

An Enhanced Risk Reduction Methodology for Complex Problem Resolution in High Value, Low Volume Manufacturing Scenarios

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ABSTRACT

This paper reports on a methodology for risk reduction, developed and tested at a brand new aerospace manufacturing facility, producing high value aero-structures. The facility was formed as part of a 'Risk Sharing Partnership' between Airbus and GKN for production of the Airbus A350 'Fixed Trailing Edge' (FTE). Whilst operating in New Product Introduction (NPI), the challenge for GKN was to increase production volume for each successive year of operations. At the time of writing, the facility was producing FTE structures at a rate of 4 per month i.e. Rate 4, and attempting to transition to Rate 6. The ultimate aim was to produce FTE structures at Rate 13 within an 8 year period whilst concurrently engineering the product and improving its processes. For schedule adherence, elimination of process failures was critical and often manifested at the final stage of assembly (integration cell). The 'integration cell' comprised of turnkey solutions where, on attempting to increase to scheduled rate, failures increased impacting on cycle times. Most failure types encountered were considered complex, since their permutations were often unknown i.e. caused through varying interactions between hardware, software and staff. To explore the problem further, a conventional Failure Mode and Effects Analysis (FMEA) was conducted but proved subjective, since the standard template was restricted to ordinal and qualitative outputs. A process FMEA (PFMEA) was then developed to account for the risks posed through safety, quality, cost, delivery and people (SQCDP). Utilising SQCDP criteria enabled a means of quantitative analysis for capturing optimal RPN values. Further, whilst the enhanced PFMEA proved effective, the method was limited for in-depth determination of root cause, apparent from the permutations of failure observed. The literature provided options, where the properties of Fault Tree Analysis (FTA) were deemed most suitable for identifying critical path, common cause and probability of failure on demand. Combining enhanced PFMEA with FTA provided a holistic means for quantitative risk prioritisation, plus in-depth determination of root cause when faced with complexity. From the root cause analysis, a set of functional requirements were derived that detailed how the solution would perform in practice. The methodology was then effectively completed once the solution had been implemented, validated and verified delivering improved Value Stream performance over the life cycle of the aircraft programme. Two cases are provided where the outputs have delivered marked reductions in process cycle time and predictability.

CITATION: Winter, D., Ashton-Rickardt, P., Ward, C., Gibbons, P. et al., "An Enhanced Risk Reduction Methodology for Complex Problem Resolution in High Value, Low Volume Manufacturing Scenarios," *SAE Int. J. Mater. Manf.* 9(1):2016, doi:10.4271/2015-01-2595.

INTRODUCTION

This paper reports on a methodological approach for risk reduction. The methodology was developed and tested in a live production scenario of a brand new aerospace manufacturing facility manufacturing high value, low volume wing structures. The facility was formed as part of a 'Risk Sharing Partnership' between Airbus and GKN Aerospace for production of the Airbus A350 'Fixed Trailing Edge' (FTE). Fig 1.0 details A350 XWB FTE in flight attitude and the region outlined highlights where the FTE resides on the wing-box structure:

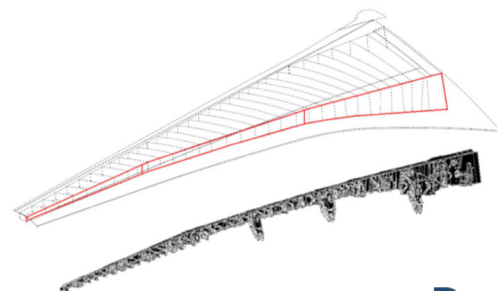


Fig 1.0. Illustrating the FTE in flight attitude relative to the wing-box structure

Importantly, the FTE consists of three carbon fibre C-sections for each port and starboard structure: Inboard (INBD), Middle (MID) and Outboard (OTBD) to which FTE components are attached. The spar C-section effectively transfers the load to the wing-box from the FTE structure to cope with the stresses imparted on take-off and landing; via the flaps, ailerons and landing gear. Fig 2.0 details an INBD carbon fibre C-section manufactured by GKN Western Approach.

