USING REAL-TIME DATA FOR INCREASING THE EFFICIENCY OF THE AUTOMATED FIBRE PLACEMENT PROCESS

Darren Winter [1], Dennis Crowley [2], Stephen Williams [3], and Carwyn Ward [4]

[1, 3] Manufacturing Engineering, GKN Aerospace, Western Approach, Bristol, BS35 4GG, UK
[1] Email: darren.winter@gknaerospace.com, [3] Email: stephen.williams@gknaerospace.com, Web page: http://www.gkn.com/aerospace/Pages/default.aspx
[2, 4] ACCIS, Queens Building, University Walk, University of Bristol, Bristol, BS8 1TR, UK
[2] Email: dennis.crowley@bristol.ac.uk, [4] Email: c.ward@bristol.ac.uk, Web Page: http://www.bristol.ac.uk/composites/

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Abstract
The Automated Fibre Placement (AFP) process has grown in popularity, with a globally increasing install base that began in earnest within the last decade. This growing popularity stems from the technique's promise of higher deposition rates, enhanced quality, and reduction of intensive manual labour. In reality these machines are still few in number compared to other automated fabrication routes; with few airframers, research centres, and suppliers proactively developing the technique. This paper reports on the non-value adding activities within AFP, that can detrimentally impact on production rate capability - such as inspection which is typically carried out manually and can account for a large percentage of the cycle time. The risk 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 (two year) longitudinal case study, identifying and accounting for the non-value adding tasks that surround the process. We show by percentage their impact, the process of targeting reducion over that period, and through a coefficient of variation how the AFP process has stabilised. Finally a new learning curve emerged that better represents cycle time reductions for each successive part produced.

1. Introduction

1.1. Background to the A350-XWB

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. In regards to 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 offering through increased use of light weight carbon composite materials and space per passenger, rendering it an option with increased appeal to airline operators.

Despite being early adopters of composite materials, for the A350-XWB Airbus needed to formulate an intensive development plan by industrialising breakthrough technologies for new applications in primary aircraft structure [2]. Furthermore, they 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

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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), housing the technologies requiring industrialisation to meet the challenge of new product introduction, transition to steady state manufacture, and a ramp-up in manufacturing rate.

1.2. Purpose of this research

This paper focusses on the industrialisation and introduction of one such technology, the Automated Fibre Placement (AFP) process, whose technology trajectory it can be said has yet to reach the rate of diminishing returns. Figure 1 illustrates the AFP process at GKN Western Approach, while Figure 2 details the Inner, Mid, and Outer Spars of the A350-XWB Fixed Trailing Edge.

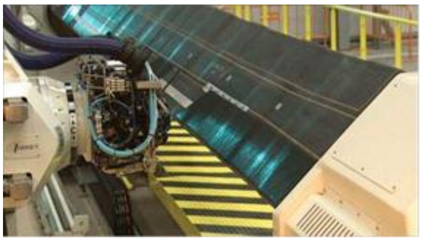

Figure 1. Depicting the AFP Process.

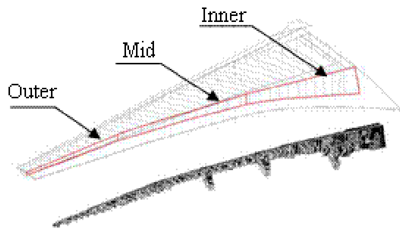

Figure 2. Inner, Mid, and Outer spars by AFP.

Despite the upward trend in the install and use of AFP technologies, these 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, research centres, and suppliers appear to be proactively developing the process. Regarding its use in serial production of components, 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 58% of the process. Our research reports on non-value adding activities that detrimentally impact upon production rate capability. For example inspection is typically still 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 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 company 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 their AFP process with typical activities captured as events throughout the manufacture of multiple parts, enabling the data to be analysed using statistical methods and other common metrics. The results, presented as normalised data sets in terms of time-consuming activities, allow for links to be determined that would aid GKN Aerospace in enhancing their future productivity and hardware.

