF). This means we expect 1.5 failures to occur over three years. The corresponding Poisson distribution is illustrated below. It tells us that there is a 22.31 % chance of have **ZERO FAILURES** in our three year period, a 33.47 % chance of having **ONE FAILURE** in our three year period and so on.



So if we want to be at least 99 % sure of having enough engines to support our truck over a three year period, we need to have 5 spares.

But as we all know, engines wear-out. And even though failure is a random process, we know that our engine will fail in predictable ways. And this is not with a **CONSTANT HAZARD RATE**

Let's instead NOT use a Poisson distribution, but conduct a more sophisticated analysis based on the actual HAZARD RATE of the engine.⁵ This allows us to model the number of failures we expect in our three year period. The results are compared with the Poisson distribution approach below (in gray).

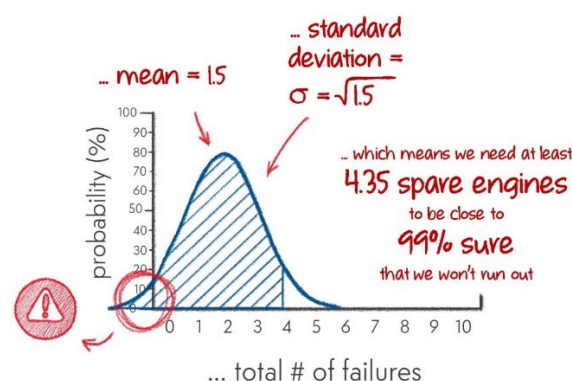


And when we do this, we can work out that we only need 3 spare engines to be (almost) 100 % certain that we will have enough to cover our three year period.

So when we study the nature of failure, we save ourselves two very expensive engines (with a combined total of \$ USD 1.4 to 1.6 million) from sitting on our shelves and likely deteriorating to an extent that we can't use them anymore.

But there are many more ways of BEING DUMB when it comes to supportability.

Another popular approach to spare parts analysis that appears in many textbooks is NORMAL DISTRIBUTION APPROXIMATION. Instead of using the Poisson distribution to estimate the probabilities of specific numbers of failures occurring, a normal distribution bell curve is used to approximate the Poisson distribution (compounding existing inaccuracies). Which gives us this 'bell curve' below. It extends below zero, which implies it is possible to have less than zero failures! It also tells us that we need to have 4.35 spare engines to be 99 % certain of us having enough spare engines for a three year period (... we can only have 4 spare engines, 5 spare engines, but not 4.35). But again, we still see this approach in many textbooks to this day.



⁵ Note that a full explanation of this process is outside the scope of this guidebook and accompanying course, but is included in other guidebooks and courses provided by www.acuifas.com.

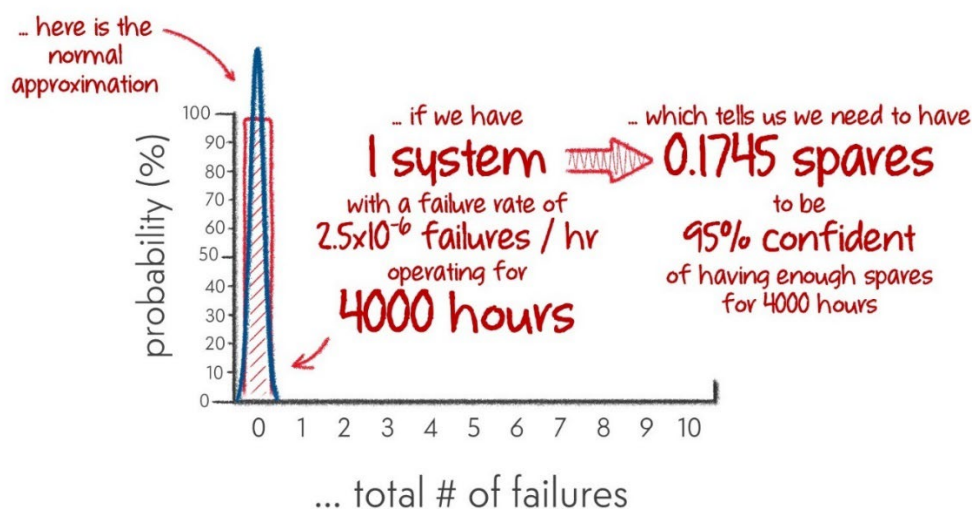
The equation that is used for this normal distribution approximation (just so you can avoid using it) is illustrated below.

$$\begin{array}{c} \text{... failure rate} \quad \text{# of spares} \quad \text{... interval} \\ = \lambda t + z_{CL} \sqrt{\lambda t} \\ \text{... standard normal variable} \quad \text{... for this level of confidence} \end{array}$$

But there is an even dumber approach to spare parts analysis than this!

