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Using Real-Time Data for Increasing the Efficiency of the Automated Fibre Placement Process

D. Winter[a,b], D. Crowley[d,e], C. Ward[d,f], S. Williams[a,c], C. McMahon[d,g] and K. Potter[d,h]

[a]*Manufacturing Engg., GKN Aerospace, Western Approach, Bristol, UK*
[b]*Corresponding Author, Email: darren.winter@gknaerospace.com*
[c]*Email: steve.williams@gknaerospace.com*
[d]*University of Bristol, Queen's Building, University Walk, Bristol, UK*
[e]*Email: d.crowley@bristol.ac.uk*
[f]*Email: c.ward@bristol.ac.uk*
[g]*Email: c.mcmahon@bristol.ac.uk*
[h]*Email: k.potter@bristol.ac.uk*

ABSTRACT:

The Automated Fibre Placement (AFP) process has grown in popularity with an increasing install base that realistically began within the last decade. This growing popularity stems from the technique's promise of higher deposition rates (>10kg/hr), enhanced quality, and reduction of intensive manual labour. However, AFP machines are still relatively few in number as compared to other automated routes for fabrication; with only a few airframers and suppliers proactively developing the technique. The purpose of this paper is to report on the non-value adding activities that detrimentally impact on production rate capability. For example, inspection is typically carried out manually and can account for a large percentage of the cycle time. The risk therefore, is that by not adequately addressing non-value adding activities, a costly level of investment could be needed to achieve the production rates required. We provide a longitudinal case study, accounting for the non-value adding tasks that surround the process. Our results show that, by percentage, these activities have been targeted and reduced over a two year period. We are also able to demonstrate, through coefficient of variation, how the AFP process has stabilized over the two years. A 92% learning curve has emerged that better represents cycle time reductions for each successive part, as opposed to the 80% learning curve traditionally adopted.

KEYWORDS:

Automated fibre placement; Automation; Composite; Process; Efficiency

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1. Introduction

1.1. Background to the A350 XWB

Brake In order to maintain and increase their market share, airframers must constantly exploit gaps in the market for their product platforms. Traditionally, exploitation can be achieved through modification of an existing product, or as a response to competitor activity threatening new platform entrants. Regarding the Airbus A350, the first proposal was billed as a modified A330 platform which received critique from the customer base, forcing the OEM to change the build philosophy and completely remodel a competitor aircraft to the Boeing 787 [1]. Airbus achieved this through conceptualising an aircraft with true second to market mover advantage. The rebranded A350 XWB exceeded the Boeing 787 through increased use of light weight carbon composite materials and space per passenger, rendering it an option with increased appeal to Airlines. Despite being early adopters of composite materials, Airbus needed to formulate an intensive development plan, industrialising breakthrough technologies for new applications in primary aircraft structure [2]. Further, the OEM introduced an 'extended enterprise' model seeking to re-distribute larger work packages to tier suppliers, reducing risk and increasing opportunity for supply chain development [3]; the ultimate goal being to reduce development time and increase rate ramp-up in manufacturing. GKN Aerospace entered into a 'risk sharing partnership' (RSP) with Airbus for manufacture of the A350 XWB Fixed Trailing Edge (FTE). The RSP entailed devolved responsibility from Airbus, where GKN assumed design authority, manufacturing development and integration for large-scale wing assemblies. In turn, GKN invested £200M into a brand new facility at Western Approach, Bristol, UK that housed the technologies requiring industrialisation to meet the challenging ramp-up in rate of manufacture.

1.2. Purpose of this research

This paper focuses on the industrialisation and introduction of one such technology, the 'Automated Fibre Placement' (AFP) process, whose technology trajectory has yet to reach the rate of diminishing returns. Fig. 1 illustrates the AFP process at GKN Western Approach, while Fig. 2 details the Inner, Mid and Out Spars of the A350XWB Fixed Trailing Edge as laid-up by the AFP Process.

