LTS Keeps Products Safely in the Air with Reduced Operational Cost

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ABSTRACT

The GKN Life Tracking System (LTS) for the RM12 Engine – powering the Gripen Multi-Role Fighter – has been in operational use for more than 10 years bringing value to the fighter in terms of lower life-cycle costs, increased operational flexibility and increased flight safety. It does so by tracking chosen properties for each individual component of the chosen part numbers, i.e., each individual piece of hardware has an individual life consumption built on data from every mission or dry run since the outset of the Gripen Program. We use the framework for Digital Twins presented by Grieves (Grieves M., 2023) to assess the maturity of the LTS as a Digital Twin, concluding that on the one through four scale it is in the top two tiers depending on interpretation. As technically challenging as bringing a tool as the LTS to an operational level where GKN constantly update the customers system with new data, we argue that the key factor is the access to and the quality assurance of data over time. The services GKN provides today builds on data going all the way back to start of the program, and importantly, it builds upon very smart decisions made four decades ago regarding information and data models. LTS as a system is constantly evolving. Being highly modular enables that better methods and tools can be introduced to enhance the accuracy of each "digital twin" in its replication of its real-world sibling.

1.0 INTRODUCTION

The traditional approach for calculating life consumption for life limited parts in jet engines are based upon one or very few engine parameters. Parts in the engines should be replaced when reaching certain life limits, as defined in the maintenance plan, these limits can for example be number of flight hours, number of flight cycles (engine start, climb, cruise, landing and shutdown), or formula-based on some accumulated engine parameters. All these life limits are however defined based upon a pre-defined and intended usage of the jet engine, for fighters this pre-defined usage is often defined as a mission mix which represents typical missions; it contains a set of and assumed distribution of different missions which should reflect the actual usage of the engine. However, it is known that actual utilization of the engines on an individual basis, especially for a military application, deviates from this pre-defined mission mix as a rule rather than the exception. For example, the intended distribution between air-to-air, air-to-surface, reconnaissance missions etc. does not fully correspond to what the individual parts in a specific engine actually have been exposed to. GKN's Life Tracking System (LTS) is a system to accurately calculate the fatigue life consumption on life limited parts. In its life consumption calculations, it communicates with the customer's maintenance system and utilizes more of the time-resolved on-board logged engine parameters in combination with off-board models. By doing so the accuracy of the life predictions are improved by reducing one of the biggest uncertainties in the life analysis chain, the uncertainty of the actual loads. Moreover, this gives a tailored result for each individual engine and its installed parts. It equals to analyzing the effect on the parts when re-flying your mission with your "digital twin engine". By having access to all this information LTS also allows the possibility to retroactively recalculate life consumption for historical flights/missions, in case new knowledge is gained (e.g., new methods, refined models, updated material data etc.).

The application as of today is the RM12 engine, a low-bypass afterburning turbofan jet engine which is a derivative of the GE F404 turbofan engine. The F404 was originally developed for the U.S. Navy and its Boeing F/A-18 Hornet. RM12 is a joint GE and GKN (formerly Volvo Aero Corporation) developed engine with special adaptations for a single engine installation, such as redesigned fan, Full Authority Digital Electronic Control (FADEC) with hydro mechanical backup, redundant ignition system, improved main fuel pump for increased reliability to mention some of the adaptations. RM12 powers the JAS39 Gripen Multi-Role Fighter currently in service with the Air Forces of Sweden, the Czech Republic, Hungary, Thailand, and South Africa.

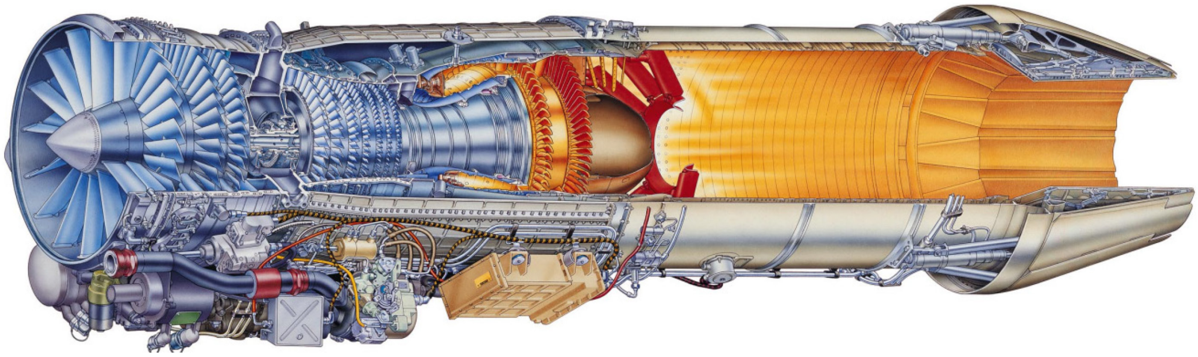

Figure 1: RM12 engine, cross-section illustration.

