Implementing Lean Six Sigma to Overcome the Production Challenges in an Aerospace Company

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Lean Six Sigma (LSS) has established itself as one of the key business process improvement strategies available to companies today. With roots based in the single strategies of Lean and Six Sigma, LSS offers a dual strategy towards systematically reducing waste and increasing value whilst resolving Critical to Quality issues that affect consistency and repeatability in a product and process. This paper proposes a Strategic Lean Six Sigma Framework (SLSSF) that attempts to create an integrated approach between the Lean and Six Sigma elements and one that is capable of achieving greater efficiency of production whilst also ensuring that CTQ issues are eradicated from the production process. The case study involves the application of the SLLF in an aerospace manufacturing company. The work highlights the key stages of the framework before closing with an analysis of its effectiveness and the difficulties encountered in its application.

When the LSS model was implemented it achieved significant improvements in business performance. The key improvements were seen as; Build time reduction of 20.5%, improved on-time-in-full (OTIF) delivery to customer by 26.5%, reduced Value Added time by 5% and, reduced Non-value added time by 44.5%. Also, estimated financial savings of over £2 Million are proposed.

Keywords: Six Sigma; Lean; Lean Six Sigma, Implementation, Case study; LSS Framework.

Introduction

Lean Six Sigma (LSS) has become a leading business improvement methodology which has been successfully applied in a wide range of businesses. LSS aims to drive business process improvements through adopting the key features of both Lean and Six Sigma and combining these features in to an integrated approach towards business performance enhancement. In so doing, companies focus on systematically creating value and reducing and removing waste (the lean element of the approach) whilst employing Six Sigma to focus on and to eradicate the Critical to Quality (CTQ) issues that affect an organisation (Zhang et al, 2015, Drohomeretski, et al, 2014). In applying this combined approach, LSS aims to achieve fast flexible flow of products and services whilst systematically eradicating any issues that could adversely affect the quality and performance of the business process.

Earlier pioneers of LSS such as George (2002) proposed combining Six Sigma with that of Lean speed in order to achieve performance improvements that could be gained quicker and more effectively than applying Lean and Six Sigma as distinctly separate strategies. His work, proposes the utilization of the Six Sigma DMAIC cycle as being the central driver to the delivery of LSS where appropriate lean and six sigma tools are applied to each stage of the DMAIC cycle as it was implemented.

This paper chronicles the application and implementation of a Strategic Lean Six Sigma Framework (SLSSF) in a medium sized UK aerospace manufacturing company. The company is a specialist manufacturer of internal aircraft structures and had for many years suffered from significant issues with production capacity and capability. This paper proposes the application of the Framework that combines the standard DMAIC cycle with that of the standard Lean thinking cycle to create a Framework that provides a clearer and more integrated approach to LSS application. This paper will therefore initially and briefly discuss the nature and structure of existing LSS models and approaches before describing through a case study, the design and application of the new SLSSF. The main aim of this paper is to show how the SLSSF was used to develop a novel strategic implementation blueprint and as such the work outlines only the key details of each LSS project stage. The paper closes with an analysis of the capabilities of the Framework by accurately detailing the manufacturing benefits achieved from its application.

Lean Six Sigma

Traditional models and applications of LSS follow predominantly a Six Sigma centric focus. Table 1 shows the results of a systematic literature review of key LSS case studies. As expected, all case studies reviewed in this work show the systematic use of the DMAIC cycle. However, with the exception of Andersson *et al* (2014) who briefly outline the Lean thinking cycle, none of the articles show the systematic application of the Lean thinking cycle in their work. Furthermore, the review also highlights that most LSS applications are primarily focused on quality improvement where improvements in throughput and overall business improvement are claimed as a result of resolving the Critical to Quality issue at hand. This suggests that the Lean thinking cycle is not used as the predominant driver for LSS implementation. Albiwi et al (2015) also offers a systematic review of academic literature on the implementation of LSS and accurately plot the various tools and techniques which have been employed at the various DMAIC stages of LSS implementation. This work confirms the already held view that tools such as Value Steam Mapping (VSM), Total Productive Maintenance (TPM), Design of Experiments (DOE), Statistical Process Control (SPC), 5S and Quality Function Deployment (QFD) etc are still key to LSS implementation success. Further analysis of their work highlights that with the exception of VSM, most implementation methodologies employ predominantly Six Sigma tools.

However, the work of Shah et al (2008) offers a slightly different perspective and suggests that from their work on identifying tool adoption patterns in lean and six sigma implementation projects that successful implementation of Six Sigma projects is greatly increased if Lean principles and tools are included in the implementation of Six Sigma. Hines et al, (2004) clearly identify the role of Six Sigma to be at an operational level and one which is used to support the strategic Lean implementation process. This would therefore suggest that Six Sigma forms part of a sub-set of operational strategies that fit in to the higher order lean thinking process.

Therefore, the role of both Lean and Six Sigma cycles within an LSS implementation framework is a key issue since most approaches towards LSS implementation has been to integrate lean tools in to a standard Six Sigma DMAIC cycle. In so doing, two key issues emerge. Firstly, in implementing LSS in this manner, Lean is viewed and utilized as a tool kit of techniques that are deconstructed from the Lean thinking cycle and inserted in to the Six Sigma methodology at various stages. In so doing, this can fundamentally undermine the lean thinking philosophy and removes the opportunity to use Lean as a strategic thinking approach within the LSS framework. Secondly, the predominance given to the Six Sigma DMAIC cycle within the existing LSS framework seems to lead practitioners and applied academics to drive quality based improvement projects rather than Lean based projects or projects that create a dual impact of both quality and efficiency improvement (see Table 1).

Considering these issues, this paper will detail the development of a new SLSSF which enables the full development of the Lean thinking framework to operate within the LSS Framework. This will be the first time that this SLSSF has been applied and the paper will attempt to highlight the early stage benefits obtained by the company through its implementation.

The case study follows the implementation of the SLSSF in to a medium sized enterprise aerospace company. Its aim is to not only systematically improve the manufacturing performance of the company but also to test and validate the SLSSF before considering its wider application in industry. Therefore, two research questions are proposed in this work namely:

(i) *To what extent does the implementation of the SLSSF assist in the improvement of a company's manufacturing performance* and,

(ii) *What specific LSS tools and techniques are best applied to each stage of the LSS cycle?*

Development of the SLSSF

Both the Lean and Six Sigma cycles have been well known amongst academics and practitioners for many years. The Lean cycle consists of five key principles in which the practitioner is guided towards implementation. These principles are: (1) *Specify Value* from the customer perspective; (2) Align the internal *value stream* with what the customer values; (3) *create flow*; (4) *pull on demand* (5) create *perfection* (Womak Jones and Roos, 2007).

Six Sigma also follows a standard five stage cycle (DMAIC) and is defined as: (1) *Define* the CTQ issue; (2) *Measure* the problem; (3) *Analyse* the problem; (4) *Improve* - to eliminate or reduce the problem; (5) *Control* the improvement to ensure the problem is resolved and the new order is frozen (Harry & Schroeder, 2006).

