Applying Lean Thinking to Improve Processes in Low Volume/High Complexity Industry: Part II

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Abstract

Low-volume/high-complexity industries are known for their unique designs and custom products, which require extremely flexible manufacturing processes. Flexible processes can improve quality, reduce process complexity, reduce changeover time and lead times, leading to success in the market. Lean principles are the best way to improve flexibility in these industries. However, the implementation of Lean principles depends on the type of production layout, processes, and business design. For example, a production process with a fixed demand target will require different Lean principles than a variable production process with a changing demand target. Part 2 of this paper explains the cost benefits of process improvement from Part 1 of the research. It then continues with process improvements in different complex areas to provide a clearer explanation of how lean thinking can make flexible processes from complex processes. The focus on process improvement in the paint and shipping processes was a direct result of customer feedback with respect to quality non-conformances, new customer development, and special process audits by new customers.

Keywords
Process improvement, Lean manufacturing, ANOVA analysis, Quality control, Design of experiment.

1. Introduction
Lean Thinking is a key to improving processes. It is not a new concept, as it derives from the Toyota Production System (TPS) and Just in Time production (Henry Ford), among other predecessors. Most manufacturing companies have adopted lean and are running successfully, while fewer small to mid-size companies have been improving using lean methodologies. However, this is changing, as big industries are now stepping towards world-class advanced lean technology and are driving out waste along their lean journeys.

In Part 1, the paint process at Jones Metal Inc. was improved using lean methodologies, specifically applied to the painting portion of the process. In Part 2, the process costs, and savings due to lean process improvements from Part 1 will be discussed, as well as the reduction in quality defects due to a Six Sigma project. Six Sigma tools and ANOVA analysis are being applied to identify the root cause of paint quality problems and to work towards solving those problems, which also fits nicely into lean methodology. Many African and Asian industries do not utilize lean due to the perception that it is costly and can result in job termination. Some experts argue that their complex processes are unsuitable for lean manufacturing, but any industry can benefit from some form of lean. This paper focuses on improving a complex process for wash-paint and shipping, highlighting the effectiveness of applying lean principles (Murthy and Kobbacy 2018).

2. Literature Review
In Part 1, many processes were improved in the paint shop to save money on material costs. When dealing with a highly complex procedure, streamlining effectively and reducing costs becomes challenging. However, a deep analysis was conducted on over spraying paint, mixing paints, and coverage estimation. Firstly, the current prices needed estimation before updating the procedure and determining the cumulative paint costs. Subsequently, efforts were made to work towards the updated procedure. If all aspects of the paint estimating process are familiar, updating the formulas for obtaining the actual cost becomes easier. To confirm proximity to the new cost, testing was required by tracking the parts or monitoring paint purchase expenses. Consequently, an estimation of the current costs is required.

2.1 Current costs:

The ERP system provides the current cost per square foot of each paint mix. It is necessary to identify all the jobs conducted this year and assess the paint coverage area of each part. Additionally, the respective paint code for each individual part should be assigned. The painted area in square feet for the current year is then visible. Multiplying the coverage by the cost per square foot yields the amount charged to customers for each paint code. The sum of all charged material costs represents the total earned amount from customers for paint materials. However, it is possible that we may have charged less than the material cost due to incorrect estimations and over spraying on some researched parts. Table 1 displays the cost per square foot for each color code in column 3, and the square footage of previously painted area in column 4. Multiplying these two cells provides the cost charged for each paint. The total material cost for the past 12 months amounted to $120,000. The mix costs include primer part A, primer part B, reducer, finish part A, finish coat part B, and thinner.