2.0 GKN LIFE TRACKING SYSTEM (LTS) – ITS RATIONALE

This chapter presents an overview of:

1) the problem set of managing the life of parts in a jet engine and how this have been done traditionally;
2) How it is now handled by means of the LTS system; and
3) Presenting the benefits of the LTS approach.

Granted, this section is deeply technical, but we made the active decision to give interested readers the possibility to understand the core problem to solve. A caveat is that some parts of the LTS system as presented in Section 3.2 are somewhat simplified for reasons of protecting IP as well as not revealing sensitive information. All readers should however benefit from the descriptions.

2.1 Traditional Approach for Calculating Life Consumption

It is important to track the used/consumed life of components in the engine in order to ensure flight safety and to be able to perform component replacements before they have reached their life limits. When parts in a jet engine are exposed to repeating loads, such as thermal or mechanical loads, it will fatigue the material in the part, this fatigue could cause cracks in the parts and the cracks could grow and eventually lead to a fracture, for rotating parts in a single engine installation it could lead to catastrophic consequences. Components in RM12 needs to be replaced when reaching their predefined life limits but components can also be replaced due to inspection findings, “on condition”.

The life limits are defined based upon the work performed by the RM12 Life Management Program running at GKN which continuously are working on improving the life calculation models. The RM12 Life Management Program identifies and models the failure modes, performs stress analysis in order to find the high stress areas, and finally performs life analysis based upon the intended mission mix. The result from this work is an analytical life for a specific part. Though, before this can be included in the maintenance plan an uncertainty analysis is performed. The objective with the uncertainty analysis is to, in a structured way, identify and calculate all distributions and uncertainties in the analysis chain that affect the analytical life.

This is done by:

- Identify all significant scatters and uncertainties in the analysis chain
- Performing a sensitivity study of the effect from each uncertainty of the life prediction
- Add the contributions from every uncertainty
- Calculate a safety factor that needs to be applied to the calculated analytical life

The life limit that goes into the maintenance plan is then the analytical life with a safety factor.

$$Life\ Limit(Maintenance\ plan) = Analytical\ Life \times Safety\ Factor$$

Figure 2: Life limit in maintenance plan, with a safety factor applied in order to take care of uncertainties in the analysis chain.

During operation of RM12 in JAS39 Gripen a number of engine parameters are recorded by the engine in the aircraft.

The traditional model for calculating fatigue life consumption is based upon only using few of these parameters, such as counting number of flight hours or for rotating parts based on Equivalent Low Cycle Fatigue (ELCF). ELCF is a simplified way to represent the damage a component has been exposed to due to changing loads (thermal and mechanical) when the engine is being used. For RM12, ELCF is based upon tracking the variation of the high pressure rotor speed (NH) which is recorded during a mission. These variations are determined by counting the number of times (number of cycles) the high pressure rotor speed goes below and exceeds certain selected and predefined levels.

Figure 3 shows an example how the number of NH-cycles is calculated counting the number of passages (cycles) between the three NH levels, this simplified model could however miss some of the speed cycles if they fail to fulfill the criteria to pass the defined levels, therefore this needs to be taken into account when handling the not known load variations when defining the safety factors associated with the life limits in the maintenance plan.

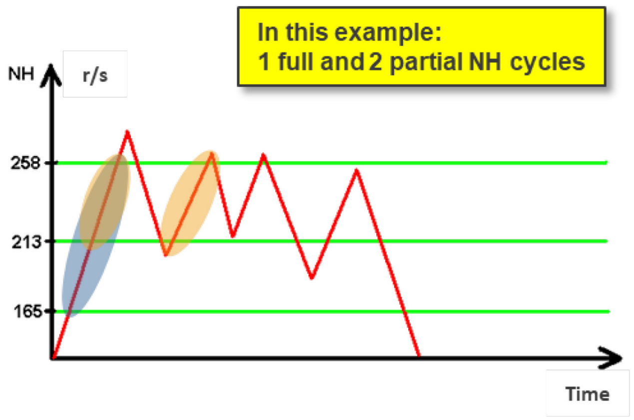

Figure 3: NH-cycle calculation.