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 relies on wider tapes of pre-impregnated material for layup of flat or mildly curved geometries (typically 300mm in width). This precursor 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. But 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 layup 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,

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and material capability. As the AFP process began to further evolve, interest was raised within the commercial aerospace sector who sought a 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 + adding methods. The number of applications for which the technology could be employed subsequently grew rapidly across numerous product platforms. In terms of programme size, a distinct advantage of the AFP process also emerged in terms of scrap reduction. Once the laminate edge of part was trimmed, typical scrap rates for the precursor process hover around 15wt% of laminate laid. Rates between 2 and 5wt% have been evident within GKN Aeorpsace 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 GKN Western Approach, the columnated AFP process was down selected and developed over a number of years prior to shop floor introduction. But in so doing, the AFP still required a major degree of industrialisation to meet the challenges and demand of the A350-XWB programme. This was further hindered in the fact that despite the AFP OEM's proving highly capable in machine manufacture, significant boundaries in their expertise became evident when it came to industrialisation of a process to meet rate demand. Thus in addition to a structured continuous improvement programme, GKN Aerospace 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 ramp-up between 'new product introduction' and 'steady state manufacture' is termed 'time to volume' and is of great importance in achieving 'time to market'; which in turn affects the 'time to profit'. The endeavour is made particularly difficult when coupled with the introduction and development of breakthrough but low maturity (in a production sense) 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. 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 into 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. These 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 the technologies themselves. In essence they refer to a gained advantage since the learning required to develop process maturity would have already taken place. From an economic point of view, it 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 on that surround and support the 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 the direct customer (Airbus), that in turn would yield

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their necessary customer appeal (operating airlines). We agree with Oppenheim [5] and James-Moore [6] on how low maturity technology 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, where the technology could be sufficiently matured. But we agree on how an OEM has sufficiently reduced its risk, where a partnership was entered into devolving responsibility.

2.3. Process waste and variation

As 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. 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, conforming to the acronym 'TIMWOOD' as in Table 1. Each 'TIMWOOD' essentially qualifies as a 'Non-Value Added' (NVA) activity and on reduction, contributes to savings in cycle time and variation within a manufacturing process. In the context of an AFP process 'Value Added' (VA) was considered to be the physical act of material deposition onto a substrate tool or mandrel, i.e. the physical layup 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, and these were termed as 'Non-Value Added But Necessary' (NVA-BN), whilst other superflouous activities were deemed as waste and considered as NVA.

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

3. Research Approach

On introducing the AFP process technology to the shop floor, it was necessary to rapidly gain an understanding of the causes that account for added time into the production cycle compared to the anticipated. Thus 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 a 'Lost Time Analysis' (LTA). The objective was to impart how reductions could be made in terms of NVA-BN and NVA activities that aid in meeting the aggressive rate ramp-up strategy. A very good example of unexpected NVA-BN was the debulk cycle performed during spar manufacture as despite no material being added, the part would not meet the stringent thickness quality requirements of the component (other quality related discussions for debulking/consolidation are not considered here). 'Non-Process' related activities were attributed to lost time i.e. lean wastes, and Table 2 summarises the data collected via the LTA.

Note that due to commercial sensitivity all data is anonymised through representation as a percentage or ratio, but which still enables trends to be inferred. Data analysis initially took the form of Pareto, breaking down the times associated with each NVA and NVA-BN activity and plotting the lost times

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as percentages taken from two consecutive years of activity; Years 1 & 2. Those data values that form the first cumulative 80% will be considered activities for reduction within Year 2 of operations. The percentage reductions between the two years will then be shown to highlight the difference in reduced cycle times as a result of the continuous improvement effort. Data analysis then simply used the Coefficient of Variation to examine how variable the cycle times were for all spar components manufactured between Years 1 & 2, inferring process stability, and highlighting any increased predictability of cycle time in light of any enoucountered variations. Finally, since the process is under a continuous state of improvement (i.e. transitioning from 'new product introduction' to 'steady state manufacture'), a measure for how cycle time reductions have contributed to process learning was explored. This was achieved by combining the percentage cycle time reduction with a simple power law (after Wright [10]), to express the rate reduction for each consecutive part manufactured.