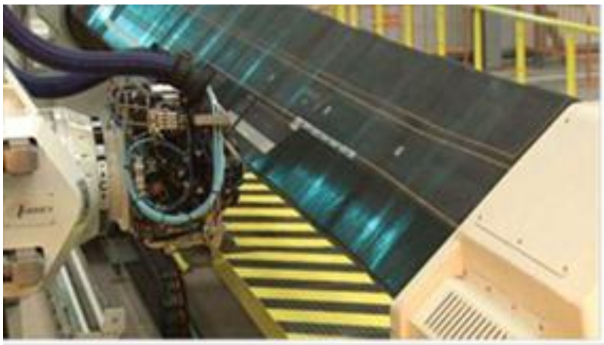

Fig. 1: Depicting the AFP process

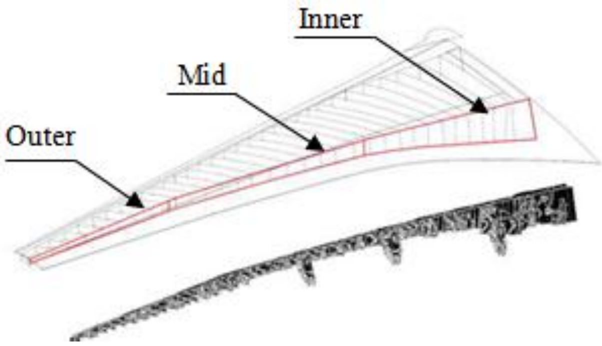

Fig. 2: Inner, Mid and Outer spars by AFP

Despite the upward trend in the use of AFP technologies, machines are still relatively few in number compared to other automated routes for machining and fabrication, and due to high capital outlay, only a few airframers and suppliers are proactively developing the process. Regarding its use, Cornforth reports on how material deposition can account for up to 42% of the labour hours required to manufacture a composite component [4], and as such, efforts should be focused on this area. We agree, and emphasise our aim of further optimising the other potential 58% of the process. Our research reports on non-value adding activities that detrimentally impact upon production rate capability. For example, how inspection is typically carried out manually and accounts for a large percentage of the cycle time. Maintenance and reliability are also observed to be significant issues. The risk therefore, is that by not addressing non-value adding activities, additional efforts and levels of investment could be misappropriated to achieve the production rates required. We rely on cycle time data, garnered from GKN Aerospace, since the firm was making significant headway in transitioning from the new technology/product introduction environment towards a desired rate of 'steady state' production. Time series data was taken from the manufacturer's AFP process, with typical activities captured as events throughout the manufacture of multiple parts; thus enabling the data to be analysed using statistical methods and other common metrics. The results enable us to present normalised data in terms of time-consuming activities and determine links between them that would aid GKN in enhancing their productivity

1.3. The AFP process in aerospace manufacturing

The main advantage of AFP lies in its ability for laying up courses of narrow pre-impregnated tows of composite material over complex surface geometries (typically 6.35mm in width). Conversely, its precursor process (ATL) relies on wider tapes of pre-impregnated material for lay-up of flat or mildly curved geometries (typically 300mm in width). Since the ATL requires fewer operations to cut and lay wider tape materials, the process has an intrinsic rate advantage when laying-up large scale laminates over simpler geometries. However, on its introduction, the AFP process proved more than capable where requirements changed to the contrary, as was the case for AFP's initial deployments for meeting military and space business cases where rate was not an apparent issue, but traceability and consistency of lay-up over complex geometries were. In light of this advantage, the commercialisation of AFP was slow, and to complicate matters further, its development has been a function of hardware, software and material capability. As the AFP process began to further evolve, interest was raised within the commercial aerospace sector who sought competitive advantage in adopting the method for its flexibility in dealing with complex geometry. To this end, the AFP process flourished under a commercial drive, yielding improvements in algorithms and design software integration/simulation, material control and mechanical cutting and adding methods. To this end, the number of applications for which the technology could be employed grew rapidly across numerous product platforms.

In terms of programme size, a distinct advantage of the AFP process emerged in terms of scrap reduction. Once the laminate edge of part was trimmed, typical scrap rates for the ATL process hover around 15% by weight of laminate laid. Rates between 2%-5% have been evident within GKN programmes indicating higher returns for greater economies of scale. With each new deployment, the down selected AFP process was typically specified to the product in question. The challenges in improving the process to meet the needs of the business case were therefore common. In the case of Western Approach, the columnated AFP process down selected and developed over a number of years prior to hitting the shop floor, but in so doing, still required a major degree of industrialisation to meet the challenging demand of the A350 XWB programme. It is also noted how the AFP OEM's proved highly capable in AFP machine manufacture, but the boundary of their expertise was evident when it came to industrialisation of a vanilla process to meet rate demand. In addition to a structured continuous improvement programme, GKN at Western Approach formulated a specialist engineering development team dedicated to the industrialisation of the AFP process in the context of wing spar manufacturing. It was here where acquisition of time series data commenced in order to quantitatively understand the causes behind lost time during the manufacturing cycle of each of wing spar component.