Let's say you have a fleet of equipment. There is a massive benefit in this. The bigger the fleet, the smaller the proportion of spare parts you need. So what you don't want to do is look at your FLEET of equipment as set of NUMEROUS INDIVIDUAL PIECES OF EQUIPMENT.

Let's say we have a fleet of 150 machines. Each machine has a failure rate of 2.5×10^{-6} failures per hour. And we are interested in having enough spares to last 4000 hours. Now let's again use that horrible normal distribution approximation that we looked at above. This gives us the graph on the following page.



If we multiply 0.1745 by the total number of machines, we get around 27. This seemingly means that we need to have 27 spares to be 95 % confident of having enough to get us through 4 000 hours of operation.

But when we look at the fleet as a whole and use the same approach as above, it turns out we only need 4 spares to be 95 % confident of having enough to get us through 4 000 hours of operation.

Being dumb is expensive!

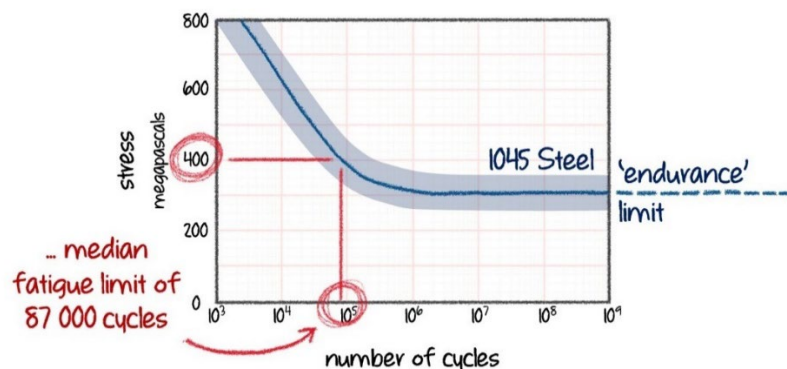
SMART MAINTENANCE means you know the FAILURE MECHANISMS

Most maintenance strategies are based on **wear-out failure mechanisms**. We have already looked at some. They all involve the accumulation of damage. This implies there is a chance for us to do something about our ageing component and part before it accumulates enough damage to cause **failure**.

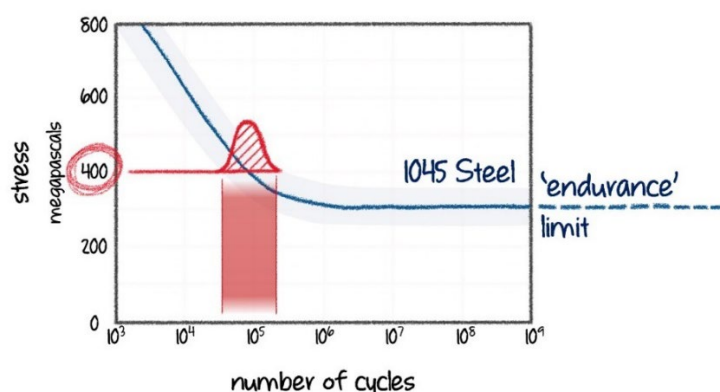
EXERCISE

Fatigue cracks grow slowly over time. They occur whenever there are repeated cyclic stresses. This involves compression and tension forces being applied to our product or system over and over. Each cycle makes the tip of our crack grow slightly. Eventually, the crack can become so large that our product or system fails.

We know fatigue characteristics for many metals. The 'S-N chart' for 1045 steel is illustrated below. 'S' represents the stress of each cycle. 'N' represents the number of cycles. We can use the 'S-N' chart to help us understand how many cycles our steel can endure at specific stresses before it will fail.



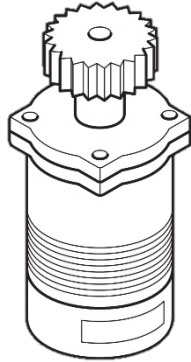
Steel has an 'endurance limit' which is a stress below which fatigue cracks will not grow. But there are uncertainties. Even though we might be able to use our 'S-N chart' to understand roughly how many cycles it will take before our 1045 steel fails, we need to incorporate the inherent uncertainty using the red 'number of cycles to failure density' curve below. And because fatigue involves wear-out, we see a classic bell curve.



EXERCISE

So let's say the shaft of the rotary gear drive of the TPS is made out of 1045 steel, and that preliminary analysis suggests that it is going to be exposed to cyclic stresses of 400 MPa. Rotary components are 'classic' fatigue cases as the rotation means that all parts of a shaft (for example) are routinely compressed and stressed as they impart torque on to another component.

Why is fatigue a 'wear-out' failure mechanism for the rotary gear drive shaft?