Table 2. Recorded types of VA, NVA and NVA-BN activities found in the AFP process.

Data	Lean Waste	Activity	Description
Machine layup	N/A	VA	AFP laying material onto mandrel
Layup issues	O	NVA	Correcting machine layup errors
Inspection	O	NVA	Inspection of layup for defects
Load creels	N/A	NVA-BN	Loading creels of material
Debulk setup	N/A	NVA-BN	Preparing for debulking operation
Debulk	N/A	NVA-BN	Evacuating air from the preform
Debulk strip down	N/A	NVA-BN	Remove debulking materials
Machine maintenance	N/A	NVA-BN	Maintenance/repair
Rework	O	NVA	Rework of composite layup
Crane downtime	W	NVA	Crane unavailable
Machine breakdown	W	NVA	Unforeseen machine failure
Thickness measurements	O	NVA	Thickness conformation
Laser projection issues	O	NVA	Errors with laser projection
Waiting material	W	NVA	Awaiting material defrosted
Waiting tooling/spares	W	NVA	Awaiting the tooling/spares
Waiting operator	W	NVA	Operator availability
Awaiting inspection	W	NVA	Awaiting inspector
Other(s)	O	NVA	Other time losses

4. Results

4.1. Lost time analysis

Figures 3 and 4 show the Pareto analysis of the NVA tasks in Year 1 and Year 2 respectively. The aim was to structure the data such that the most time-consuming NVA and NVA-BN tasks became apparent by their percentage contribution, allowing comparison of older production data to more recent parts manufacture. In Year 1 there were five activities which were within the 80% cumulative percentage boundary of the Pareto analysis: 1. Rework; 2. Inspection; 3. Lay-up Issues; 4. Maintenance, and; 5. Debulk setup. Chiefly, the NVA activity of Rework formed the highest amount of time spent on a NVA activity with the other four activities considered to be NVA-BN. Year 2 data shows an improvement whereby the number of activities with 80% cumulative percentage had fallen to three, but the former chief NVA activity had reduced to second in the ranking. To make further continuous improvements by Pareto analysis, only three activities should be focussed on to increase cycle time. Therefore inspection, rework, and lay-up issues still remain key factors in the lost time analysis, but have now been shown to reduce as the process matures along its technology trajectory.

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

Figure 5 details the percentage difference in the time taken between Years 1 & 2 production data. 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.

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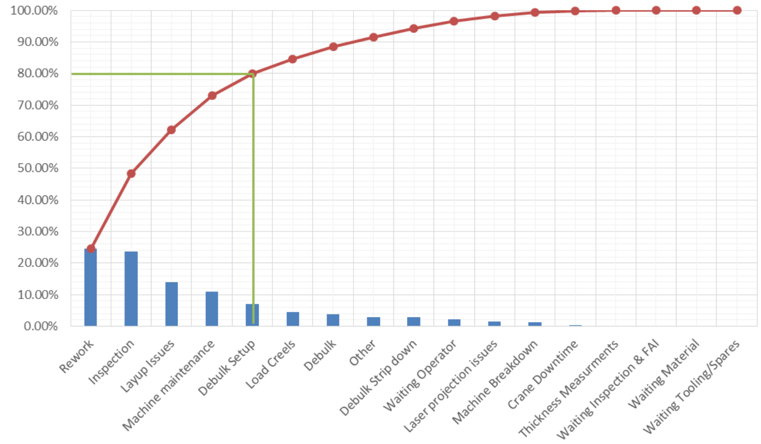

Figure 3. Detailing the Pareto results from Year 1 data of AFP operations.