2. Literature review

2.1. Process industrialisation

The process of manufacturing ramp-up between 'new product introduction' and 'steady state manufacture' is termed 'time to volume' (TTV) and is of great importance in achieving 'time to market' (TTM); which in turn affects a firms 'time to profit' (TTP). The endeavour is made particularly difficult when coupled with the introduction and development of breakthrough but 'low maturity' manufacturing technologies. Oppenheim [5] and James-Moore [6] posit how 'lower maturity' manufacturing technologies pose work flow related problems as opposed to existing 'known' technologies. However, the reality is that new products must make use of new technologies, processes and materials in order to appeal to potential customers and effectively diffuse in the market. The lifecycles of products and technologies employed in their manufacture must therefore be effectively managed. Azizian et al. [7] discuss maturity assessment approaches for managing product lifecycles and cite Tetlay et al. [8], stating the importance of sufficiently maturing a technology prior to its introduction. The authors propose increased use of 'readiness levels' and 'maturity gate' systems for managing technologies that will eventually be used in the manufacture of saleable products.

Dietrich et al. [9] consider process and technology maturity as part of a broader supply chain and report on a method for concurrently assessing risk alongside manufacturing maturity levels quoted by Azizian et al. [7] stating OEMs may prefer to adopt current suppliers of technology to reduce risk, rather than develop technologies themselves. In essence the authors are referring to the advantage that can be gained since the learning required to develop the process maturity would have already taken place. From an economic point of view, it therefore stands to reason that an appreciation of the rate of learning would be beneficial to future business cases. In his seminal work, Wright [10] outlines the use of learning curves for monitoring the decreasing cost of aircraft as worker proficiency increases utilising what is essentially a 'fixed' process. We understand and complement this with an appreciation of learning in terms of a fixed process, plus those activities that can be improved that surround and support a new technology. Contextually, the situation at GKN Western Approach was one where a balance had to be struck between utilising technologies and materials that would satisfy our direct customer (Airbus) that in turn would yield the necessary customer appeal (Airlines). After Oppenheim [5] and James-Moore [6], we agree how low maturity technologies can cause work flow related problems. Further to Azizian [7], contextual circumstances such as aggressive ramp-up strategies did not lend themselves to long periods of development time where the technology could be sufficiently matured. However, we agree how an OEM has sufficiently reduced its own risk where a partnership was entered into devolving design and manufacturing responsibility.

2.2. Process waste and variation

The objective of this paper is to highlight how non-value added activities contribute to variable and lengthier cycle times within a production scenario utilising new technologies. The Lean philosophy was relied on to classify the types of waste encountered. Hines et al. [11] report how the Lean philosophy was derived from Japanese manufacturers who developed methods for increasing performance with fewer resources. Womack et al. [12] codified the principles of Lean for performance enhancement: 1. Specifying 'Value' from the perspective of the customer, 2. Identifying each process step of the 'Value Stream', 3. Enhancing the 'Flow' of operations, 4. Manufacturing only what the customer will 'Pull' from the operation and 5. The continual pursuit of 'Perfection'. In essence, the Lean philosophy provides implementable methods for waste elimination and problem solving for production systems. Womack et al. [12] go on to identify seven wastes associated with production operations. These conform to the acronym 'TIMWOOD' as highlighted in Table 1.

Table 1: A breakdown of Lean wastes after Womack et al. [12].

Lean waste	Criteria of associated waste
Transport	Unnecessary shipping of movement of products around the production system
Inventory	Accrual of excess product in various states of process, occupying precious space
Motion	Excessive ergonomic movement of individuals
Waiting	Stoppage in the actions of staff or equipment whilst awaiting further input
Overproduction	Unbalanced stages of production, over producing ahead of actual demand
Overprocessing	Excessive treatment or processing, due in part to poor process design
Defects	Excessive effort involved for reworking and rectifying components produced

Each waste essentially qualifies as a 'non-value added' activity and upon reduction, contributes to savings in cycle time and variation within a manufacturing process. Within an AFP context, 'value added' (VA) was considered to be the physical act of material deposition onto a substrate tool or mandrel i.e. the physical lay-up of composite material itself. In this sense, VA could be termed as 'Process' related activity. However, further activities existed that were necessary to the success of the operation, these were termed as non-value added 'but necessary' (NVA-BN); other activities were deemed as waste and considered as non-value added (NVA).