To calculate the number of consumed ELCF-cycles the formula in Figure 4 is used. This formula contains KF and KP, which are used as scaling factors on the identified full (NHfull) and partial (NHpart) NH-cycles. These K-factors are analytically calculated in the RM12 Life Management program and are based on the defined operational profile/mission mix. For RM12 this mission mix consists of a distribution between predefined fighter, attack, and reconnaissance missions.

$$ELCF = K_F \times NH_{full} + K_P (NH_{part} - NH_{full})$$

Figure 4: ELCF formula with part number specific scaling factors.

The components should be replaced when the accumulated ELCF value reaches the ELCF limit as defined by RM12 Life Management program in the maintenance plan for the engine. If the engine is not used according to the operational profile, the life tracking of the life limited parts would not be completely accurate.

2.2 Introducing the GKN Life Tracking System (LTS)

Life Tracking System (LTS) is a software developed and operated by GKN Aerospace which enables quite accurate life consumption calculations. This is made possible by having access to the following:

- Engine related parameters measured during each mission, these parameters include time-resolved temperatures, rotor speeds, pressures, altitude, aircraft speed, control mode, power level angle and more.
- Engine models which supplement the measured information from the engines with additional model based information.
- Valid (accurate and approved) life analysis models as developed by the GKN Life Management program.
- Historical and present engine configuration for matching serialized parts with performed missions.

Figure 5 shows how the LTS system interacts with the ground and maintenance systems. A first data reduction takes place in the aircraft by storing data only at the times when it has changed more than one prescribed value for each variable since the previous stored data point. The reduced data is stored by the aircraft's computer. After flight, data is transferred to a ground station where the mission can be analyzed, and engine related parameters are calculated and transferred to the maintenance system. The engine time-resolved related parameters (e.g., Temperatures, rotor speeds, pressures, error codes etc.) are transferred to GKN for analysis. Data from basically all missions carried out since 1992 with RM12 have been transferred to GKN.

LTS then calculates the life consumption for each performed mission, matching it with the installed serialized parts and feeds back the corrected life consumption to the maintenance system. By utilizing more of the measured parameters and more detailed analysis models it is possible to track the consumed part life per mission independently of the need to follow predefined mission profiles (mission mix).

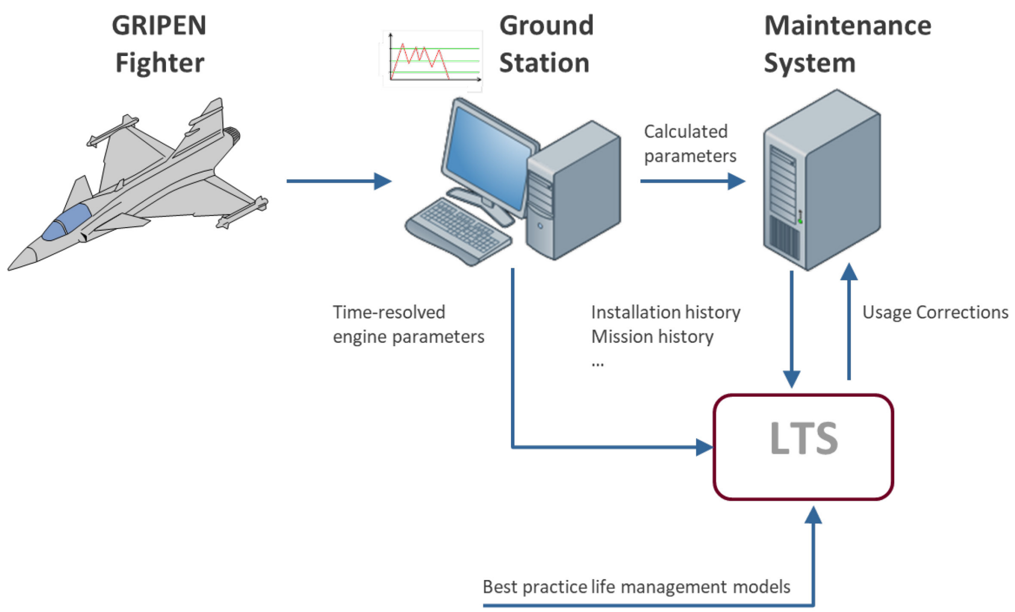

Figure 5: LTS interaction with the ground station and maintenance system.