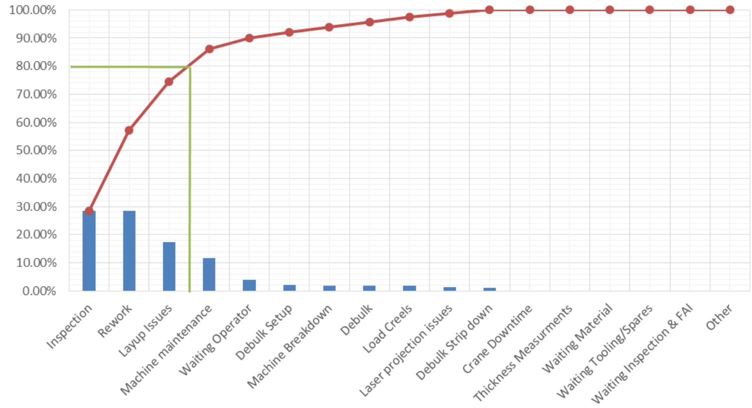

Figure 4. Detailing the Pareto results from Year 2 data of AFP operations.

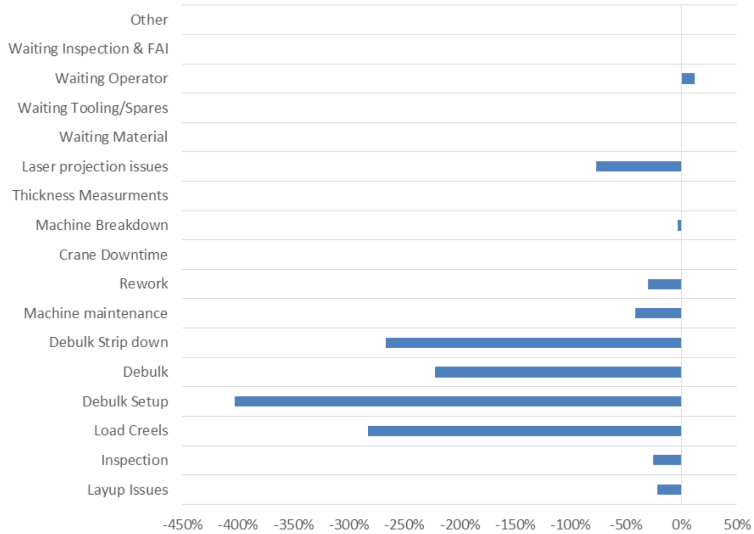

Figure 5. Detailing percentage cycle time differences between Years 1 & 2 of AFP operations.

4.3. Variability analysis

In addition to cycle time reductions, it is advantageous to identify how the AFP process has stabilised over time; to ascertain how parts can be produced at predictable rates. Table 3 highlights the difference between Years 1 & 2, where the ratio of average cycle times between the years are calculated against a desired rate of 13 shipsets per month. Coefficient of Variability (CoV) was used as a measure to

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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. Thus the CoV was multiplied by the part-to-part variance - i.e. the percentage difference in cycle time between the current and previous parts. This allowed the result to be negative as well as positive, and gave the output shown in Figure 6. It is readily observable that on average, the variation in cycle time has reduced considerably between Years 1 & 2. Figure 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 the timecycle.

Table 3. Highlighting co-efficient of variance change between Years 1 & 2.