3. Research approach

On introducing AFP process technology to the shop floor, it was necessary to rapidly gain an understanding of the causes that account for time added into the production cycle. For each spar laid-up on an AFP machine, a detailed log was kept highlighting and classifying the type of activity that added to the overall cycle time. The data would then be analysed for lost time, hence: 'Lost Time Analysis' (LTA). The objective of analysing the data was to impart how reductions could be made in terms of NVA-BN and NVA activities that aid GKN in meeting the aggressive rate ramp-up strategy. A good example of NVA-BN was the de-bulk cycle performed on an uncured composite laminate cycle. Despite no material being added, the part would not meet the stringent thickness quality requirement. 'Non-Process' related activities were attributed to lost time i.e. Lean wastes. Table 2 summarises the data collected via LTA.

Table 2: A breakdown of the types of VA, NVA and NVA-BN activities

Data	Lean Waste	VA, NVA, NVA-BN Activity	Description
Machine Layup	N/A	VA	AFP laying material onto mandrel
Layup Issues	Overprocessing	NVA	Correcting machine layup errors
Inspection	Overprocessing	NVA	Inspection of layup for defects
Load Creels	N/A	NVA-BN	Loading creels of material
Debulk Setup	N/A	NVA-BN	Preparing for de-bulking operation
Debulk	N/A	NVA-BN	Evacuating air from the pre-form
Debulk Strip down	N/A	NVA-BN	Remove de-bulking materials
Machine maintenance	N/A	NVA-BN	Maintenance/Repair
Rework	Overprocessing	NVA	Rework of composite lay-up
Crane Downtime	Waiting	NVA	Crane unavailable
Machine Breakdown	Waiting	NVA	Unforeseen machine failure
Thickness Measurements	Overprocessing	NVA	Thickness conformation
Laser projection issues	Overprocessing	NVA	Errors with laser projection
Waiting Material	Waiting	NVA	Awaiting material defrosted
Waiting Tooling/Spares	Waiting	NVA	Awaiting the tooling/spares
Waiting Operator	Waiting	NVA	Operator availability
Awaiting Inspection	Waiting	NVA	Awaiting inspector
Other	Overprocessing	NVA	Other time losses

Regarding commercial sensitivity, all data contained herein will be anonymised to protect the intellectual property of the firm in question. Anonymisation will take the form of displaying data as a percentage or ratio, still enabling the trends from the data to be inferred. The first form of data analysis from Table 2 will be a Pareto, breaking down the times associated with each NVA and NVA-BN activity. Here, the unit of analysis is the time associated with each NVA and NVA-BN activity. The Pareto achieves this by plotting the lost times as percentages taken from two consecutive years of activity; Year 1 and Year 2. Those data values that form the first cumulative 80% will be considered activities for reduction within Year 2 of production operations. The percentage reductions between the two years will then be shown; highlighting the difference in cycle time reduced as a result of continuous improvement effort. The second form of analysis utilises 'Coefficient of Variation' (Std. Dev / Mean). The analysis will be conducted examining how variable the cycle times were for all spar components manufactured between Year 1 and Year 2.

The reader can infer how stable the process became, highlighting the increased predictability of cycle time in light of any variation encountered. Since the process is under a continuous state of improvement i.e. transitioning from 'new product introduction' to 'steady state manufacture', a further measure for how cycle time reduction has contributed to process learning will be presented. By percentage cycle time reduction, we present learning curves that express the rate reduction for each consecutive part manufactured using a simple power law after Wright [10]. In turn, the curves presented can be used as predictors for future rates of production. The learning curves presented are contrasted against a traditional aerospace 80% learning curve where actual cycle time reductions are expressed alongside.

4. Results and discussion

4.1. Lost time analysis

The first unit of analysis was a standard Pareto of the non-value adding tasks. The aim of this was to structure the data such that the most time-consuming NVA and NVA-BN tasks became apparent by their %age contribution. This then allowed us to compare older production data from Year 1 to more recent parts manufactured in Year 2. The first plot from Year 1 is shown in Fig. 3 and then Year 2 is shown Fig. 4.