Figure 6 shows the basic building blocks of the LTS. Pre-processing is where model based data is added, and sensitive information is removed from the time resolved engine mission data. The next block Organize and administer results, matches the engine mission data with the parts that have been installed in the used engine for each mission. This block also communicates with the Life calculation block which calculate the life consumptions for specific missions and life limited serialized parts. Periodically the user's maintenance systems are updated with more accurate life consumptions based on the corrected ELCF-cycles. The updated formula presented in Figure 7 includes a LTScorr term in order to correct the traditionally calculated ELCF-cycles that are based on a mission mix. Traditional ELCF-cycles are used if no engine mission data for the mission is available in LTS.

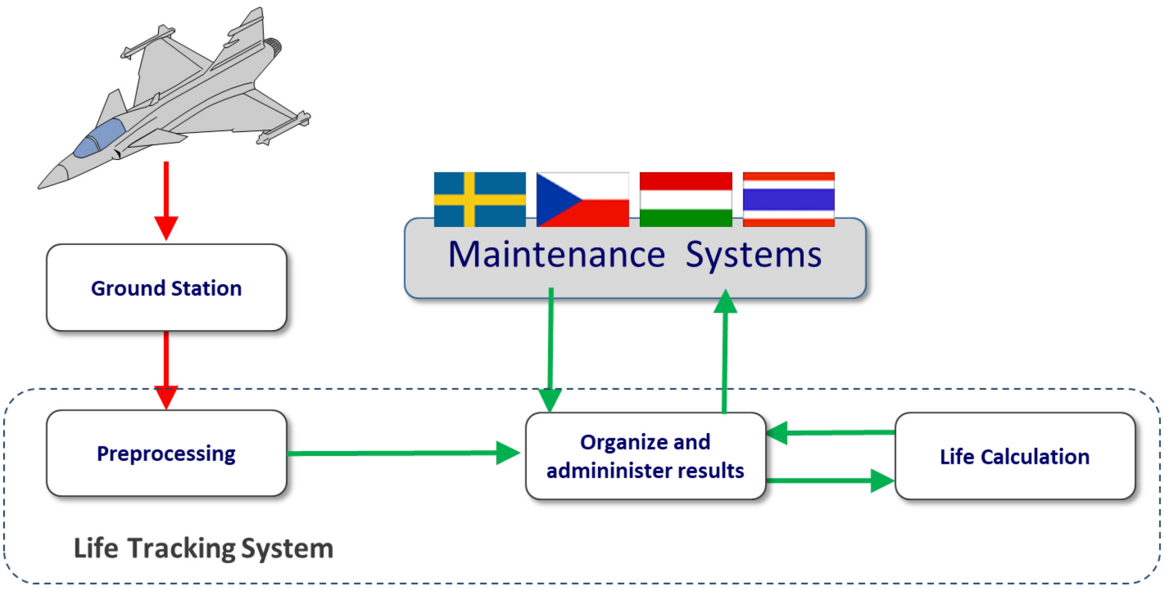

Figure 6: Basic building blocks of LTS.

$$ELCF_{corrected} = K_F \times NH_{full} + K_P\left(NH_{part} - NH_{full}\right) + LTS_{CORR}$$

Figure 7: Updated ELCF formula with part number specific scaling factors and LTS correction added.

2.3 The Effect of Using GKN Life Tracking System (LTS)

LTS has been in service for the RM12 for more than 10 years, reducing operational cost and enabling for a more flexible operation. Instead of limiting the utilization of the engine by settled pre-defined mission mix, it enables the user to operate the engine according to the operational needs. This is possible since LTS calculates life consumption per component and mission independent from a pre-defined mission mix. LTS is therefore also a facilitator for safe pooling of spare parts between operators even though they might operate the system totally differently. Additionally, there is no need to adjust the common maintenance plan according to the user who have the toughest operational usage. Figure 8 and Figure 9 shows that extending the utilization of many parts have led to increased system availability, less or shorter shop visits, and reduced life cycle cost for the RM12 operators. LTS also contributes to maintaining increased flight safety by knowing the real utilization of life limited parts and their residual life.

Figure 10 showcases a principal illustration of LTS impact on engine parts service life. The "traditional curve" illustrates the relation between consumed cycles vs. engine operating time, what you normally would see in a maintenance system. The "LTS curve" is the actual life consumption regularly corrected in the maintenance support system by GKN. The initial LTS correction can be larger while the number of missions being included in the correction is large, the following corrections will be smaller while the number of additional/new missions being corrected are fewer between each correction. LTS will perform a recalculation of all historical missions if the RM12 Life Management team releases a new life model. The real benefit is when it is possible to prolong the service life by regularly correcting the actual consumption before reaching the pre-defined life limit as stipulated in the maintenance plan.