In an attempt to address the issues previously highlighted around the limitations of the current LSS methodology, the authors propose a new development of the LSS approach. Figure 1 shows a conceptual development of the proposed SLSSF. In this approach, the DMAIC cycle is implemented at each point in the Lean thinking cycle and proposes the simultaneous implementation of both Lean and Six Sigma in a correctly balanced Lean Six Sigma format. This paper will now focus upon the implementation of this new LSS Framework and will highlight the key tools and techniques that were employed and will later objectively analyse its effectiveness in improving business performance. Firstly though, an introduction to the company is made in the next section.

Case Study – AEB Ltd

The case company is an aerospace manufacturing company that specializes in the manufacture of internal aero structures to a global client base. The company has a significant reputation in the manufacture of high quality products but had known for some time that it was losing market share to its competitors but had failed to identify the root cause of the issues that surrounded its poor market performance.

Initial sales analysis identified that the company was only converting 21% of its quotes in to firm orders. However, due to a lack of market intelligence, they were unable to establish whether this was above or below industry norms. Closer analysis of the company's on-time-in-full (OTIF) delivery of products to customer showed that their 57 day lead time was being met on approximately 72% of the time with a further 20% of the products delivered within 2 days of the 57 day target value.

Therefore, in an attempt to drive process improvement and ensure the OTIF target was improved, the company initiated several separate Lean and Six Sigma programmes with significant investment being made on in-company training and pilot improvement projects. However, after four years of these various initiatives, the company conceded that the full impact of both Lean and Six Sigma implementation had not been seen. This failure was largely put down to the lack of a coherent approach to multiple project delivery and the lack of strong project management and leadership.

However, through closer analysis of the business improvement strategies adopted, the failure of the Lean and Six Sigma projects to yield the expected benefits could not be fully blamed on the lack of a clear approach to project implementation. A major factor which affected performance was the actions of the sales team and the senior leaders within the company. Frequently, as a result of falling sales, the company would agree to taking on orders for products that their competitors would turn down either due to the lack of sufficient lead time or, due to the complexity of the product which would require specialist equipment that the competitor companies would consider too much of risk to take on. Therefore, when the company took on these orders, all resource would be diverted to producing these products. This in turn meant that labour costs became crippling (due to high overtime and the taking on of project based staff to push the products through the company) resulting in marginal profits (if any) being made. Furthermore, if OTIF was not met, the company would face penalties for missing the Aircraft on Ground (AoG) slot thus resulting in significant financial loss to the company. Whilst these issues adequately explain the financial losses experienced by the company, the loss to the company from being unable to continue developing their Lean and Six Sigma projects as a result of these disruptions, damaged the long term viability of the company.

In 2012, the company sought help from the authors of this paper to employ a new approach to business process improvement. This provided the authors with an opportunity to develop and implement the SLSSF to overcome the key performance issues within the company.

Rationale for Implementing the LSS Framework

The company had for many years developed and deployed Lean improvement teams in the company in the form of Kaizen Blitz teams. Therefore, the company were used to implementing basic Lean techniques such as 5S, TPM and visual management boards. However, the company often employed these approaches in an unstructured and piecemeal way and, much of the higher level thinking strategies around waste reduction and identifying customer preferences and value were not being employed. This was amply exemplified through a discussion with a shop floor worker who stated '*we can save $2 on a bolt by changing supplier but miss the delivery point with our customer costing us thousands of dollars'*.

Attempts to employ Six Sigma in to the company was introduced a number of years later where a simplified DMAIC approach was used to systematically reduce quality related problems around their CNC facility. This brought modest savings but no major impacts to the production system. Six Sigma was initially employed to try and aim for OTIF so that missed delivery points with AoGs could be avoided. However, once it was found that Six Sigma could not in itself provide the solution, the approach was then employed on individual areas of production rather than where it needed to be used in order to benefit the whole production system. This meant that company moved towards multiple Lean and Six Sigma applications rather than a strategic and systematic approach to their application. Furthermore, the company was now operating two separate improvement strategies which caused confusion and a lack of a single top-down, management supported and committed improvement strategy. This often led to confusion and conflicting opinions on which was the most effective improvement approach to employ.

Following detailed discussions with the company management, a series of scoping studies which focussed on analysing the operational systems in the company were employed and, an outline LSS implementation framework was proposed (see Figure 2 and Table 5). The Framework was developed after a number of meetings with top and middle level management and engineering staff of the company where the key processing parameters were identified and quantified so as to obtain a clear picture of the true extent of the operational systems employed.

Prior to the implementation phase being adopted, all of the company's staff were trained in order to prepare for changes that they were going to encounter. The work of Kumar *et al,* (2011) and that of Kumar and Antony (2010) and Spina *et al,* (1996), stress the issue of ensuring company 'preparedness' before venturing in to the full implementation programme. Therefore, an awareness raising programme was initiated and ran for three months in which the implementation process was outlined and where all staff were given the opportunity to contribute to the implementation process and to jointly discuss the direction of travel. Work Based Learning training sessions were introduced for staff in order to develop expertise in LSS implementation. Also, the project team delivered practitioner level training to production staff who would need to carry out much of the practical tasks (autonomous maintenance, problem resolution through Six Sigma teams etc). Most importantly, the senior management and board members of the company were given awareness sessions. Once the company were in a position to move to the implementation phase, the first LSS workshop commenced which was focussed on the first Lean cycle element (Specifying value). The following section outlines the key work undertaken in each phase of the LSS cycle.

The next key stage in the process was to clearly identify the LSS tools and techniques to be employed in the project. In identifying early the typical tools and techniques to be employed, suitable and timely training on them could be executed. This included sufficient time being allocated to collect data and information on order to deploy the tools and techniques effectively. Selection of the correct tools is critical to any LSS event. However, much debate exists around which are the most important to use in order to maximize performance. For instance, Belekoukias et al (2014) identify that tools and methods such as automation and JIT have a much higher impact on Lean implementation than the like of Kaizen, TPM and VSM. Kirkham et al (2014), on the other hand identify that the tools and methods based around the Six Sigma methodology are often seen as the more influential on the success of improvement projects.

Darlington et al, (2015) outline the effectiveness of using the Drum Buffer Rope method associated with the Theory of Constraints as being the more effective improvement driver and that the use of a wide range of improvement tools and methods were not required if such a methodology was used.

With these issues in mind, the project team mapped the tools and methods required for each stage of the LSS cycle. The aim was to minimise the over-use of tools and techniques so as to develop a core set of key tools for implementation. Therefore, within the Lean and Six Sigma phases of this work, the project team firstly analysed the range of tools available and then settled on a coherent set that were capable of driving change. These were: Kano, Quality Function Deployment (QFD), VSM, Optimised Production Technology (OPT), Design of Experiments (DoE), Kanban systems, Poka Yoke and Control Charts. Table 5 shows at which stage each tool and technique was employed.