Table 1. Current paint material costs

Code	Description	cost / Sq. foot (Before improvement)	Number of Sq. foots painted in 2017	Total Material Cost
Z-P100-MIX	Yellow Primer	$0.16	139087	$22,253.92
Z-P111-MIX	CAT Yellow	$0.53	700	$371.00
Z-P112-MIX	Pebble Gray (Solar Gray top coat	$0.62	27027	$16,756.74
Z-P114-MIX	Waukesha Orange	$0.42	122	$51.24
Z-P115-MIX	Cummins Red	$0.37	488	$180.56
Z-P116-MIX	Ansi Gray	$0.49	4181	$2,048.69
Z-P117-MIX	Cement Gray	$0.37	1611	$596.07
Z-P118-MIX	Fire Red	$0.54	0	$0.00
Z-P119-MIX	Silver Gray	$0.87	3265	$2,840.55
Z-P120-MIX	Cummins Beige	$0.58	238	$138.04
Z-P121-MIX	Mid Gloss Black	$0.40	2495	$998.00
Z-P124-MIX	Brilliant Blue	$0.40	286	$114.40
Z-P125-MIX	Traffic Blue	$0.16	0	$0.00
Z-P129-MIX	MTU onsite Silver Gray	$0.14	2817	$394.38
Z-P140-MIX	Cummins Red Primer	$0.59	1890	$1,115.10
Z-P150-MIX	Gray Primer	$0.49	4491	$2,200.59
Z-P700-1-MIX	White (INSIDE)	$0.50	26	$13.00
Z-P700-2-MIX	Gray (OUTSIDE)	$0.86	13221	$11,370.06
Z-A100-MIX	White Primer	$1.01	388	$391.88
Z-A111-MIX	Kato Equipment Yellow (Cat yello	$1.01	3576	$3,611.76
Z-A112-MIX	Pebble Gray	$1.01	5913	$5,972.13
Z-A113-MIX	Pure White	$1.13	45	$50.85
Z-A114-MIX	Ansi Gray	$1.01	395	$398.95
Z-A116-MIX	Flame Red	$1.03	63	$64.89
Z-A117-MIX	Light Gray	$0.93	2439	$2,268.27
Z-A120-MIX	Green Gray	$0.93	0	$0.00
Z-A121-MIX	Grass Green	$1.01	7531	$7,606.31
Z-A122-MIX	Brilliant Blue	$0.30	0	$0.00
Z-A417-MIX	Light Gray (OUTSIDE ONLY)	$0.81	0	$0.00
Z-K100-MIX	Military Green Primer	$0.46	104	$47.84
Z-K111-MIX	Military Gray	$0.81	10575	$8,565.75
Z-K112-MIX	Military White	$0.69	139	$95.91
	Millitary White	$0.77	87	$66.99
Z-K411-MIX	Military Gray (OUTSIDE ONLY)	$0.70	0	$0.00
Z-K700-1-MIX	Military White (INSIDE)	$0.71	536	$380.56
Z-K700-2-MIX	Military Gray (OUTSIDE)	$0.70	552	$386.40
Z-H100-MIX	Green - 150 (Military green primer	$0.69	0	$0.00
Z-H111-MIX	Haze gray - 151	$0.52	984	$511.68
Z-H700-1-MIX	White - 152	$0.48	60	$28.80
Z-H700-2-MIX	Haze gray - 151	$1.03	60	$61.80
Z-J001-MIX	Safety Yellow	$0.62	436	$270.32
Z-J002-MIX	JLG Orange	$0.33	119	$39.27
Z-J003-MIX	Repnet Purple	$0.53	3333	$1,766.49
Z-J004-MIX	SVT Blue	$0.59	268	$158.12
Z-J005-MIX	Anderson Red	$0.34	265	$90.10
Z-J006-MIX	AgChem Yellow	$0.35	0	$0.00
Z-J007-MIX	Carc Green	$0.33	404	$133.32
Z-J008-MIX	Carc Tan	$0.45	0	$0.00
Z-J009-MIX	High Heat Black	$0.43	390	$167.70
Z-J010-MIX	Wilmar White	$0.58	0	$0.00
Z-J011-MIX	Cat Yellow Primer	$0.45	4959	$2,231.55
Z-J012-MIX	Cat Yellow	$0.96	14778	$14,186.88
Z-J013-MIX	Cat Black	$0.56	9532	$5,337.92
Z-J014-MIX	Gray Primer	$0.33	8483	$2,799.39
Z-J015-MIX	Black Primer	$0.53	0	$0.00
Z-J016-MIX	White Primer	$0.59	0	$0.00
Z-J017-MIX	Gloss White	$0.34	70	$23.80
Z-J018-MIX	Gloss Black	$0.35	3996	$1,398.60
Z-J019-MIX	Gloss Black	$0.33	0	$0.00
Z-J020-MIX	Signal Black	$0.45	90	$40.50
Z-J021-MIX	FS 26307 Gray Epoxy	$0.43	3	$1.29
		Total amount charged to customers on paint material costs in 2017=		$120,598.36