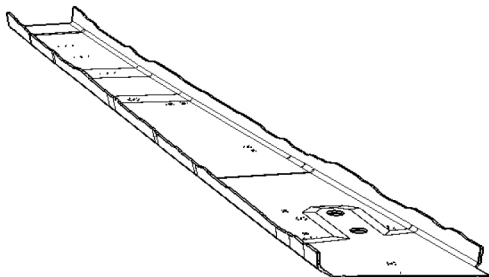


Fig 2.0. Detailing an A350 XWB C-section INBD wing spar, the primary stiffening member of the wing-box structure

The FTE attachments for each of the three C-section spars are assembled and fastened while held in jigs. These jigs are then loaded into an integration fixture where all three assembled INBD, MID and OTBD FTE's are then aligned. Fig 3.0 shows a section of the integration fixture where 'A' highlights the inside of the wing spar surface and 'B' details the outside surface. The 'Outboard' direction towards the wing-tip is also shown. On assembly, the Spars are aligned and fastened 'end to end' by joint plates to form the final component spanning 30m.

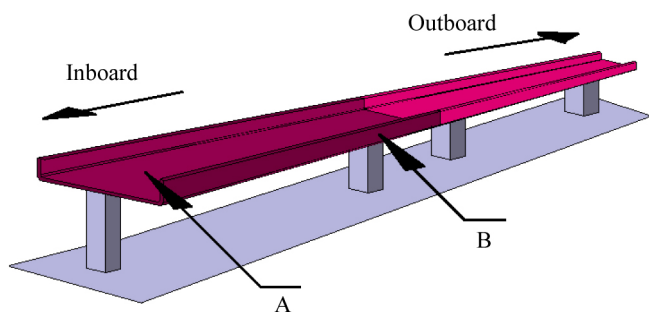


Fig 3.0. Representation of the FTE structure 'in jig' as part of the Integration Fixture.

The challenge for GKN was to increase production volume for each successive year of operations whilst concurrently engineering the product and improving its manufacturing processes. For schedule adherence, elimination of process variation and failures was critical and often manifested at the final stage of assembly i.e. The Integration Fixture. The causes of these failures were broad and ranged from subtle variations in process times, to maintenance issues beleaguering the performance of the cell. To explore the problem further, the Initial Requirements of the process were first examined. If a series of failures were evident, a conventional Failure Mode and Effects Analysis (FMEA) was conducted. However, in practice the traditional FMEA proved subjective. This was due in part to the standard template being restricted to ordinal and qualitative outputs. Consensus on risk priority numbers (RPN) often proved difficult to reach since responses varied between various members of the focus group. To counter this, a

methodology was developed, beginning with a process FMEA (PFMEA) to account for the risks posed through safety, quality, cost, delivery and people criteria. As a result, a means of quantitative analysis was therefore enabled, capturing optimal RPN values and easily reaching consensus of opinion. Whilst the enhanced form of PFMEA proved effective, the method was still limited for in-depth determination of 'root cause'; as apparent from the high mix of failure permutations observed. The literature provided many options for 'root cause analysis' (RCA), ranging from 5 whys, Ishikawa diagrams, cause and effect matrices to Fault Tree Analysis (FTA). It was here where the focus group would down-select an appropriate form of RCA, according to the nature in which the hardware (HW), software (SW) and human machine interface (HMI) were affected. In situations where the HW/SW/HMI elements were interacting, the failures were often considered complex. Therefore, FTA was often down-selected in these instances as a means of establishing and quantifying the causes of failure. A high risk Failure Mode (FM) would form the top event of the Fault Tree, under which, the causes of that failure mode formed the first tier failures that contributed to the top event. Further, FTA readily aided in identifying critical path, the common mode/cause and probability of a failure on demand (PFD), thus enabling a more deductive and quantitative form of analyses. On understanding the root cause of a complex failure, Requirements Engineering was then relied on to encapsulate how a solution should perform in practice; naturally building on the initial requirements. The requirements specified would then influence the solution generated, such that it could be verified and validated post implementation. Hereafter, the methodology was effectively completed once the improved Value Stream performance was measured. In this sense, the verified improvements could be catalogued and the new increased rate of manufacture could be reported. This paper provides two approaches for how the methodology was employed to resolve failure modes identified by PFMEA. The first example details a simple case where the Failure Modes identified were resolved purely through functional requirements generation. The second case was more complex in nature and utilized the full methodology: PFMEA, FTA, Requirements Engineering and finally a prediction of future performance.

LITERATURE REVIEW ON THE USE OF FMEA AND FTA

This review aims to appreciate FMEA and FTA as standalone tools and then, through the combined use of FMEA and FTA, the review identifies strategies adopted by various authors for enhancing reliability across a range of systems. Importantly, the review also aims to understand the grounds on which FMEA-FTA has been justified, and why other methods were discounted. The review also gives an appreciation for the efficacy of FMEA in combination with FTA by quantitatively detailing the results of the papers reviewed.