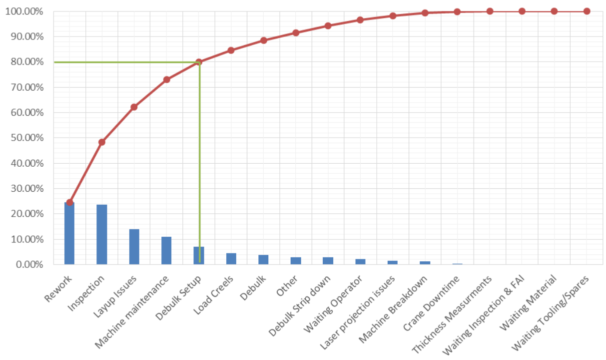

Fig. 3: Pareto results from Year 1 data of AFP operations

From Year 1, there were 5 activities which within the 80% cumulative percentage boundary of the Pareto analysis: 1. Rework, 2. Inspection, 3. Lay-up Issues, 4. Maintenance and 5. De-bulk setup. Chiefly, the NVA activity of Rework formed the highest amount of time spent on a NVA activity. The other four activities are considered to be NVA-BN. The Year 2 data shows an improvement where, not only had the number of activities with 80% cumulative percentage fallen to 3, but the former NVA chief activity had reduced to second in the ranking. That is to say that, to make improvements by Pareto, three activities should be focussed on to increase cycle time as a result. Therefore inspection, rework and lay-up issues still remain key factors in the lost time analysis, but have been shown to reduce as the process matures along its technology trajectory.

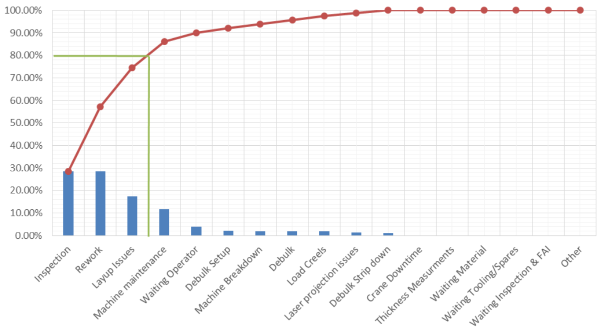

Fig. 4: Pareto results from Year 2 data of AFP operations

4.2. Percentage difference between Years 1 and 2 NVA and NVA-BN task times

Fig. 5 details the percentage difference in the time taken between Years 1 and 2 production data. In this figure, the improvements made to the various stages of the de-bulking cycle and the creed loading time can be observed, along with more modest improvements in rework, inspection and laser projection issues.

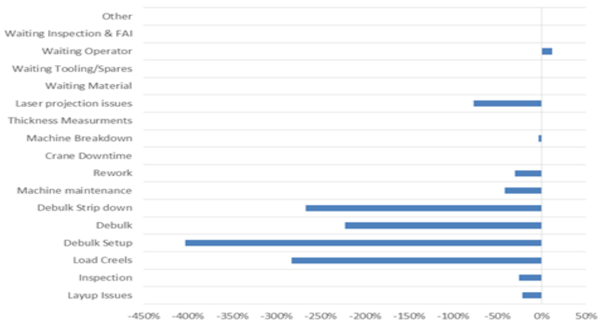

Fig. 5: Percentage cycle time difference between Years 1 and 2 of AFP operations

4.3. Variability analysis

In addition to cycle time reductions, it must also be demonstrable how the AFP process stabilised over time; so as to ascertain how parts can be produced at predictable rates. Table 3 highlights the difference between Years 1 and 2 of the case study where the ratio of average cycle times between Years 1 and 2 are calculated against the desired rate of 13 shipsets per month. A 'coefficient of variance' was used as a measure to anonymise the data. However, due to the expected time reductions, as part of the continuous improvement plan, there would always be a degree of variance. Therefore, the coefficient of variance was multiplied by the part-to-part variance i.e. the percentage difference in cycle time between the current and previous part. This allowed the result to be negative as well as positive and gave the output shown in Fig. 6. It is readily observable that on average, the variation in cycle time has reduced considerably between years 1 and 2. Fig. 6 shows a high degree of variation is evident at the earlier stages of production (particularly for Mid rear spar components), yet it can be appreciated how part-to-part variability reduces over time.