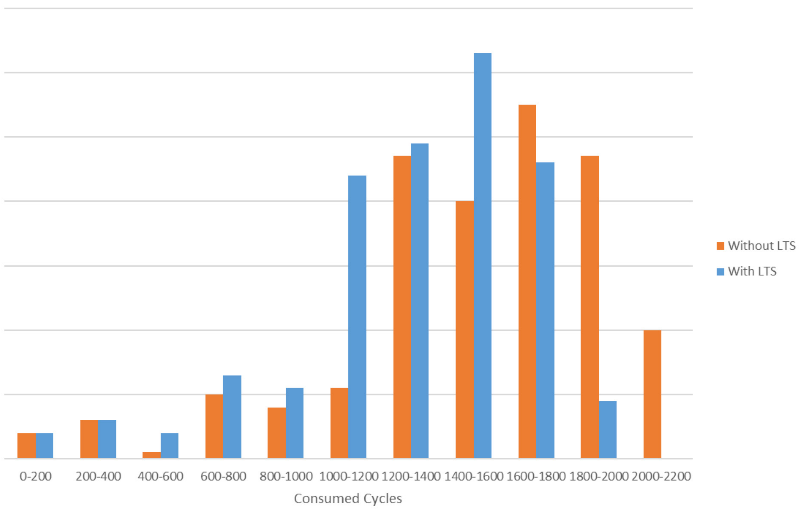

Figure 8: Actual example for one RM12 component where the number of consumed ELCF cycles are illustrated with and without LTS Corrections applied, with LTS the components can be used much longer before reaching their life limit.

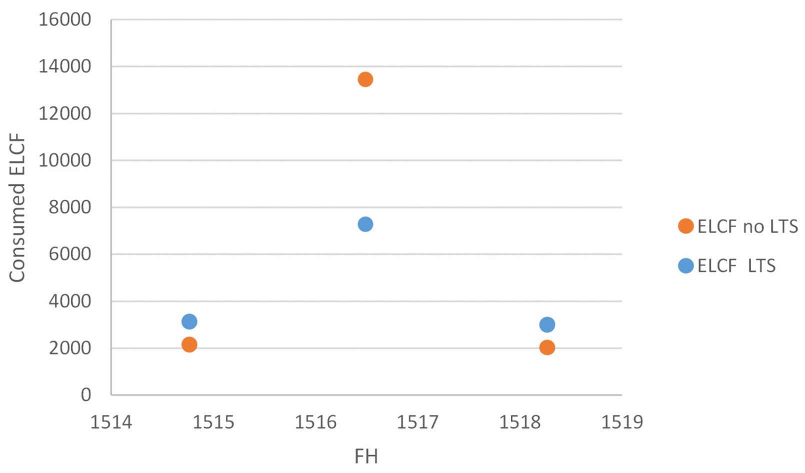

Figure 9: Actual example for one RM12 component where the number of consumed ELCF cycles are illustrated with and without LTS Corrections applied, here it is possible to see that even if the parts have been used almost the same number of flight hours the number of cycles can differ. In this actual example LTS both reduces the consumption for one part and for two other parts increases the consumption. This is all due to how the engines has been used and how much they have deviated from the assumed and predefined mission mix.

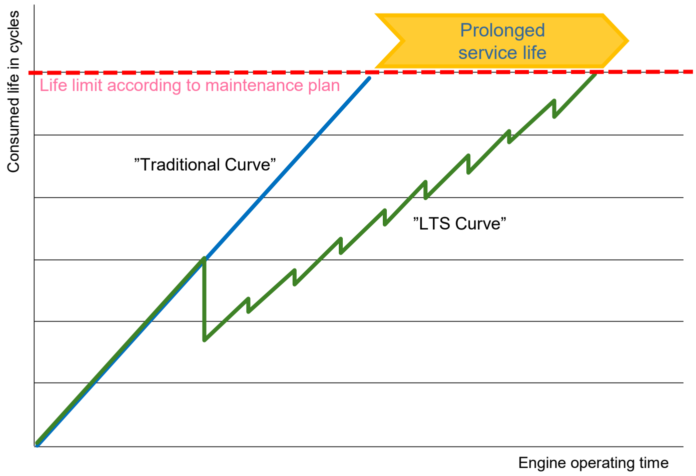

Figure 10: Principal illustration of LTS impact on engine parts service life, the LTS curve showcases what the customer sees in their maintenance systems, recurring adjustments to the life consumption.