A Brief Appreciation of FMEA

FMEA can be defined as a risk management tool for 'evaluating a system, design, process or service for possible ways in which failures can occur' (Stamatis, 2003). FMEA originates from reliability engineering where it was first codified by American military standard MIL-P-1629 (Military, 1949). Successive decades saw FMEA achieve global recognition through deployment within commercial

aviation, space and the automotive sectors ([Arnzen, 1964](#)).

Commonly, FMEA is employed as early as possible in a product lifecycle for risk mitigation and reduction of failure modes. As a product design matures, greater consideration is given to how economically a design may be manufactured; nominally in terms of time, quality and cost. It is here where Process FMEAs are employed (PFMEA) to focus on existing and potential failures that occur during manufacture. PFMEA output is also of importance for 'knowledge based engineering' since manufacturing feedback can influence a design to meet the manufacturing capability of a given process ([Teoh and Case, 2004](#)). In scenarios where production is already underway, a PFMEA can mitigate existing process risks by reducing variation and enhancing production flow. [Stamatis \(2003\)](#) classifies a range of FMEA types, each tailored to suit a particular context: Systems, Services, Equipment, Design or a Process. Traditionally, all FMEA's impart a 'Risk Priority Number' (RPN) whose size is established through a Failure Mode's Severity (S), Probability (P) and Detection (D). The RPN is typically scaled from 1 to 10 and factored S·P·D to yield RPN. It is important to note that the S ranking is assigned on the effects of a Failure Mode. The P ranking is based on Cause, and the D ranking is based on the level of control employed to prevent the failure from occurring ([Ford internal, 2004](#)). Once established, individual RPN's are ranked in descending order to highlight the risk posed by the Failure mode, and in turn, prioritise which should first undergo corrective action ([Palady et al., 1994](#)). A review of the extant literature has revealed how RPN is an ordinal number, merely possessing rank not magnitude ([Kmenta and Ishii, 2000](#)). [Rhee and Ishii \(2003\)](#) agree but also question the subjectivity of the S, P and D criteria; particularly if the same standard FMEA template is applied across a range of scenarios. Rhee also warns that Detection 'D' could be applied either at the point of manufacture, or worst, where the failed product is in the hands of the customer. [Narayanagounder and Gurusami \(2009\)](#) and [Franceschini and Galetto \(2001\)](#) have stipulated how the three S, P and D indices can equate to identical RPN numbers and propose methods for differentiating aggregate RPN scores. It is therefore important that, when dealing with a multitude of RPN numbers, a means of segregation is provided to ensure high priority risks are dealt with first.

A Brief Appreciation of FTA

[Ericson \(1999\)](#) classifies FTA as a rigorous deductive form of graphical systems analysis. The method logically identifies and displays failure pathways, faults, errors and normal events that lead to an 'undesirable' top event (UE). The method originated from Bell Laboratories in 1961, where it was first employed in military systems before its widespread adoption in aerospace towards the latter end of the 1960s ([Ericson, 2011](#)). The method is commonly employed in mission critical systems where a qualitative and quantitative understanding of the probability of root causes is required. [Lee et al., \(2004\)](#) provide four key steps for Fault Tree Analysis: 1. System definition, 2. Fault Tree construction, 3. Qualitative evaluation, 4. Quantitative evaluation; here, the system definition refers to the failed state i.e. where the UE has occurred. The Fault Tree is essentially constructed downward away from the top event, where sub-tier modes of failure are transversely listed. Further sub-tier causes are continually categorised downwards, via logic gates, until all relevant causes are captured and the primary

sub-events are established. The Fault Tree branches are then rationalised and reduced into Minimum Cut Sets i.e. the shortest possible routes to failure, such that further reduction is not possible without affecting the accuracy of the UE. A case for using software over manual Fault Tree construction is given by [Powers and Tompkins \(1974\)](#), since large scale or complex systems can prove arduous and critical pathways can be inadvertently overlooked.