Stage 1 Lean Cycle – Specify Value

Define:
A focus group made up of end users was arranged and a 3 day conference held in which customers (airline flight attendants and engineers) were asked to discuss the key Critical to Quality issues and the value adding features that they required from the product. The focus group followed the *Kano* approach and listed the key Basic, Performance and Delighter features required. Table 2 highlights the key issues from the Kano study.

Measure:
The key features were identified and the focus group asked to rate the company's performance on providing those features against those of their major competitors in order to measure their performance and assess the gaps in product and service performance.

Analyse:
Following the 'measure' stage, the company undertook a Quality Function Deployment (QFD) Exercise at HOQ 1 level in order to establish the key customer requirements and to map those requirements to how the company could meet the customer needs. Figure 2 shows the QFD chart.
Key QFD outputs included the systematic reduction of OTIF target down to 45 days from current 57 days with a cost saving on product being 20% lower than current price and, a 5% reduction in price year on year for five years after.

Improve:
The company then identified the key product and process features required and assesses capability to deliver the new requirements. Any key investments were identified and balanced against return on investment.
The key outputs included; a 10 day reduction in production lead times achieved through Lean design, a 2 day reduction in design lead time to achieve cost reductions and to enable production to start earlier in order to meet the stage gate deadlines. This also highlighted the need for OTIF delivery of designs (and CNC programmes) to the production facility with zero variation on target.

Control:
These new requirements were then locked in to the ERP system and the designs and production plans were then developed. Senior management signed up to achieving the new KPIs and agreed to manage progression against the targets.

Basic	Performance	Delighter
Achieve build time of 57 Days without variation. Achieve 100% OTIF Maintain Quality, Cost and Delivery KPIs at current state. Achieve consistency.	Provide greater range of product options on assembly	Reduce Build Time to 45 Days without variation. Achieve 100% OTIF Reduce product cost by 20% Reduce product weight by 5%.

Table 2 Outputs from Kano Study

Stage 2 Lean Cycle – Align Internal Value Stream

Define:

From stage 1 of the process, the project was defined as ensuring that a ten day reduction in the company's manufacturing operations was to be achieved with a further two days from is design process. This paper will focus on the reduction in manufacturing process time and, in achieving the OTIF delivery target on a consistent basis of 45 days +/- 0 days variation.

Measure:

A Value Mapping (VM) exercise was conducted by a multi-disciplinary team of engineering and production staff. The processing times as well as the VA/NVA activities at each stage of the manufacturing process were calculated and key process areas identified for further analysis. Figure 3 shows the VM exercise undertaken and Tables 3 and 4 show the VA/NVA analysis stages on the current and future state analyses respectively.

Analyse:

The multi-disciplinary team identified that a significant area for improvement would be in removing the cycle circled on the VM. This was to remove the need to reassemble the structure after first stage inspection. If this could be achieved then the company would come close to meeting the ten day reduction target. The team focussed on this area and set up an improvement group to resolve the issue. Figure 4 shows the graphical representation of the VA and NVA on the current state Value Analysis. Here it is possible to see that the issue of dis-assembly is seen as highly wasteful since it necessitates the build team to disassemble the whole structure once it has been passed as being correct by QA (further information provided later).

Improve:

The improvement team worked on providing a solution of removing the need to disassemble the structure and then reassemble again with adhesive. This work cost the company 2 days to disassemble and a further five days to reassemble with adhesive. The focus was to develop a process whereby adhesive could be applied immediately after the structure had been dry assembled and subsequently passed by QA. This was achieved by modifying the tongue and slot arrangement to allow adhesive to be injected in to the rear of each tongue and slot through a series of injection holes that were drilled in to the slot faces at the CNC cutting stage. In so doing, the company could build the structure in its dry condition and move straight to adhesive application following inspection.

Control:

Process engineers developed an adhesive injection procedure including investments in the new machinery and systems to support adhesive injection. The engineering team also developed specific test procedures to test the injected tongue and slot arrangement to ensure new test data is made available to the design department and regulatory authorities.

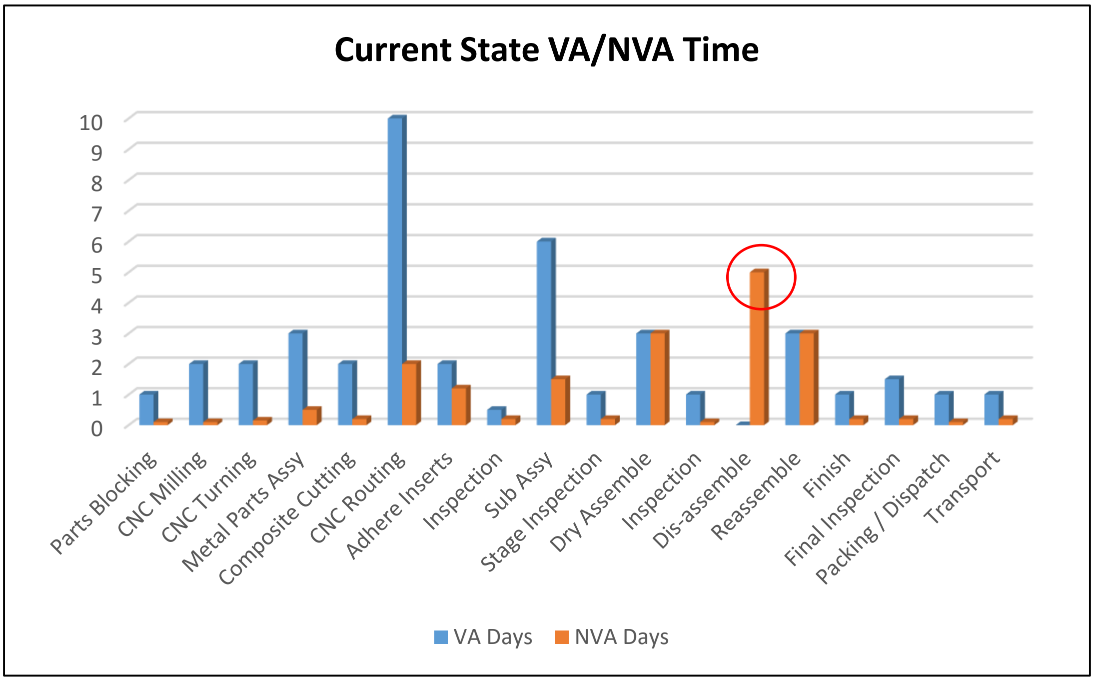


Figure 4 Current State Analysis of VA ad NVA activities

Process	% VA	VA Time (Days)	NVA Time (Days)	Mean Process Time (Days)
Parts Blocking	90	1	0.1	1.1
CNC Milling	95	2	0.1	2.1
CNC Turning	93	2	0.15	2.15
Metal Parts Assy	86	3	0.5	3.5
Composite Cutting	91	2	0.2	2.2
CNC Routing	83	10	2	12
Adhere Inserts	63	2	1.2	3.2
Inspection	71	0.5	0.2	0.7
Sub Assy	80	6	1.5	7.5
Stage Inspection	83	1	0.2	1.2
Dry Assemble	50	3	3	6
Inspection	91	1	0.1	1.1
Dis-assemble	0	0	5	5
Reassemble (Wet)	50	3	3	6
Finish	83	1	0.2	1.2
Final Inspection	88	1.5	0.2	1.7
Packing / Dispatch	97	1	0.1	1.1
Transport	83	1	0.2	1.2
TOTALS		**41**	**17.95**	**58.95**