2.2 New costs:

Part 1 explains how the formula provides accurate new costs, including miscellaneous tasks. Table 2, column 1, displays updated costs per square foot for each paint, while column 2 shows the painted square footage in the past 12 months. Multiplying these columns gives the estimated charge for each paint over the next 12 months with the updated prices.

Table 2 . New paint material costs

cost / Sq. foot (After improvement)	Number of Sq. foots painted in 2017	Projected material costs with improved process
$0.46	139087	$63,980.02
$2.22	700	$1,554.00
$1.39	27027	$37,567.53
$1.99	122	$242.78
$1.75	488	$854.00
$1.37	4181	$5,727.97
$1.79	1611	$2,883.69
$0.51	0	$0.00
$1.67	3265	$5,452.55
$3.40	238	$809.20
$2.12	2495	$5,289.40
$1.95	286	$557.70
$1.96	0	$0.00
$1.63	2817	$4,591.71
$0.51	1890	$963.90
$0.51	4491	$2,290.41
$2.79	26	$72.54
$2.25	13221	$29,747.25
1.79	388	$694.52
$1.79	3576	$6,401.04
$1.42	5913	$8,396.46
$1.79	45	$80.55
$1.45	395	$572.75
$1.41	63	$88.83
$1.79	2439	$4,365.81
$1.79	0	$0.00
$1.79	7531	$13,480.49
$1.41	0	$0.00
$1.41	0	$0.00
$0.81	104	$84.24
$2.34	10575	$24,745.50
$1.58	139	$219.62
$1.96	87	$170.52
$2.34	0	$0.00
$1.58	536	$846.88
$2.34	552	$1,291.68
$0.69	0	$0.00
$2.63	984	$2,587.92
$2.76	60	$165.60
$2.60	60	$156.00
$3.38	436	$1,473.68
$3.84	119	$456.96
$3.42	3333	$11,398.86
$3.47	268	$929.96
$3.42	265	$906.30

2.3 Profits and savings:

Profits and savings are two similar terms, although they have distinct meanings. In this case, money is being saved by enhancing the process. The current costs, before process improvement, result in losses due to inadequate estimation of over spraying, mixing, and expired paints. These losses are compensated for by overhead and labor charges. The challenge lies in accurately determining the required amount of paint for each job, leading us to charge less than the actual cost. By knowing the paint quantity, we can adjust the figures to increase the profit percentage. Overall, this improvement allows us to achieve both profits and savings. Table 3 clearly shows a savings of $208,000. This change includes miscellaneous items, which account for 30% of the cost improvement. Considering the amount of paint used at $230,000, the total savings amount to $109,000.