Contrasting the Combined use of FMEA and FTA

As part of their review into continuous improvement strategy, [Satrino et al., \(2013\)](#) highlight a gap in the knowledge regarding combinatorial approaches with FMEA. The authors discuss the application of FMEA as a standalone technique within a range of environments, before considering its use with other methods such as SWOT analysis, quality functional deployment (QFD), theory of constraints (TOC) and the TRIZ methodology. The review omits any reference to the use of FMEA alongside, or in combination with FTA. However, the authors were open in their conclusions regarding the scope of the review and encouraged researchers to consider the gap highlighted in future publications regarding improvement strategy. The use of FMEA in combination with FTA was being considered as early as the 1970s, where the two methods were being contrasted for their usefulness in the face of broadening complexity within chemical processing systems. [Powers and Tompkins \(1974\)](#) review risk management methods and the consequences of failure in light of unpredictability in large-scale chemical reactions. From a systemic viewpoint, the authors state how the relationship of the system, its environment and the possible pathways of failure are manifest, given the probabilities of their occurrence. In more recent years, case studies utilising both methods have been reported on, ranging from analyses of hardware and software for a range of applications. [Nadji et al. \(2004\)](#) published their findings on the application of FMEA and FTA for reliability analyses of uninterrupted power supply Systems; stating FMEA as an inductive and FTA as a deductive technique respectively. The authors offer insight as to the qualitative and quantitative nature of the two methods, and conclude with an 'unavailability' calculation and state how redundancy must be built into the system under analysis. The authors omit detail on the quantitative nature of the FMEA from the results provided. A more thorough systems analysis is provided by ([Aksu et al., 2006](#)) who investigated the reliability of marine pod propulsion systems through FMEA and FTA. From a systems perspective, the system boundaries were explored; outlining the scope of their analyses via spatial reliability block diagram (RBD), detailing the system configuration under scrutiny. On appreciation of the boundary and spatial analysis, the authors conduct a functional FMEA which, although omitted, 'provided the basis for the FTA'. A quantitative FTA is then given relying on a rich set of failure data including: time dependant reliability calculations (failure rates), enabling the authors to derive reliability curves for the mission duration time. The FTA makes full use of gate symbology and includes detailed sub-events; thus enabling minimum cut sets and full probabilistic analysis. The work is further complimented by [Birnbaum \(1975\)](#) and 'Fussell and Vesely' (1972) importance measures, plus a Markov analysis detailing the minimum operational units for the pod propulsion system to function; thus enabling the authors to deduce a maximum pod operating time (hours). Given the extent of the analyses, the results were very brief

but the authors' state how their findings were in agreement with manufacturer's reliability criteria, enabling confidence in design and use in service. Despite the extensive FTA analysis, little evidence of the FMEA was provided; thus, an opportunity to state how failure modes were prioritised and their corresponding relationship with the FTA was omitted.

Morello et al. (2008) report on the development of FTA methodology as applied to heavy commercial gearboxes. The authors construct a FTA that identifies four critical components of a gearbox system: microprocessor, sensors, actuators and relays. Qualitative FTA data was entered into a FMEA template (the content of which was omitted from the paper) and on so doing, the authors found difficulty in connecting the FTA output with that of FMEA and claim: *'FMEA doesn't help in connecting the physical causes to the final effects and thus, presents a gap between the two levels of abstraction in the reliability analysis'*. The FMEA had apparently revealed differing modes of failure unconnected from the findings of the FTA. A statistical 'sensitivity' analysis was then conducted with the purpose of understanding the failure distributions of each component from the FTA output; an eight step methodology was then proposed. In redacted form, the methodology commences with the collection of failure rate data to acquire an understanding of failure distributions. An FTA is then constructed to infer reliability before conducting a statistical sensitivity analysis. The final step sees that the sensitivity analysis is applied to the original FTA for the purpose of optimising its quantitative output for accurate prediction of Mean time to failure (MTTF). The authors claim that through factorial analysis, the MTTF can be predicted to within a 2% error. de Queiroz Souza and Álvares (2008) report on the application of a 'Reliability Centred Maintenance' methodology (RCM) for hydraulic turbines and consider a case study using FMEA and FTA independently of each other. Within the report, FMEA is incorrectly detailed as a deductive technique, usually the realm of FTA. It could also be argued the FMEA criteria presented are incorrectly assigned under each heading i.e. the inputs for each Functional Failure, Failure Mode, Cause and Effect. Encouragingly, the authors tailor the Severity, Probability and Detection criteria specifically for the product under scrutiny, thus enabling a quantitative appreciation and providing a means for the focus group to easily reach consensus. Post FMEA, the system was analysed via FTA utilising comprehensive failure rate data. The authors provide an in-depth analysis via FTA, yielding failure rates/hour for critical components suffering from unfiltered debris. However, the corresponding results between the FMEA and FTA appear fragmented, with only a single causal link drawn between the two. The intent of the paper was to improve the structure of planned maintenance and only a single event was exploited in the results i.e. the original objective of the paper for how the system was improved was not met. Povolotskaya and Mach (2012) provide a further case study addressing the final bond quality of electrically conductive adhesives in electronic assembly. On commencing their analyses, the authors rely on a 'cause and effect matrix' (C&E) to aid in the construction of a qualitative Fault Tree. A FMEA template is then populated from the qualitative FTA output to complete the analyses. The authors