Table 3 Current State Analysis of Value and Non Value Added Activities

Process	% VA	VA Time (Days)	NVA Time (Days)	Mean Process Time (Days)
Parts Blocking	90	1	0.1	1.1
CNC Milling	95	2	0.1	2.1
CNC Turning	93	2	0.15	2.15
Metal Parts Assy	86	3	0.5	3.5
Composite Cutting	91	2	0.2	2.2
CNC Routing	83	10	2	12
Adhere Inserts	63	2	1.2	3.2
Inspection	71	0.5	0.2	0.7
Sub Assy	80	6	1.5	7.5
Stage Inspection	83	1	0.2	1.2
Dry Assemble	50	3	3	6
Inspection	91	1	0.1	1.1
Dis-assemble	**0**	**0**	**0**	**0**
Inject Adhesive	**50**	**1**	**0.1**	**1.1**
Finish	83	1	0.2	1.2
Final Inspection	88	1.5	0.2	1.7
Packing / Dispatch	97	1	0.1	1.1
Transport	83	1	0.2	1.2
TOTALS		**39**	**10.05**	**49.05**

Table 4 Future State VA/NVA Analysis

Stage 3 Lean Cycle – Create Flow

Define:

The aim of this stage was to create fast flexible flow of parts through the production system. In order to do this, the team focussed upon providing a solution to removing the system constraint of dismantling and rebuilding the structures. Therefore the ‘define’ stage was to ensure that the joint strength obtained from the adhesive injection method was at least comparable to the traditional manually applied method thus achieving significant savings in build time whist ensuring joint strength is left unaffected.

Measure:

Laboratory tests were undertaken on the new injection process to ensure product integrity could be maintained. At this point however, the process showed that adhesive injection method produced a joint strength value which was 1.5kN lower than the traditionally applied joint application method. Therefore, a CTQ issue arose at this point which needed eradication before the process could be accepted.

Analyse:

Macroscopic analysis of the failed joints identified that using the current joint design did not allow sufficient adhesive ingress in to the slot when the injection method was used. Joint redesign was required which enabled an improved flow of adhesive in to the slot without affecting the integrity of the joint.

An experimental design study was undertaken where each of the key joint variables were changed in order to identify the optimal joint settings. The experimental design stage needed to find a single joint arrangement which would provide the appropriate strength values for the joint under three loads of; Transverse, Longitudinal and Tensile. A multi-disciplinary team used Pareto and C+E analysis to identify five key variables of; slot length, slot width, tongue depth, tongue length and, adhesive type. Two interaction effects of slot length x tongue length and tongue depth and slot width were also considered. An eight experiment array (L8) was developed at two levels. An ANOVA for each load condition was also applied.

Improve:

The experimental design study yielded a new joint arrangement which could potentially be used to resolve the strength issues around the joint. A confirmation run with the new joint arrangement was made, the results of the confirmation run identified that the new joint design enabled improved adhesive ingress with joint strength being within 2% of the traditionally applied adhesive. Homologation testing was subsequently undertaken to achieve aviation standards approval.

A simulation of the production flow using the expected new processing times was undertaken in an attempt to identify any further system constraints which could be reduced or eliminated. A further two days reduction in processing time was achieved through increasing flow through the paint shop whilst the amount of inspection reduced due to the elimination of the need to rebuild the structure. This brought the build time down to 46 days in total, one day short of the target build time.

Control:

The new joint arrangement was tested further to ensure it met homologation standards. The new joint parameters were then sent to the design engineers who then updated the standard operating procedures. The production engineering department subsequently changed the CNC programme codes for the new joint design thus freezing the new design arrangements going forward.

Stage 4 Lean Cycle – Pull on Demand

Define:

The aim of this stage was to ensure that pats could be pulled through the production system within the new 45 day target time. Up to this point, only simulations of the production system had been made and this work suggested that it may be possible to pull through the system at the required rate to meet customer requirements.

Measure:

Following manufacturing system redesign and working with the existing supply chain companies in educating them of the new requirements, the company moved towards an effective pull system. Figure 5 shows the build times of the first seven products through the system. Whilst significant improvements were seen in build time improvement, total build time could not be improved past 47 days.

Analyse:

The production engineering team analysed the manufacturing process and identified the constraints in the system that limited the build time to 47 days. It was found that a possible 1-2 day saving could be achieved by focussing on redesigning and increasing the number of sub-assembly tooling that was available to the build team.

Improve:

In conjunction with investments in new tooling and support equipment, minor adjustments and small industrial engineering projects chipped away at the build time to reduce the total build time to 46 days in total. For instance, Kanbans were set up for insert and sub-panel availability at final build stage.

Control:

New tooling was employed and old tooling scrapped to ensure the team could not revert back to old habits. Poka Yoke devices were employed such as new CNC programmes were produced that pre-drilled the injection holes so that consistency of build was achieved.

Stage 5 Lean Cycle – Create Perfection

Define:
The company decided that at 46 days build time, the remaining one day reduction in build time could be achieved through minor continuous improvements on the shop floor. However, at this stage there was a need to ensure that the build time of 46 Days was achieved on a consistent basis and, variation in build time was to be reduced

Measure:
The build time values were measured for the next ten parts coming off the production line. The variation in build time was measured as 46 Days + 1 day, - 0 days with earlier stage parts being manufactured closer to 48 days before systems started to operate correctly thus moving the variation closer to the 46.5 day marker (See Figure 5).

Analyse:
Most variation was created from the lack of synchronicity between sub-assembly build and the final build which in turn caused stock shortages at final build stage.

Improve:
A detailed study of the CNC router area identified key issues around panel set-up times being far too long. This impacted upon build throughput time which led to final build shortages. An industrial engineering study was undertaken by a Lean Six Sigma Blitz team which reduced panel build set-ups using Single Minute Exchange of Die (SMED) principles. A further ten build times were measured and a market improvement was seen on OTIF values although some further improvement is still required. Figure 6 shows the twenty sequential parts that were built showing the systematic reduction in build time variation.

Control:
SMED procedures were consistently applied and continuous measurement and systematic continuous improvement was undertaken to reduce variation further.