Table 3. Paint material savings

Code	Description	cost / Sq. foot (Before improvement)	Number of Sq. foots painted in 2017	Total Material Costs/we charged	cost / Sq. foot (After improvement)	Number of Sq. foots painted in 2017	Projected material costs with improved process	Savings / Sq. Foot
Z-P100-MIX	Yellow Primer	$0.16	139087	$22,253.92	$0.46	139087	$63,980.02	$41,726.10
Z-P111-MIX	CAT Yellow	$0.53	700	$371.00	$2.22	700	$1,554.00	$1,183.00
Z-P112-MIX	Pebble Gray (Solar Gray top coat	$0.62	27027	$16,756.74	$1.39	27027	$37,567.53	$20,810.79
Z-P114-MIX	Waukesha Orange	$0.42	122	$51.24	$1.99	122	$242.78	$191.54
Z-P115-MIX	Cummins Red	$0.37	488	$180.56	$1.75	488	$854.00	$673.44
Z-P116-MIX	Ansi Gray	$0.49	4181	$2,048.69	$1.37	4181	$5,727.97	$3,679.28
Z-P117-MIX	Cement Gray	$0.37	1611	$596.07	$1.79	1611	$2,883.69	$2,287.62
Z-P118-MIX	Fire Red	$0.54	0	$0.00	$0.51	0	$0.00	$0.00
Z-P119-MIX	Silver Gray	$0.87	3265	$2,840.55	$1.67	3265	$5,452.55	$2,612.00
Z-P120-MIX	Cummins Beige	$0.58	238	$138.04	$3.40	238	$809.20	$671.16
Z-P121-MIX	Mid Gloss Black	$0.40	2495	$998.00	$2.12	2495	$5,289.40	$4,291.40
Z-P124-MIX	Brilliant Blue	$0.40	286	$114.40	$1.95	286	$557.70	$443.30
Z-P125-MIX	Traffic Blue	$0.16	0	$0.00	$1.96	0	$0.00	$0.00
Z-P129-MIX	MTU onsite Silver Gray	$0.14	2817	$394.38	$1.63	2817	$4,591.71	$4,197.33
Z-P140-MIX	Cummins Red Primer	$0.59	1890	$1,115.10	$0.51	1890	$963.90	-$151.20
Z-P150-MIX	Gray Primer	$0.49	4491	$2,200.59	$0.51	4491	$2,290.41	$89.82
Z-P700-1-MIX	White (INSIDE)	$0.50	26	$13.00	$2.79	26	$72.54	$59.54
Z-P700-2-MIX	Gray (OUTSIDE)	$0.86	13221	$11,370.06	$2.25	13221	$29,747.25	$18,377.19
Z-A100-MIX	White Primer	$1.01	388	$391.88	1.79	388	$694.52	$302.64
Z-A111-MIX	Kato Equipment Yellow (Cat yello	$1.01	3576	$3,611.76	$1.79	3576	$6,401.04	$2,789.28
Z-A112-MIX	Pebble Gray	$1.01	5913	$5,972.13	$1.42	5913	$8,396.46	$2,424.33
Z-A113-MIX	Pure White	$1.13	45	$50.85	$1.79	45	$80.55	$29.70
Z-A114-MIX	Ansi Gray	$1.01	395	$398.95	$1.45	395	$572.75	$173.80
Z-A116-MIX	Flame Red	$1.03	63	$64.89	$1.41	63	$88.83	$23.94
Z-A117-MIX	Light Gray	$0.93	2439	$2,268.27	$1.79	2439	$4,365.81	$2,097.54
Z-A120-MIX	Green Gray	$0.93	0	$0.00	$1.79	0	$0.00	$0.00
Z-A121-MIX	Grass Green	$1.01	7531	$7,606.31	$1.79	7531	$13,480.49	$5,874.18
Z-A122-MIX	Brilliant Blue	$0.30	0	$0.00	$1.41	0	$0.00	$0.00
Z-A417-MIX	Light Gray (OUTSIDE ONLY)	$0.81	0	$0.00	$1.41	0	$0.00	$0.00
Z-K100-MIX	Military Green Primer	$0.46	104	$47.84	$0.81	104	$84.24	$36.40
Z-K111-MIX	Military Gray	$0.81	10575	$8,565.75	$2.34	10575	$24,745.50	$16,179.75
Z-K112-MIX	Military White	$0.69	139	$95.91	$1.58	139	$219.62	$123.71
	Military White	$0.77	87	$66.99	$1.96	87	$170.52	$103.53
Z-K411-MIX	Military Gray (OUTSIDE ONLY)	$0.70	0	$0.00	$2.34	0	$0.00	$0.00
Z-K700-1-MIX	Military White (INSIDE)	$0.71	536	$380.56	$1.58	536	$846.88	$466.32
Z-K700-2-MIX	Military Gray (OUTSIDE)	$0.70	552	$386.40	$2.34	552	$1,291.68	$905.28
Z-H100-MIX	Green - 150 (Military green primer	$0.69	0	$0.00	$0.69	0	$0.00	$0.00
Z-H111-MIX	Haze gray - 151	$0.52	984	$511.68	$2.63	984	$2,587.92	$2,076.24
Z-H700-1-MIX	White - 152	$0.48	60	$28.80	$2.76	60	$165.60	$136.80
Z-H700-2-MIX	Haze gray - 151	$1.03	60	$61.80	$2.60	60	$156.00	$94.20
Z-J001-MIX	Safety Yellow	$0.62	436	$270.32	$3.38	436	$1,473.68	$1,203.36
Z-J002-MIX	JLG Orange	$0.33	119	$39.27	$3.84	119	$456.96	$417.69
Z-J003-MIX	Repnet Purple	$0.53	3333	$1,766.49	$3.42	3333	$11,398.86	$9,632.37
Z-J004-MIX	SVT Blue	$0.59	268	$158.12	$3.47	268	$929.96	$771.84
Z-J005-MIX	Anderson Red	$0.34	265	$90.10	$3.42	265	$906.30	$816.20
Z-J006-MIX	AgChem Yellow	$0.35	0	$0.00	$3.49	0	$0.00	$0.00
Z-J007-MIX	Carc Green	$0.33	404	$133.32	$2.16	404	$872.64	$739.32
Z-J008-MIX	Carc Tan	$0.45	0	$0.00	$1.91	0	$0.00	$0.00
Z-J009-MIX	High Heat Black	$0.43	390	$167.70	$2.59	390	$1,010.10	$842.40
Z-J010-MIX	Wilmar White	$0.58	0	$0.00	$2.96	0	$0.00	$0.00
Z-J011-MIX	Cat Yellow Primer	$0.45	4959	$2,231.55	$0.91	4959	$4,512.69	$2,281.14
Z-J012-MIX	Cat Yellow	$0.96	14778	$14,186.88	$2.20	14778	$32,511.60	$18,324.72
Z-J013-MIX	Cat Black	$0.56	9532	$5,337.92	$2.52	9532	$24,020.64	$18,682.72
Z-J014-MIX	Gray Primer	$0.33	8483	$2,799.39	$1.39	8483	$11,791.37	$8,991.98
Z-J015-MIX	Black Primer	$0.53	0	$0.00	$1.45	0	$0.00	$0.00
Z-J016-MIX	White Primer	$0.59	0	$0.00	$1.38	0	$0.00	$0.00
Z-J017-MIX	Gloss White	$0.34	70	$23.80	$2.99	70	$209.30	$185.50
Z-J018-MIX	Gloss Black	$0.35	3996	$1,398.60	$2.87	3996	$11,468.52	$10,069.92
Z-J019-MIX	Gloss Black	$0.33	0	$0.00	$2.35	0	$0.00	$0.00
Z-J020-MIX	Signal Black	$0.45	90	$40.50	$2.35	90	$211.50	$171.00
Z-J021-MIX	FS 26307 Gray Epoxy	$0.43	3	$1.29	$3.78	3	$11.34	$10.05
		Total amount charged to customers on paint material costs in 2017=		$120,598.36		Total Savings / Year		$208,120.16