discuss the merits of risk analysis methods in terms of qualitative and quantitative terms. Further, they elaborate on the basic methods of data acquisition for risk analysis, namely: 1. Analogy, 2. Expert opinion, 3. Statistical methods and 4. Modelling. From 1, the authors state that analogies can originate from a range of sources; but do not discuss their potentially detrimental effects i.e. how sensitive results may be to contextual bias. Since failure rate data from the FTA was omitted, the FTA was not galvanised and a temporal failure rate analysis was unable to be completed. Further, the FMEA RPN numbers were not based on quantitative inputs, leaving the output open to a higher degree of subjectivity; particularly where, as discussed above, analogous inputs were relied on. Objectively, the authors claim the methodology applied to be an appropriate estimation of risk. The author feels that by characterising the variation in the bond (via ANOVA), an appreciation of the influencing factors would be developed i.e. through 'Design of Experiments' (DoE). Ongoing statistical analysis through 'Statistical Process Control' (SPC) may have also been of benefit in serial production for monitoring the tolerance of bonded components. The authors fail to report any quantitative improvements made as result of using FMEA-FTA.

FMEA-FTA analysis has also been applied to a 'safety critical' software application. In their conceptual work, Han and Zhang (2013) utilise 'preliminary hazard analysis' (PHA) early on in an iterative software development cycle prior to FMEA. On reaching an appropriate degree of maturity, their aim was to enhance the reliability of software outputs via FTA for industrial system control. The authors claim a direct correspondence between the granular output of FMEA and FTA; such that *'the FMEA output could input directly into the FTA itself'*. Further, the authors also propose a stepped method for their analyses: 1. Identify hazards via PHA, 2. Conduct a FMEA enquiring into the system and its sub- systems, 3. Conduct an FTA utilising the output from the FMEA and finally 4. Verify the corresponding failures and faults between the FMEA and FTA conducted. Critically, the authors state that steps 2 to 4 should be cyclically repeated until a reversible systems analysis is complete and thus, direct correspondence between the FMEA and FTA is achieved. In their conclusions, the authors claim novelty and a differing perspective utilising a combined FMEA-FTA method. They claim a gap exists with traditional software analysis, since software is merely tested and verified as opposed to pro-actively seeking out how failure modes or faults could occur, before conducting mitigation activity. Objectively, solid examples were omitted and neither the outputs of the FMEA nor FTA was included in their report.

In summary, the extant literature has revealed how FMEA is used in combination with other techniques for enhancing reliability. Individually, FMEA and FTA have been used in a complementary manner, yet often separately for analyses of the same process or system. Single setting case studies were the most common research strategy where the two methods were adopted to yield credible internal validity, yet no authors present their findings over longitudinal time periods. In this sense, there appears to be a gap in the body of knowledge, particularly where authors have yet to report on a generalisable combined FMEA-FTA approach with a

high degree of external validity over longitudinal time horizons. Most works utilise FTA as the mainstay of the analyses and report extensively on its output. To this end, the FMEA element is somewhat marginalised or incomplete. It has also been the case that FMEA-FTA has been forcefully applied where the problem at hand may have been resolved by simpler means i.e. the justification for its use in general and in combination was lacking. Regarding FMEA alone, some authors have mixed views as to how failure modes, causes and effects should be applied, but in some cases, do include quantitative criteria for enhancing the severity, probability and detection for establishing RPN numbers. Despite there being a general appreciation for the inductive nature of FMEA, there appears to be a lack of appreciation for why the outputs of either FMEA or FTA should be different. There are instances in the literature where attempts have been made to homogenise the FMEA and FTA outputs with scant regard for how the methods are two distinctly different forms of analyses. The lack of understanding stems from how FTA analysis imparts the interaction between faults and events that culminate in a top event failure, something that is not possible by conventional FMEA. In turn, this leads to a subsequent lack in understanding for how FMEA-FTA should be employed in combination to yield synergistic outputs. To conclude, the literature contains a varied picture for how FMEA and FTA can be applied in a cross-sectional sense; yet no firm means or systemic approach has been reached for managing complex industrial processes over longitudinal time horizons i.e. the purpose of this paper. Future research efforts should focus on how the two techniques may best be combined to yield a rigorous methodology, culminating in a longitudinal approach to systems improvement in the manufacturing arena.