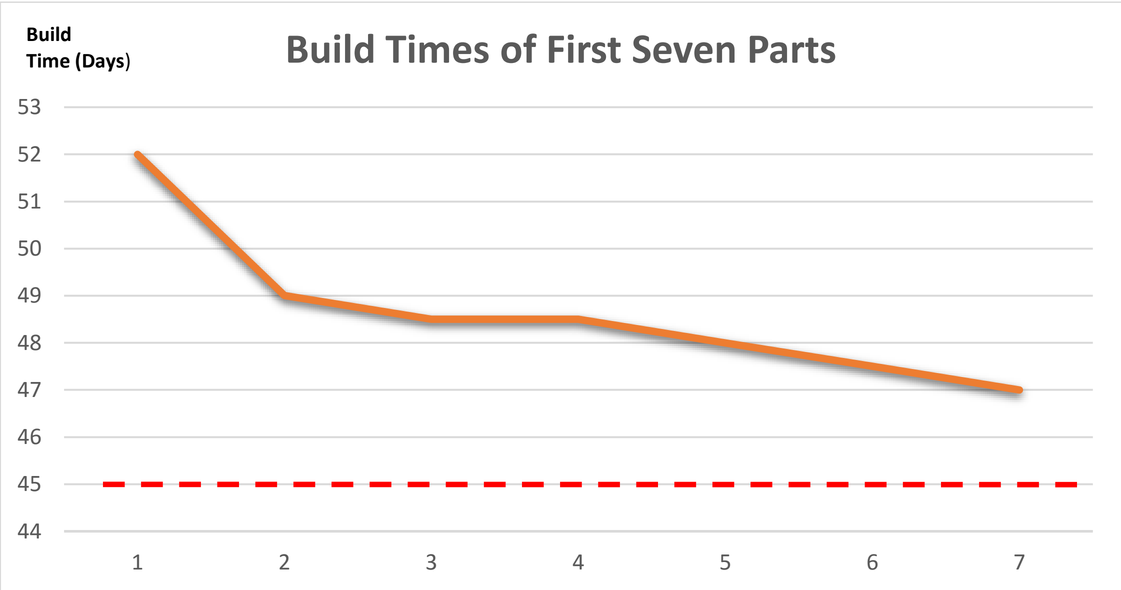


Figure 5 Build Time of Consecutive Parts.

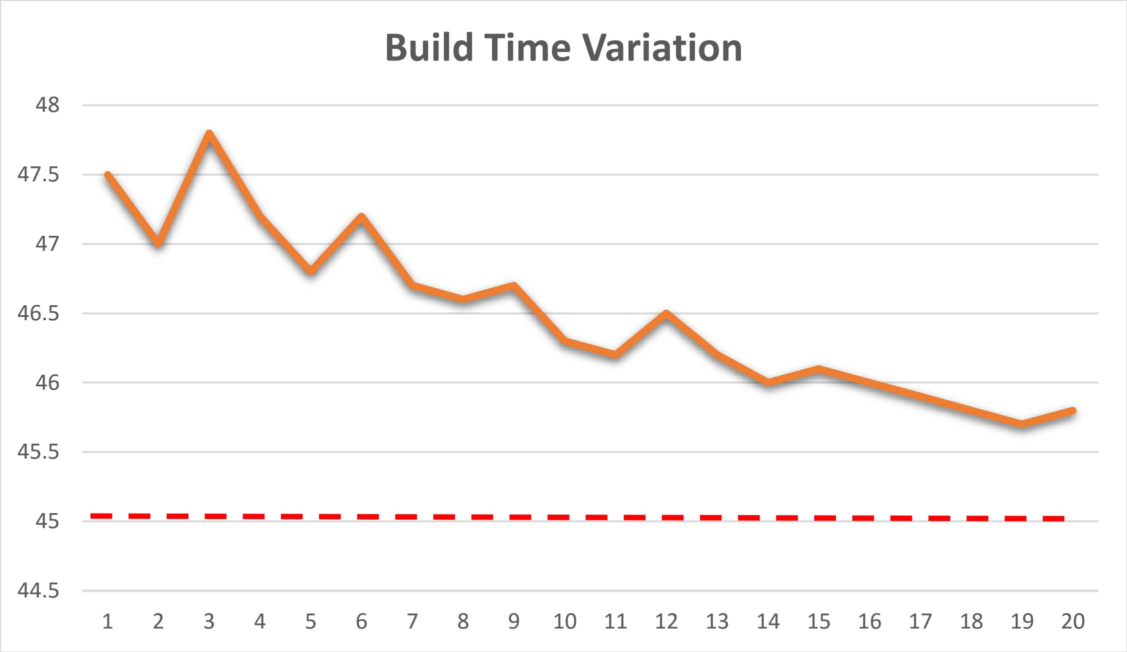


Figure 6 Build Time Variation of Consecutive Parts.

Results and performance of SLSSF Implementation

Table 2 outlines the initial set of client performance measures that the company worked towards achieving. The initial focus was to drive towards delighting the customer and to achieve a 45 day build time. In achieving this target value, greater shop floor capacity would be released thus enabling the company to reduce production cost. With a clear focus being taken to reduce total build time, four key measures of performance were used to assess the effectiveness of the SLSSF implementation. Figure 7 shows the improvements made:

- Build time reduction - 58 days to 46 Days (20.5%)
- OTIF improvement – from 72% to 98% (26%),
- VA time reduction - 41 Days to 39 Days (5%)
- NVA time reduction -18 Days to 10 days (44.5%).

These measures were selected since the OTIF and Build Time Reduction KPIs were identified from the early stage customer analysis. The VA/NVA measures were used as a means of tracking the effectiveness of the waste reduction strategies employed during the implementation stages. Figure 7 provides a graphical representation of the performance improvements achieved

By the end of the project, the company had not met the customer delighter target for build time reduction. This was set as 45 Days whereas the company achieved 46 Days by the end of the project. However, the company were confident that through continuous improvement, the 45 Days target would be reached comfortably. Likewise, the OTIF target of 100% was not fully achieved by the end of the project. However, the improvement trends seen following LSS implementation suggest that 100% OTIF is likely to be achieved within the next 15 aircraft sets as the new production system settles down and experience of new build assembly improves.

The ability of the company to reduce its build time by eleven full days and achieve consistency of delivery around 46 days has significantly improved the financial viability of the company. Whilst still in its early stages, the company expects increases in sales of some £3Millon over the next year due to increased responsiveness to customer demands brought about by improved productive capacity. Likewise, a reduction in cost per aircraft set totalling some £45000 has been achieved with an estimated annual total saving of £2.8Million likely.