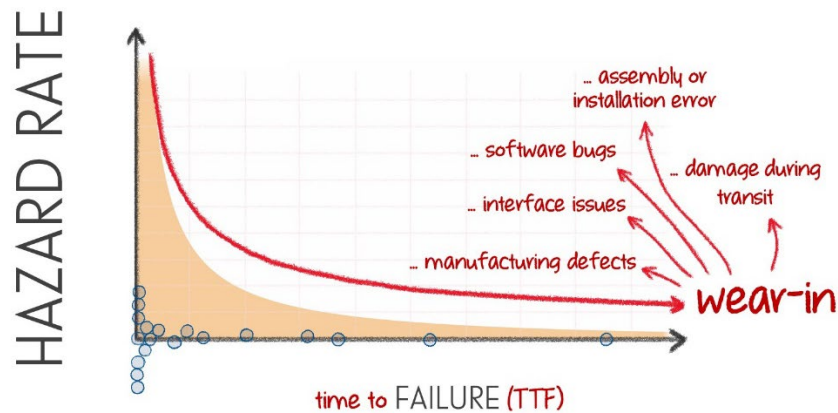
Condition Based Maintenance (CBM) involves maintenance based on 'sensors' or 'triggers' that maintenance staff will use to dictate when proactive maintenance is conducted.

What 'predictive' or Condition Based Maintenance (CBM) action MIGHT work for the rotary drive shaft?

What Preventive Maintenance (PM) action MIGHT work for the rotary drive shaft? ... on what interval?

Which approach would you suggest? Factors include the consistency of the stress, understanding cycles, PREDICTING versus WARNING.

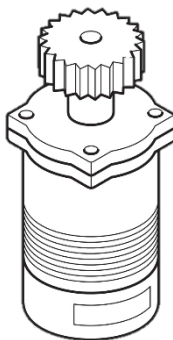
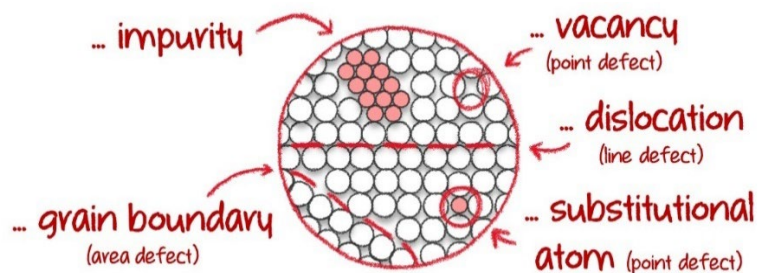
The opposite to **wear-out failure mechanisms** are those that **wear-in**. These **failure mechanisms** are usually caused by defects, flaws and anomalies that appear in only a fraction of your products, systems or services.



These sorts of **failures** usually involve maintenance that only repairs the product, system or service but removes the defect or flaw. So over time, reliability appears to increase.

EXERCISE

Let's say that FMEA or FMECA identifies that there is a **CHANCE** that A **FRACTION** of rotary gear drive shafts will have **MANUFACTURING DEFECTS**.

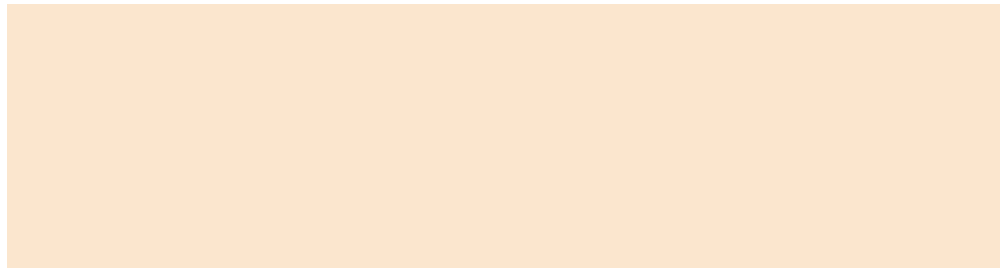


If these defects start (**HIGHLY ACCELERATED**) fatigue cracking, is this still wear-out or is it now wear-in?

What preventive or predictive maintenance action would you recommend for fatigue cracks caused by **MANUFACTURING DEFECTS**?

EXERCISE

What WORDS need to appear in the ROOT CAUSE STATEMENT on the relevant FMECA to be able identify the right maintenance action?



you can't make your product SUPPORTABLE after you have designed it

Whether it is a smart lock where it would be really useful for a customer support representative to be able to 'log in' and remotely interrogate it, or a TPS where it would be useful to monitor the cycles and stresses your rotary drive shaft experiences, you cannot make something **supportable** after it has been designed.

Coming up with a support plan is based on supportability.

A support plan doesn't improve supportability.

And because **supportability** often revolves around preventing and correcting **failures**, **FMEAs** and **FMECAs** are incredibly helpful for coming up with a **supportable** design. This can be through getting your **supportability functions** right AND using **corrective actions** that align with your **supportability requirements**.