3.0 LTS AS AN INNOVATION IN CONTEXT OF A DIGITAL TWIN FRAMEWORK

"Effective innovations start small. They are not grandiose." (Drucker, 2002)

We believe this quote from the well-known Management Researcher Peter F. Drucker serves well as a backdrop for this discussion. While the process that led to the LTS-system we have today is certainly the result of a larger strategic effort, it is equally true that during early explorative stages it was a small funding stream among many others. It eventually survived and flourished into an operational system as it in incremental steps showed its business value and technical feasibility.

3.1 History of the GKN Life Tracking System (LTS)

A lot of work were performed at GKN (former Volvo Aero Corporation) in the late 1990s related to next generation product support demands for the military and commercial operators. As part of this work, GKN focused on identifying novel and potential commercial tools in combination with internal development of tools and demonstrators which could enhance the product support for the customer. It was identified that the field of managing “in service data” was still an uncharted field where the big ERP and PLM suppliers did not have any available solutions for. Thoughts related to making better use of actual recorded data from each flight leading to a more accurate life analysis aroused during this time. By making use of the data, it could support decreasing the maintenance cost while maintaining and even improving flight safety. Performing complete life analysis for one part in the engine is however something that requires large computing power and computing time, which was one of the challenges. Another challenge was the potential conflict to develop a system that could hurt company revenues as first indications showed great impact on spare part sales and maintenance actions. It truly represents a shift away from the “transactional” view of business to the “relational” view, meaning the focus on long-time benefits for both parties. Thanks to a long term relationship between GKN, Swedish Air force, FMV (Swedish Defence Material Acquisition Agency) and SAAB, the focus on breaking the cost curve for the Gripen system and the development of LTS was completely in line with GKN’s mission.

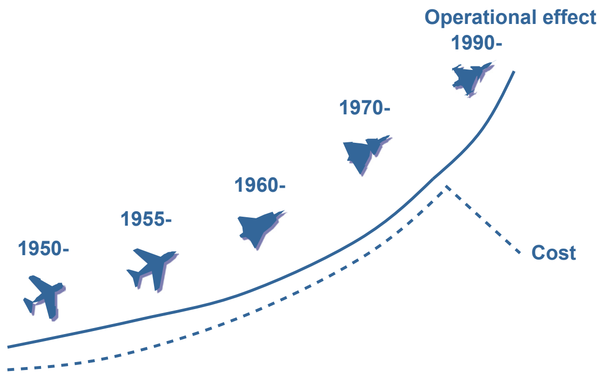

Figure 11: Breaking the cost growth while increasing the operational effect was a requirement when developing the Gripen system.

Figure 12 illustrates some of the major milestones in the development and deployment of the Life Tracking System for RM12. Multiple demonstrators have been developed along the way to prove that the concept was possible and produced the desired effect. It is important to note that there was a strategy behind the LTS system becoming reality. What started small with Thesis works and small scale projects – and the drive within a dedicated group of people – became over time a mature product based on a number of unique patents. But suffice to say, thanks to a customer that understood the concept and its potential early on was absolutley critical to its realization. From the first idea to the system being operational was a journey of approx 15 years. It can seem like a long time, but rather it illustrates the persistance needed and the importance of funding initative building on or being enabled by new technology even in early stages. Currently the system have been in operation for more than 10 years and continues to provide value for our customers.

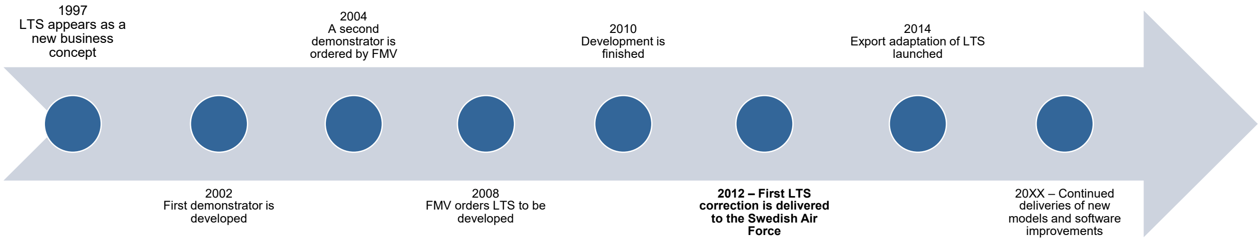

Figure 12: Major milestones for the LTS.