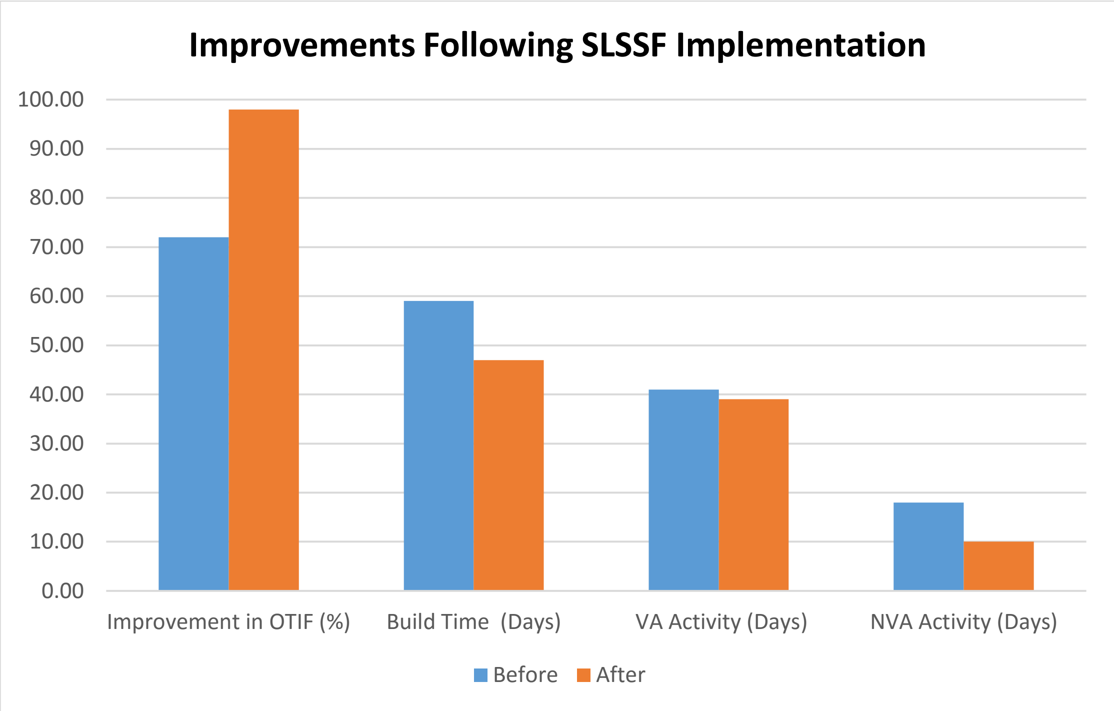


Figure 7 Improvements in Production Performance Following SLSSF Implementation

Limitations with the SLSS Framework

A number of valuable lessons were learned from this project. Highlighting these issues within this paper is critical in that it offers a perspective to other LSS implementers of the key issues that should be taken care of while starting the new project. In this case, as with the work of Kumar et al (2006), convincing top management was the most difficult task. Although initially the management were enthusiastic towards implementing the SLSSF, when it came down to the full implementation and, the issue of changing the build stage to allow for adhesive injection, it became increasingly difficult to motivate management towards maintaining focus on the SLLSM. Senior management felt that investing in a new build method would adversely affect the quality. When it was found that the initial injection approach did not provide the strength characteristics of the traditional system, the project nearly collapsed. However, through continued discussion and through a single minded determination to resolve the strength issues of the new adhesive injection method, the team was able to keep the LSS project on track. Therefore, the issue of ensuring that strong leadership and a single minded attitude to succeed must be seen as critical to any LSS implementation project.

A second major issue was in encouraging staff to adopt more advanced Lean and Six Sigma methods. As a company, only basic lean tools and techniques had previously been employed (5S, TPM etc). Therefore, trying to implement strategic thinking tools such as Kano, QFD and, statistical tools such as experimental design techniques was a significant challenge. Largely seen as an approach which could only been really applied in large manufacturing companies, the authors had a significant challenge to convince both management and shop floor personnel that LSS is an effective approach that requires time and commitment but not necessarily the capital expenditure they initially imagined if the projects are well thought out and solutions are sought that do not need significant capital spend.

Conclusion

This paper proposes an innovative development on the traditional LSS approach through designing, developing and implementing an integrated Lean Six Sigma implementation framework. The framework aims to provide a more balanced approach to LSS implementation whereby the Lean thinking cycle provides the impetus to the application of lean and six sigma tools and whereby the traditional DMAIC cycle is implemented at each of the key Lean stages. In so doing, the framework attempts to drive systematic business improvement beyond the short-term gains that the traditional method of LSS implementation provides and, guides practitioners to apply a deeper more sustainable path of improvement. This is achieved through the application of a wider set of lean and six sigma tools which are systematically implemented in to a lean thinking strategy in order to achieve multiple benefits in performance. The implementation of the Lean Six Sigma Framework (LSSF) provides an impetus within the company for establishing best practice. Moreover, it also provided the operational blueprint on which they could base future performance enhancement programmes.

In relation to research question, to what extent does the implementation of the SLSSF assist in the improvement of a company's manufacturing performance?. Figure 7 outlines the performance benefits gained through the implementation of the SLSSF. The estimated financial benefits gained through savings and increased sales total over £5 Million. In relation to the second research question, what specific LSS tools and techniques are best applied to each stage of the LSS cycle?. Table 5 outlines the key LSS tools and techniques that were employed. When analysed in conjunction with the performance and financial benefits, the applications of the tools were seen to be effective.

The most difficult aspects of implementing the SLSSF was seen in the work around the first lean cycle stage. Both workers and management did not fully engage in this process for a number of weeks. There was a clear assumption that the company knew what the customer wanted and there was a need to rapidly move to stage 2 of the LSS cycle. It was not until the customers attended the conference that the company staff realised that this stage was the most critical stage in the process in that finding the unspoken or latent needs of the customer from the Kano study provided significant new knowledge to work on.

The successful implementation of the SLSSF has created a step change in improving the culture within the business. Roll out of the SLSSF to other parts of the business is being planned where it is expected that the teething problems experienced on this application are less likely to reoccur due to the new knowledge and experience gained but also due to the motivation and cultural change that has occurred. Further roll out will also enable the SLSSF to be further adjusted and validated in a number of new areas within the company. From this roll out, it may be possible to identify how new tools and techniques could be integrated in to the framework but also, it will be possible to compare the effectiveness of this framework against the traditional DMAIC driven LSS models that are available.