Table 4 displays projected savings of $109,000 over the next 12 months. The process improvement altered the internal paint purchasing procedure, streamlining the update of new paint costs. It also reduces the time required by engineering and purchasing to update the ERP system accurately. The worksheet facilitates communication between engineering and purchasing, ensuring the correct value is entered into the ERP system and enabling more accurate quotes for customers. This improvement enhances quality and visibility for the internal team at Jones Metal Inc. and provides customers with precise paint pricing.

Table 4. Forecasted paint material savings

		Savings
Includes miscellaneous works	$328,718.52	$208,120.16
Right amount of paint charge	$230,102.96	$109,504.60

3. Methodology

Lean Six Sigma is a combination of lean methodologies and six sigma problem identification and analysis. Successful lean improvement often requires the use of six sigma tools and analysis of design of experiments to understand factors for sustaining improvement. The methods and tools of lean thinking facilitate the development of improvement projects related to processes, while six sigma helps to focus on areas for improvement. Improving the process based on machines is not always easy; time trials and quality trials are necessary to adjust the process and gather valuable data for appropriate analysis. Six sigma tools such as five whys, ANOVA, brainstorming, fishbone, cause and effect, control charts, and FMEA are used. Lean methodologies do not always provide the answer, so other tools are needed. This chapter addresses problem-solving and process improvement in complex industries. Volume 1 focuses on process improvements using lean concepts, while volume 2 discusses cost and process improvements utilizing lean and six sigma tools. Quality issues could not be resolved with lean alone, leading to the use of six sigma tools and process control methods in this project. Jones Metal Inc. is considered a complex industry with custom designs, fabrication procedures, and projects.