3.2 The LTS System Maturity as a "Digital Twin"

While scholars and people in industry may argue about what constitute a Digital Twin we choose to anchor ourselves in the definition of the US DoD as it will likely be what western defence industry will embrace. According to this definition a Digital Twin is: "*An integrated multiphysics, multiscale, probabilistic simulation of an as-built system, enabled by Digital Thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin.*" (DoD office of Systems and Architecture, 2023)

Roots and concept of the "Digital Twin" dates back to a presentation at the Society of Manufacturing Engineering (SME) conference in Troy, Michigan in October of 2002 by Dr Michael W. Grieves. (Grieves M. , 2002) The same author elaborates on of the birth of the concept in a recent book (Grieves M., 2023) where he present an interesting model depicting the different maturity stages of a Digital Twin shown in Figure 13.[1] Based on this model we will argue that the LTS-system in many ways are on level three to four depending on how it is interpreted. We do not do it for the complete engine system, but for the parts where we (and our client) see a clear value proposition. But for those parts, we will argue that we are past stage four, or perhaps better put, we see the progress of maturity a bit different than the authour.

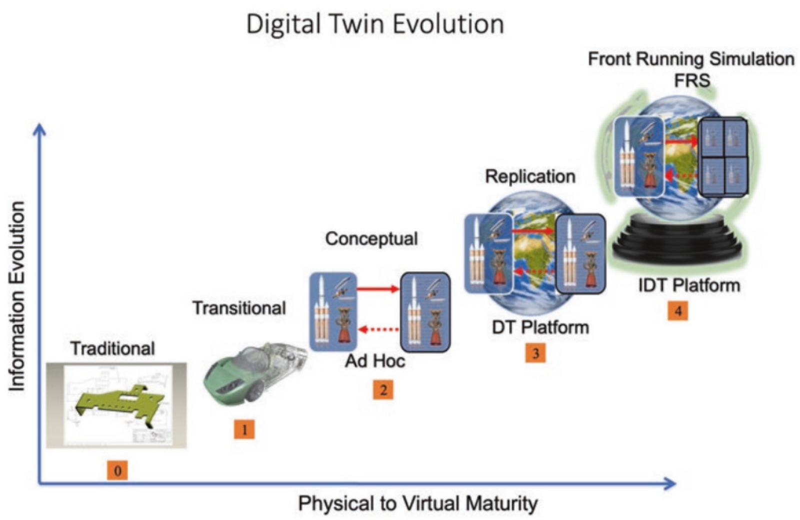

Figure 13: The maturity stages of digital twins (Grieves M., 2023).

[1] As this is not an academic paper, we choose not to spend time on elaborating on eventual competing models or definitions, i.e., it is not a literature review with a follow-on synthesis. However interesting that would be, what is presented we believe fulfill its purpose – namely giving the LTS-tool a context by putting it into a recognized framework.

This is one of the key sentences describing a Stage 3 Digital Twin according to this model: "*…being able to collect the data of the product as it is in use and replace wasted physical resources*." This is spot-on what the LTS-tool provide for the user, and it is fundamentally the underlying idea and value proposition of the tool. Stage 4 is at least in part characterized by: "*Front Running Simulations (FRS) that are constantly occurring with a product's Digital Twin.*" and "*The Digital Twin is "intelligent" because AI is employed to constantly be assessing the data and making predictions.*"

So where does this place the LTS-Tool in terms of maturity? The tool is constantly (in our use case by a pre-defined cadence agreed with our customer) tracking and making adjustments on individual parts in individual engines – hence absolutely capturing the essence of stage 3. What may go unnoticed to a layperson is the enormous undertaking getting to stage 3 from stage 2. Instead of talking about a "Digital Twin", the term "Digital Twins" would be better suited as we now hold in our repository a vast amount of "as used" digital replicas of individual parts, e.g., one individual compressor blade in an individual assembly in an individual engine and its whole history. Through this, the amount of data 1) needed and 2) created increases drastically.

For stage 4, "constantly" is important. While that is a given it is of uttermost important to understand what decision-making cycle is supported. The cadence needed is determined by customer needs and customer value, i.e., what is the OODA-loop[2] requirements? We can fully disclose that the cadence for the LTS-system is not "immediately", as in terms of by the minute or even by the day. Presently it is not assessed that higher cadence contributes to increased value, but this may be reevaluated if needed. A main reason is that any replication of a physical product and its properties, while good and valuable, is not on the level of giving the pilot a warning describing e.g., "*due to the mission profile, you have consumed too much life in compressor stage 4 blade no. 12. The following restrictions of aircraft and engine usage apply for the rest of the mission…* ". As engineers we would certainly go out of our way to make it happen, and given time it probably will happen, but fact is that we are not that close to the edge when dealing with the life consumption of rotating parts! That is not to say that the functionality is not closer at hand for other applications where the LTS-tool framework can be conceptually used.