Lean Six Sigma Article Review													
Author	**Article Type**	**DMAIC Cycle**	**Lean Cycle**	**Quality Focus**	**Lean Focus**	**Main Tools Employed**						
						VSM	**DOE**	**TPM**	**5S**	**VoC**	**CTQ**	**ToC**
Kumar et al, 2006	Case Study	✓		✓		✓	✓					
Chen and Lyu, 2009	Case Study	✓		✓		✓	✓			✓		
Gnanaraj et al, 2012	Case Study	✓		✓	✓	✓	✓					
Vinodh et al, 2012	Case Study	✓		✓		✓			✓			
Laureani et al, 2013	Case Study	✓		✓	✓	✓				✓		✓
Chakravorty & Shah, 2012	Case Study	✓		✓		✓	✓					
Vinodh et al., 2011)	Case Study	✓		✓		✓	✓		✓			
Corbett, 2011	Case Study	✓		✓	✓	✓	✓		✓			
Van Den Bos et al, 2014	Case Study / Survey	✓		✓		✓				✓		
Andersson et al, 2014	Case Study	✓	✓	✓	✓					✓	✓	

Table 1 Systematic Review of Lean Six Sigma Applications Literature

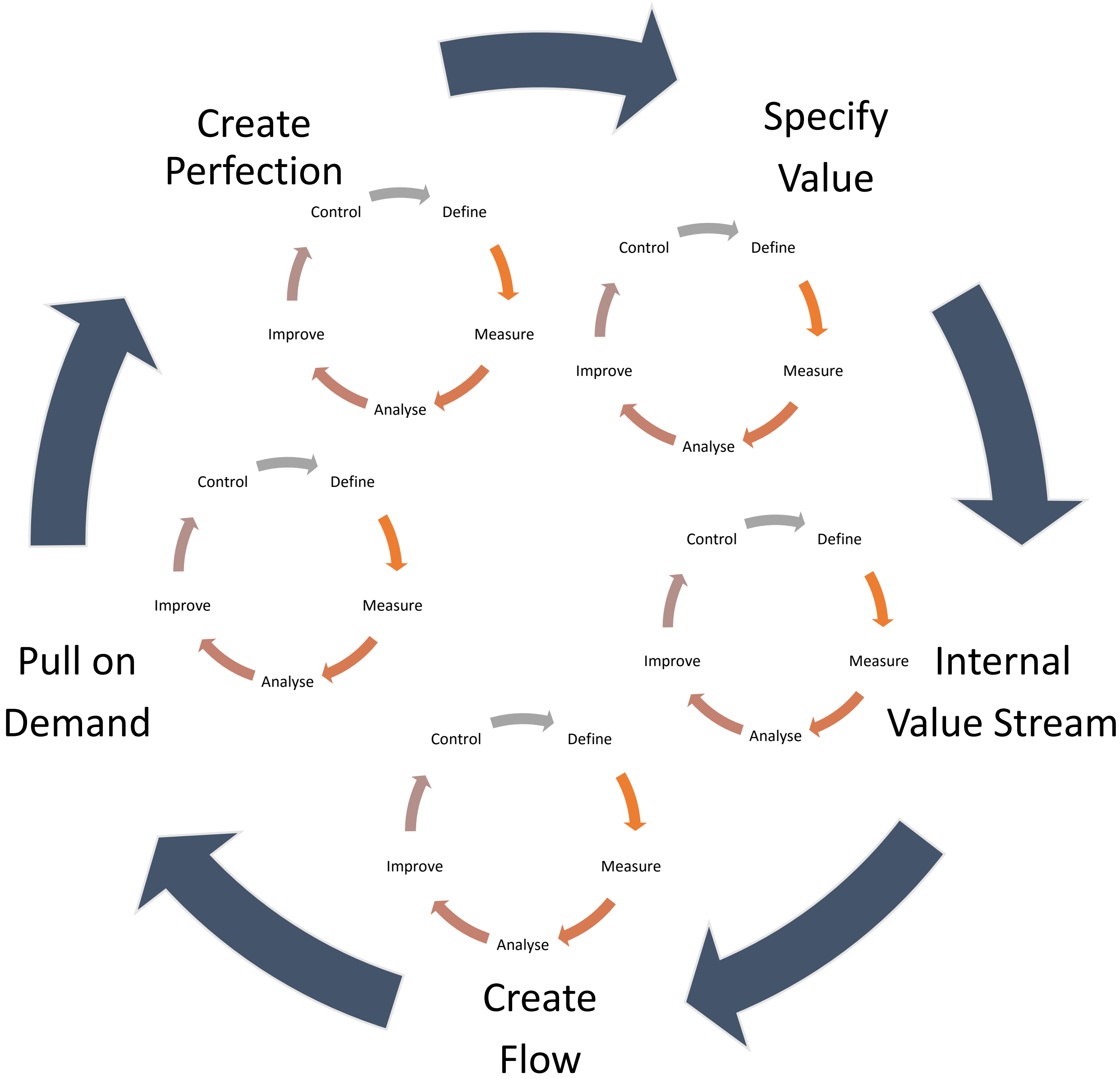


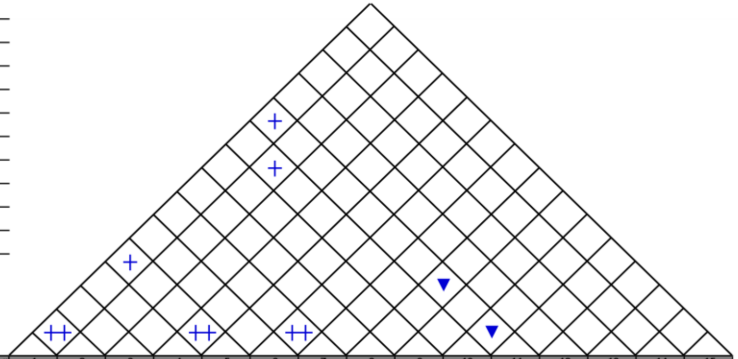
Figure 1 – The Lean Six Sigma Cycle

Title:

Author:

Date:

Notes:



Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
—	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Parametric Programming of CNC Router Cell	Develop solid modelling capabilities	Flexible tooling systems	Remove need for structure disassembly following build inspection	Improve efficiency of CNC router cell	Improve accuracy of job routings	Improve accuracy of production planning	Reduce Inspection volume	Increase training/competency of staff	Change composite panel specifications	Review stress analysis on fittings					Our Company	Competitor 1	Competitor 2	Competitor 3	Competitor 4	Competitor 5
				Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Competitive Analysis (0=Worst, 5=Best)					
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	▼	▼	▼	x	x	x	▼	▲	▲	▲										
1	9	18.2	10.0	On Time Delivery In Full	O		▲	Θ	▲	▲	▲	▲								2	3	3	2	4	2
2	9	16.4	9.0	20% Reduction in Product Cost	▲			Θ	▲	▲	▲			Θ	O					0	2	3	2	2	3
3	9	14.5	8.0	Target delivery 45 Days from order	▲		▲	Θ	▲	▲	▲	▲								0	5	5	4	3	5
4	3	12.7	7.0	5% weight reduction		▲								O	O					2	4	3	4	4	3
5	3	10.9	6.0	Target design phase to first review of 14 days	O	▲	▲				▲									3					
6	9	9.1	5.0	Zero design iterations at first design review	▲	Θ							O							2					
7	9	7.3	4.0	Repeatable quality between aircraft sets		▲	Θ	Θ	O				O							2	3	4	3	4	4
8	9	5.5	3.0	Improved communication (Customer/Company)		O	▲			Θ	O		O							1	4	4	3	4	4
9	3	3.6	2.0	Improved responsiveness to design modifications		O							▲							2	3	4	3	2	4
10	9	1.8	1.0	Improved quality of finished build	▲	▲	O	O	Θ	O			Θ	O	▲					3	3	4	4	5	3
				Target or Limit Value																					
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	7	8	4	9	4	2	2														
				Max Relationship Value in Column	3	9	9	9	9	9	3	1	9	9	3										
				Weight / Importance	129.1	141.8	120.0	512.7	87.3	103.6	76.4	32.7	85.5	190.9	89.1										
				Relative Weight	8.2	9.0	7.6	32.7	5.6	6.6	4.9	2.1	5.4	12.2	5.7										