3.1 Problem identification:

Paint adhesion is considered one of the most critical attribute for Jones Metal Inc. to meet customer requirements, and that is the focus of this section. Generally, paint adhesion is a major consideration in paint quality for all parts in any industry. It is influenced by several significant factors that need to be understood and controlled. Multiple trials are conducted to gather data sets, which are then analyzed using ANOVA to identify the most significant factors. Factors and levels in the paint process must be defined. 3/8" steel parts, known for their susceptibility to paint adhesion issues, are selected for testing. Coupons are created to evaluate adhesion. The process begins with laser cutting of mild steel using oxygen gas as an assist gas. Subsequently, the parts are subjected to two different paths for chemical cleaning and two different paths for the painting process. Thus, four sets of 3/8" thick steel plates are considered as testing samples. Two types of chemical washes are utilized for removing grease, rust, and applying a coating to the steel. Pressure wash is employed for cleaning the testing samples. The procedure for pressure wash cleaning is explained in Part 1, while Figure 1 shows the pressure wash area and sample coupons. The sample pieces are treated with a mixture of 50% BH-38 and 50% water, soaked for 2 minutes. Before BH-38 dries, pressure is applied using water at 120 degrees temperature mixed with GF prep 618. This completes the cleaning procedure. Next, the factors influencing paint adhesion need to be identified to proceed with the experiment.

Figure 1. Cleaning samples in pressure wash area

3.2 Fishbone analysis:

The Fish Bone diagram is considered the best tool for identifying the factors that are affecting a particular process. This tool is derived from the six-sigma DMAIC principle, which is used to identify the factors involved in the process. Here, ten major factors that can affect paint adhesion are identified.

They include:

a) Measurement: Adhesion can be influenced by material thickness, washing time, and washing temperature.
b) Environment: Adhesion can be affected by humidity, temperature, and time.
c) Materials: The type of steel, material thickness, wash chemistry, and primer and paint type can impact adhesion.
d) Method: Adhesion can be influenced by the type of laser gas cutting, spray wash, tank wash, and the method of applying the primer and finish coat.
e) People: Adhesion is affected by the knowledge of individuals involved in the laser and washing processes.
f) Machines: Adhesion can be influenced by the laser tech table and the type of assist gas used.
g) Uncontrollable factors: While there is control over setting a minimum temperature, the process is halted when the temperature exceeds a certain threshold. The same applies to humidity in the paint area. Therefore, these factors, which can affect paint adhesion, are considered uncontrollable.
h) Nuisance Factors: Materials and supplies, such as brushes, sandpapers, and recycled metal sheet supplies, as well as the operators, fall into this category and can impact paint adhesion.
i) Held Constant Factors: Cold rolled and hot rolled materials, along with the applied wash procedure, can also affect adhesion.
j) Controllable design factors: Wash temperature, wash chemistry, and the time between the wash and paint process are all factors that can be controlled.

All of these factors can potentially affect the paint adhesion of a product. Once the factors have been identified, the Design of Experiments methodology can be applied to determine the significant factors that require control. Based on the results, improvement projects can be undertaken to optimize the process for better outcomes. Figure 2 illustrates the fishbone diagram for this process.