Stage 4 is also characterized by the essence of "*Front Running Simulations (FRS)"*, and while it would be fully viable to feed the LTS-system with assumed missions, it is not something that is currently used on a broad scale. On the other hand, and this is important, we fully comply to another key characteristic of a step 4 model, namely "*The Digital Twin is constantly looking at the vast amount of data it has access to from the different sources that it is connected into and, with its cues from the user, providing information that it perceives that the user needs to know about.*" This is a true statement when it come to the LTS-tool. Also, it highlights a key enabler that is certainly more important than whether the cadence of the system is one second, one week or one month: the access to high quality data over time. Without data there are no Digital Twins. There are two keywords here to notice: 1) Quality and 2) Access. Without both, one could have the best tools and the largest High Performance Cluster (HPC) the world have ever seen without being able to create any value for any customers. Thankfully, at the outset of the Gripen Program in the late 1970s or early 1980s some really smart decisions were made by people at the Swedish Defense Material Procurement Agency (FMV) and the partners[3] to make sure a reliable and ambitious data/information-model was created. We sit on a goldmine of data that we still – four decades later – benefit from daily. There is not a single engine run that is not in the repositories. Knowing what an enormous undertaking this is with systems spanning long lifecycles, we can only speculate to what degree this is actually replicated elsewhere? In any case, we will argue that this is probably a key hurdle to overcome for anyone creating Digital Twins. We live in a world where data harvesting is a buzz word but having a lot of data is not the same thing as having good-quality data. And without proper control over the data, we believe no serious actor would likely make calls

[2] The OODA (Observe-Orient-Decide-Act)-loop is credited to United States Air Force Colonel John Boyd. While his application was military operations it has since became widely used in other fields.

[3] SAAB, Volvo, and Ericsson.

that directly affect flight safety. It simply cannot be overstated: do not underestimate the amount of work needed to lay this fundamental piece!

To conclude, LTS as a tool/system is in terms of the framework provided by Grieves (Grieves M., 2023) a highly mature Digital Twin within its selected area of application. While it as of today does not cover the complete engine, it covers the parts where the customer see a benefical value proposition. Based upon a solid dataset carefuly matured over time in close cooperation with our customers, we provide valuable services to lower system costs and increase system safety. In the end, if the LTS-tool constitute a Stage 3 or Stage 4 model may be of limited interest. Having stated that, it still is reassuring that the tool as such fit well into an accepted model/framework for what represent the future of life-cycle management.

4.0 SUMMARY AND CONCLUSIONS

> *"It may be difficult, but knowledge-based innovation can be managed. Success requires careful analysis of the various kinds of knowledge needed to make an innovation possible."*
>
> (Drucker, 2002)

- The GKN Life Tracking System (LTS) for the RM12 Engine provides tangible values in terms of better operational flexibility (availability), increased flight safety and decreased operating cost for the fighter, i.e., better and safer usage of the materiel at hand.
- Being operational for over ten years, GKN's LTS-system is a true Digital Twin as it tracks the actual life consumption for individual components in individual engines throughout their life. It does so based on data from every single mission flown from the start of the JAS 39 Gripen program. It replicates a digital twin based on what every individual piece of hardware has seen in terms of real-life loads and conditions throughout its entire life. Using the framework for Digital Twin maturity presented by Grieves (Grieves M. , 2023) we argue that it is at level three to four depending on interpretation.
- The key to creating Digital Twins is: 1) Access to data and 2) Ensuring quality of the data over time. Without wise decisions four decades ago at the outset of the GRIPEN program the pre-conditions for the LTS-system would not have existed. Persistence over time is key.
- We argue that something like the creation and operationalization of the LTS-system is not possible without a close customer involvement and a high degree of trust and confidence between the involved parties. Co-creation in early phases is necessary as there is very much a joint learning to the point of understanding where the value proposition is. During the operational phase the same trust and confidence is needed as sensitive data constantly flows between the parties, i.e., we are highly dependent upon each other to make this a reality.
- The LTS-system is inherently modular and can thus benefit from a constant evolvement as domain knowledge, tools and computer power makes better digital replications possible. The Digital Twins thus benefits from both more data as time progress but also as new knowledge and developments within tools and methods becomes available.
- Digital Twins as a conceptual framework is highly useful. We strongly believe that a key factor is to understand the value proposition of each aspect one intends to replicate in a digital twin. Also, creating that understanding is a learning where the customer has to be highly involved and where there has to be a lot of understanding between operational reality (what decision process are we supporting) and the technical possibilities.

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