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

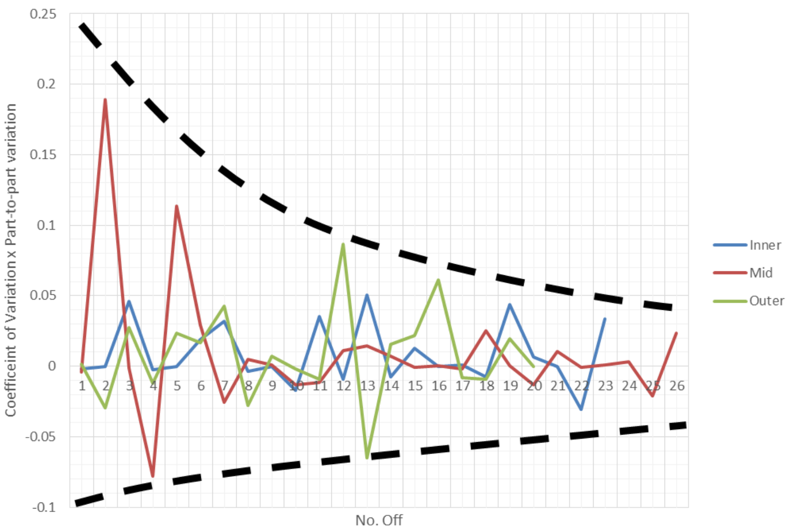

Figure 6. Highlighting co-efficient of variance as multiplied by part to part variance.

4.4. Learning curves

Figure 7 details how well the data contrasts against the traditional 80% Learning Curve of Wright [10], based on the initial cycle time of the AFP process as an average of the 3 off spars (Inner, Mid and Outer). Coupled with this curve is a modelled curve from the time series data analysed, conforming to a power law and exhibiting a rate of 93% learning - i.e. a lower rate of learning than that forecast by the traditional case. The results suggests 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 only serves as an indicator, since the R^2 values derived exhibit a fit of 78%. Despite this, it shows a continued rate of learning, reducing cycle time, and progressing towards desired rates of manufacture.

5. Discussion

The data presented indicates how, during Years 1 & 2 of the analyses, the AFP process was prone to over-processing and waiting times. A high degree of NVA activity was initially evident; whilst the NVA-BN activities have decreased considerably over Years 1 & 2, as over-processing was evident with the debulking process. The data has illustrated how cycle times are reducing with each successive part manufactured, and it can be appreciated how the process has become more stable with time. This can be further elaborated by the average learning curve for cycle time, Figure 7. Here, the traditional fit for aircraft production is shown to be not applicable. Rather, a learning curve of 93% demonstrates a much more useful measure for future performance prediction. This has important implications in the

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costing, and time to profit calculations for new projects introducing brand new breakthrough technologies of this kind. 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. But the data was also 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 had occurred.

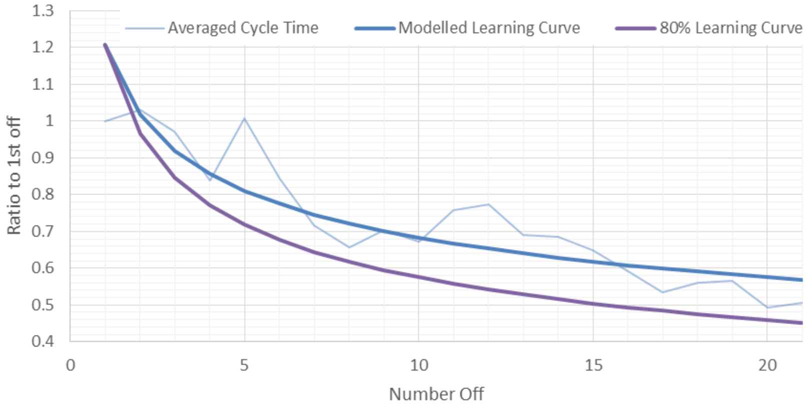

Figure 7. Traditional 80% learning curve contrasted against the 93% learning curve generated over two successive years of manufacture.

6. Conclusions

This paper has reported on the non-value adding activities within AFP, that can detrimentally impact on production rate capability. A two year longitudinal case study has identified and accounted for the non-value adding tasks that surround the AFP process, shown by percentage their impact, and the process of targeting reducion over that period. Through applying a coefficient of variation how the AFP process has stabilized has been demonstrated, as well as demonstrating the emergence of a new learning curve that better represents cycle time reductions for each successive part produced.

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