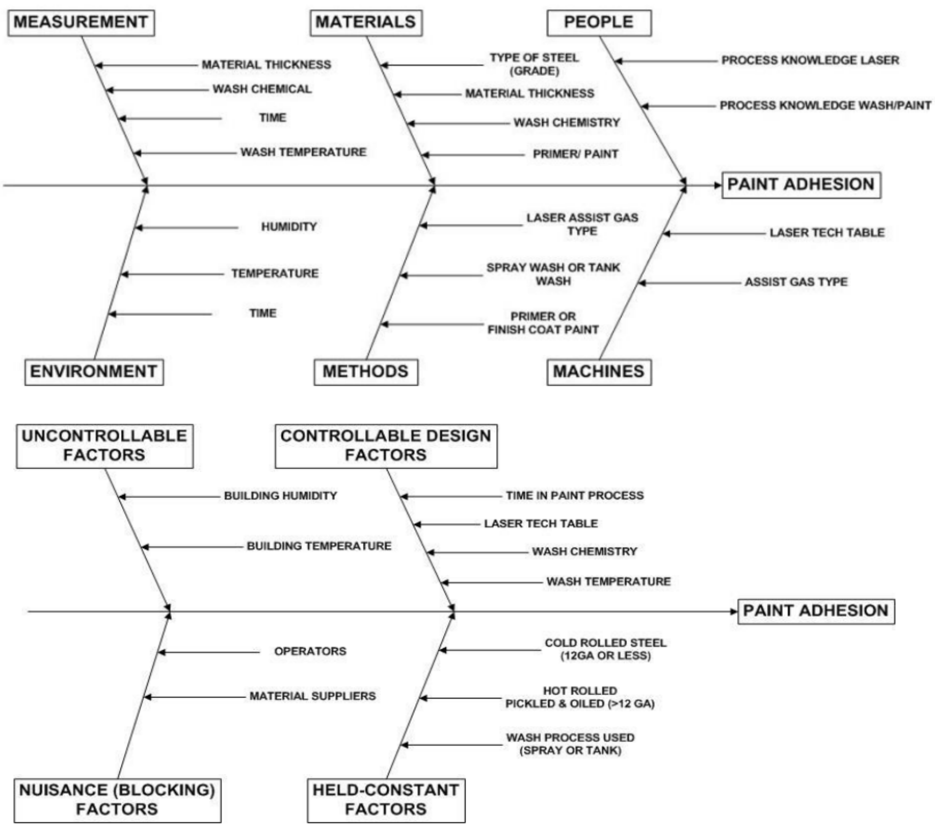


Figure 2 . Fishbone diagram

3.3 Design of experiments:

Design of experiments techniques are considered as one of the most powerful tools in relation to the improvement of manufacturing process issues. By their application, the real root cause of the problems faced can be identified by companies, and measures can be taken to control the process and prevent future nonconformities. The factor of design: 2^k Factorial design where K=3

The factors and levels are displayed in Table 5. For the experiment, two levels of factors are being considered: Surface (A), Wash (B), and Paint (C). Before the process is run, the experiment's methodology needs to be designed, following which the factors can be applied to perform ANOVA.

Table 5. Factorial table

		Factors		
		A (Surface)	B (Wash)	C (Paint)
Levels	-1	Face	Tank	Hot Pot
	1	Edge	Spray	P-Mix

The factors for adhesion were identified and the trends were explored. The procedure has been obtained and it is time to develop the factorial design project, which will be subsequently applied to test the process. The process, when tested, provides the data needed to make decisions using statistical tools. The finalization of the process relies on the testing technical reports derived from the experiment's outcome. Figure 3 shows the methodology of the process.

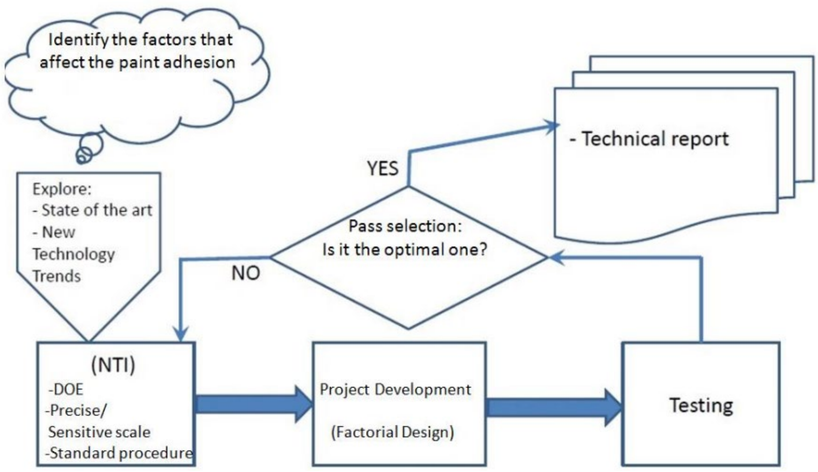


Figure 3. Methodology

The hot pot paint process and P-mix process are used to create the factorial experimental table. In Table 6, the mixing ratios for spraying Part A and Part B can be observed. The table of experiments displays Factorial A, B, and C, each with 9 replicates, and presents the corresponding results. Based on this table, the effects are estimated. The major factors influencing paint adhesion can be determined through the effects and percentage of contribution.