Table 3: Co-efficient of variance change between years 1 and 2

Year	Outer	Mid	Inner
1	0.19	0.20	0.21
2	0.17	0.09	0.13

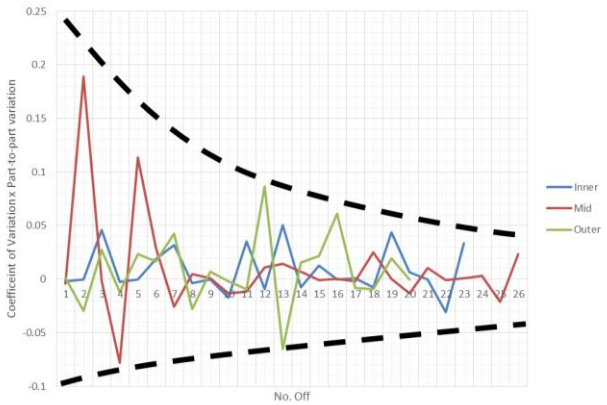

Fig. 6: Co-efficient of variance as multiplied by part to part variance

4.4. Learning curves

Fig. 7 displays a conventional 80% learning curve based on the initial cycle time of the AFP process. The 80% curve shown is an average of the 3 off spars (Inner, Mid and Outer). Coupled with this, curve is a modelled from the time series data analysed, the curve conforms to a power law, exhibiting a rate of 93% learning i.e. a lower rate of learning than that forecast by the traditional 80% curve of Wright [10]. This is indicative that, upon introducing breakthrough technologies into a serial production environment, a lesser rate of learning may be more applicable for production scheduling and financial projections. The 93% curve serves as an indicator, since the R2 values derived exhibit a fit of 78%. Despite this, the figure shows a continued rate of learning, reducing cycle time and progressing towards desired rates of manufacture.

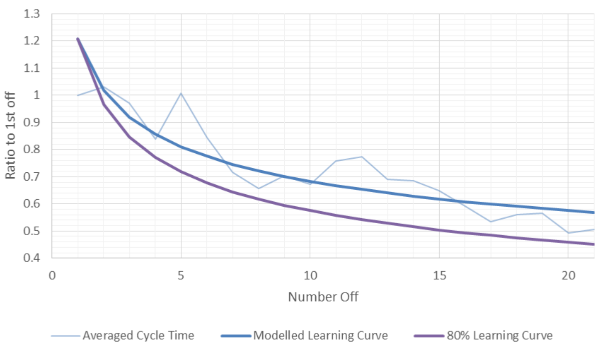

Fig. 7: 80% learning curve contrasted against 93% curve over two successive years of manufacture

5. Conclusion

The Pareto from Fig. 5 highlights five activities where larger amounts of lost time have occurred, namely:

Rework, Inspection, Lay-up Issues, Maintenance and de-bulking. These activities were prioritised for time reduction during year 1 and the Pareto for Year 2 shows how the lost time for these have reduced accordingly. The Pareto for Year 2 shows three remaining activities that should be targeted for waste reduction: Re-work Inspection and Lay-up Issues. Fig. 7 details how times associated with de-bulking and creel set-up have reduced considerably. The data shown in Table 2 indicates how, during years 1 and 2 of the analyses, the process was prone to over-processing and waiting times. A high degree of NVA activity was evident, but in relation to Fig. 6, it can be appreciated how the process has become stable over time. The NVA-BN activity shown in Table 2 such as those associated with de-bulking have decreased considerably over years 1 and 2; Fig. 7 indicates how, despite being considered NVA-BN, over-processing may have been evident with the de-bulking process. Table 3 details the ‘coefficient of variation’ as aligned against the rate 13 targets for production operations. Fig. 6 illustrates how cycle time is observed to be reducing with each successive part manufactured. The process is therefore becoming stable over time. This can be further elaborated on by the average learning curve for cycle time shown in Fig. 7. Here, the traditional 80% learning curve for aircraft production is shown to be not applicable on introducing brand new breakthrough technologies. Rather, a learning curve of 93% demonstrates a much more useful measure for future performance prediction. This has important implications in the costing, and time to profit calculations for new projects of this kind.

6. Limitations and further work

Naturally, the results from the data gathered are contextually dependant and valid within the single-setting from which it was derived. As a case study, whose unit of analyses was AFP cycle time reduction as a function of time lost within a process, cycle time reduction and increased process stability have been demonstrated. However, the data was prone to factors that could make it more subjective such as production stoppages associated with factory shut downs. Other factors that could sway the data may have been where re-prioritisation in manufacturing occurred. We plan to continue the analyses of the AFP process by reconfiguring the data gathered such that production anomalies can be more clearly distinguished. Further, we plan to account for improvements to the AFP process that can be attributed to cycle time reduction through engineering efforts that enhance an AFP machine’s performance.

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