RESEARCH APPROACH

This paper reports on a methodology using FMEA, FTA and Requirements Engineering in combination where the techniques are used extensively, and appropriately, to achieve deeper insight into the causes of complexity within manufacturing processes before sustainable solutions can be generated. The problem resolution process consists of 5 stages and is aimed at resolving highly complicated or complex production issues. The 5 step risk reduction methodology is based on the classical risk reduction cycle. [Figure 4.0](#) outlines the steps necessary for reducing process risk. Stage 1 examines the problem statement by way of a 'query note' from production operations, where manufacturing engineers will typically review and supply solutions to minimise faults, variation and the potential for defects to occur. It is here where an adept systems understanding of the production cell is required. Process mapping is often relied on where each process step and its dependencies are understood. Process mapping can also be performed in-depth via parameter diagrams (p-diagrams) or boundary diagrams to depict the cell or operation in question. Appreciating the systemic view of a process aids the Engineer in their understanding of the ideal and failure states. Stage 2 of the process is implemented where an indeterminable level of risk and/or variation has been identified. An enhanced PFMEA is conducted via focus group to inductively evaluate and prioritise risk and provide Optimal RPN numbers.

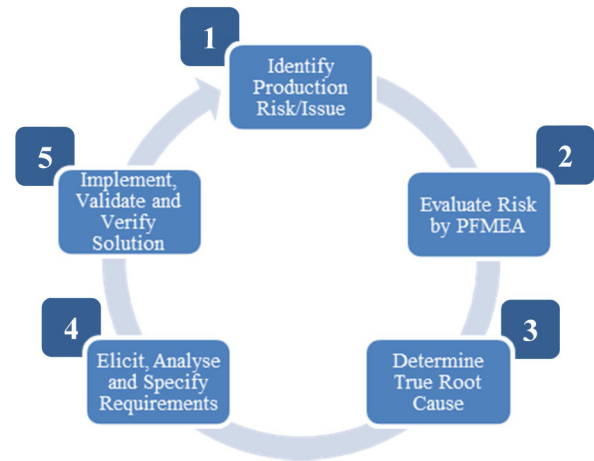


Figure 4.0. The five step risk reduction methodology proposed

Stage 3 utilises the PFMEA output to perform a root cause analysis on each of the causes associated with the failure mode in question. The type of root cause analysis conducted was in accordance with the level of complexity posed. For the simplest of problems, one may need no root cause analysis at all and hence, proceed directly onto step 4 to generate requirements. However, as complexity increases, the root cause analysis down-selected becomes more thorough. One may adopt 5 Why's analysis, or for more complex issues a Fishbone diagram, and so on to more deductive engineering approaches such as FTA. Stage 4 relies on the findings from the root cause analysis to generate functional requirements. Operating within the problem domain, requirements are elicited, analysed and specified prior to the generation of any solutions. This measure alone ensures the focus group agrees and understands how a given solution should perform in practice, such that the provision of inadequate solutions is avoided. Operating within the solution domain, Stage 5 enables the development of solutions based on the agreed and complete set of requirements. Considerations such as solution longevity are considered i.e. whether a short, medium or long term solution is appropriate. In addition, the sustainability of the solution derived is considered to deal with efficacy issues such as future proofing. Time, quality and cost aspects are also considered to minimise time to implementation. Lastly, the solution is verified, validated and its contribution to Value Stream performance is catalogued. Thereafter, the methodology is further employed where the facility wishes to improve rate for any given process. The methodology therefore becomes part of cyclical improvement process, see [Fig 5.0](#).

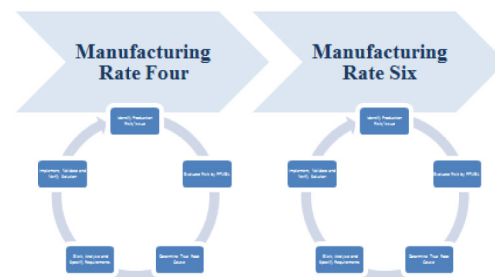


Fig 5.0. detailing cyclical improvement as manufacturing rate is increased