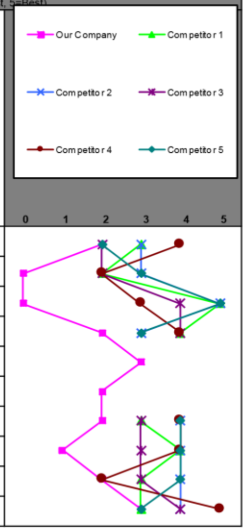


Figure 2 **Quality Function Deployment Chart**

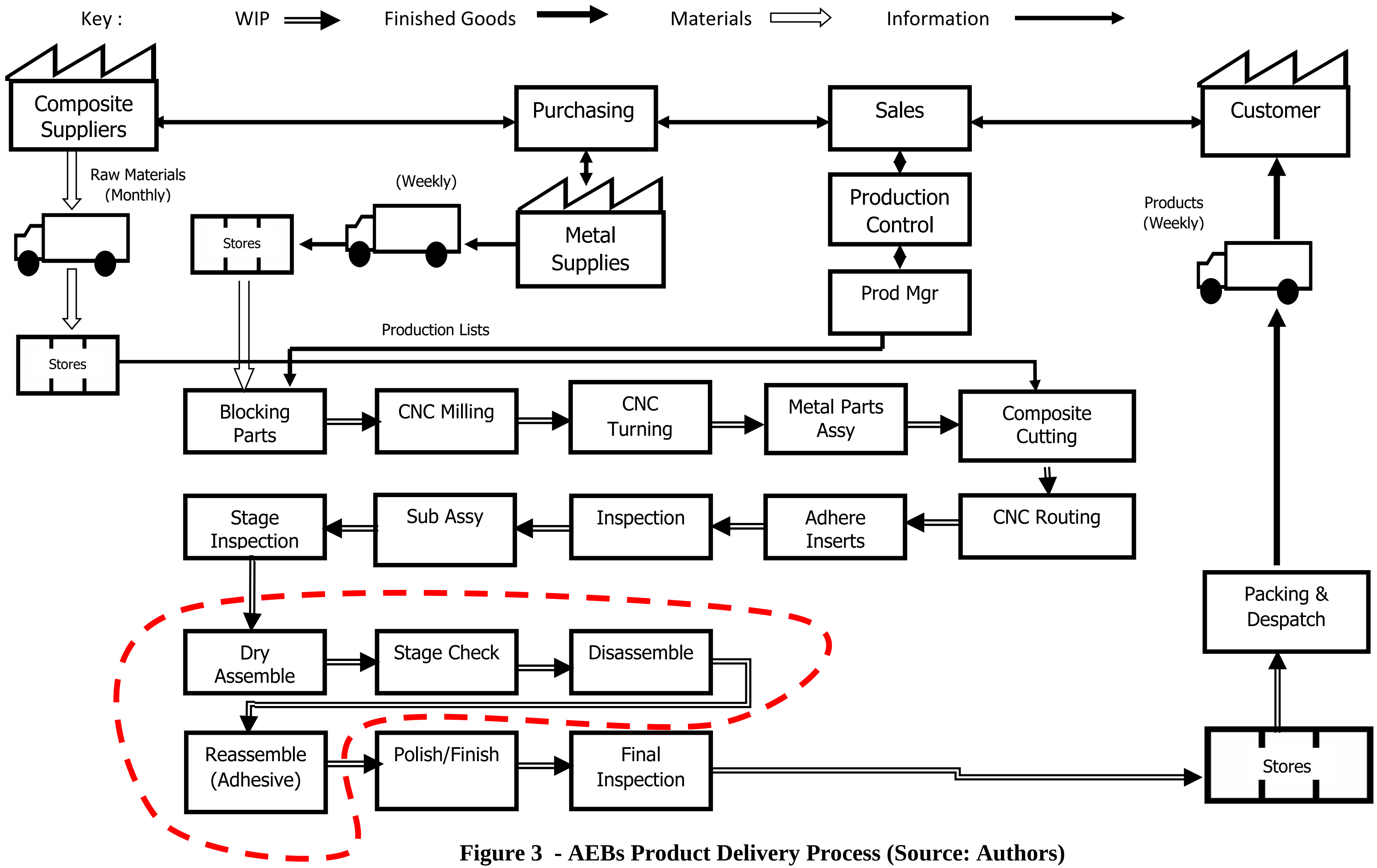


Figure 3 - AEBs Product Delivery Process (Source: Authors)

Six Sigma Cycle	Lean Cycle				
	(1) Specify Value	**(2) Synchronise Internal Value Stream**	**(3) Create Flow**	**(4) Pull on Demand**	**(5) Create Perfection**
Define	3 Day End User conference to identify key product factors affecting customer satisfaction	Identify value stream that aligns with product from (1)	Identify features that will inhibit flow through plant. Define flow routes.	Define customer volume and delivery expectations.	Identify the areas affecting process variation
Measure	Customer focus groups, to determine performance against competitors	Undertake full **VSM** identifying all VA, NVA activities features.	Simulate flow through system and effects that bottlenecks have.	Measure existing production delivery capabilities and analyse against customer requirements	Measure existing levels of variation using **control charts**
Analyse	Using **Kano model**, identify Basic, Std and delight criteria	Identify areas of NVA to eliminate and VA/NVA to reduce. Set **Future State Map (See Figure 4)**	Establish **experimental design methods** to identify new joint parameters	Identify the features capable of rapid delivery of products. Identify all constraints affecting delivery capabilities	Identify the processing and supply issues that affect variation. Pinpoint causes and set up improvement teams
Improve	Complete **Quality Function Deployment (QFD)** exercise HOQ 1. Identify customer requirements and establish manufacturing requirements	Systematically reduce all NVA areas identified. Identify adhesive injection method	Systematically focus on removing bottlenecks from system using **OPT** techniques. Use DOE techniques to eradicate CTQ issues that emerge.	Establish and embed logistics and **ERP** systems, **kanbans** to support rapid manufacture and delivery.	Establish Lean **Six Sigma blitz** teams to systematically improve
Control	Lock in new design and process features with design & Prod Eng Depts	Lock in new map as the new process optima	Determine new flow system and ensure adherence to new flow paths	Manage new order and embed practices to ensure consistent ops	Set new process specifications and manage the new process order.

Table 5 **Completed SLSSF Matrix indicating the key tools and techniques**

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