Table 6. Table of experiments

		Factors			Replicates (n = 9)									
Run		A (surface)	B (Wash)	C (Paint)	1	2	3	4	5	6	7	8	9	Total
1	(1)	-1	-1	-1	0.0010	0.0002	0.0008	0.0008	0.0012	0.0007	0.0003	0.0003	0.0002	0.0055
2	a	1	-1	-1	0.0042	0.0016	0.0014	0.0004	0.0015	0.0010	0.0120	0.0009	0.0006	0.0236
3	b	-1	1	-1	0.0005	0.0018	0.0016	0.0005	0.0007	0.0009	0.0002	0.0008	0.0007	0.0077
4	ab	1	1	-1	0.0004	0.0007	0.0007	0.0004	0.0011	0.0025	0.0006	0.0013	0.0016	0.0093
5	c	-1	-1	1	0.0010	0.0012	0.0008	0.0005	0.0006	0.0010	0.0002	0.0001	0.0004	0.0058
6	ac	1	-1	1	0.0014	0.0008	0.0015	0.0018	0.0016	0.0008	0.0015	0.0006	0.0008	0.0108
7	bc	-1	1	1	0.0026	0.0021	0.0014	0.0011	0.0012	0.0013	0.0009	0.0007	0.0013	0.0126
8	abc	1	1	1	0.0009	0.0013	0.0012	0.0017	0.0014	0.0013	0.0016	0.0010	0.0003	0.0107

The percentage of contribution clearly indicates that Washing (B) has a lower percentage of 1.6, while Surface has a higher contribution of 28%. As a result, Surface and Washing have a combined contribution of 29.5% that affects paint adhesion. The significance can be determined by examining the ANOVA. Table 7 depicts the effect estimate summary.

Table 7. Effect estimates summary

	Contrast	Main Effect	Sum of Squares	% of contribution
A - Surface	0.02280	0.000633	0.00000722	28.0%
B - Wash	-0.00540	-0.000150	0.00000040	1.6%
C - Paint	-0.00620	-0.000172	0.00000053	2.1%
AB	-0.02340	-0.000650	0.00000761	29.5%
AC	-0.01660	-0.000461	0.00000383	14.8%
BC	0.01880	0.000522	0.00000491	19.0%
ABC	0.00960	0.000267	0.00000128	5.0%

3.4 ANOVA testing:

Table 8 shows the Minitab results that indicate the P-value of all factors is greater than 0.05, which is not significant. Thus, it is concluded that all factors are not significant, except for the product of surface and wash, which has a P-value of 0.051, indicating approximate significance. While statistically insignificant, this factor demonstrates a close proximity to significance. Hence, it can be inferred that the product of washing and surface has a stronger impact compared to the other factors involved.

Table 8 – Minitab ANOVA test results

Source	DF	Adj SS	Adj MS	F-Value	$F_{\alpha,v1,v2}$	P-Value
Surface	1	0.000007	0.000007	3.76	5.32	0.057
Wash	1	0.000000	0.000000	0.21	5.32	0.648
Paint	1	0.000001	0.000001	0.28	5.32	0.600
Surface*Wash	1	0.000008	0.000008	3.96	5.32	0.051
Surface*Paint	1	0.000004	0.000004	1.99	5.32	0.163
Wash*Paint	1	0.000005	0.000005	2.56	5.32	0.115
Surface*Wash*Paint	1	0.000001	0.000001	0.67	5.32	0.417
Error	64	0.000123	0.000002			
Total	71	0.000149				

The Residual plots need to be analyzed to confirm the factor. The trend in the graph is shown by the normal probability plot in Figure 4. One data point deviates from the normal. In the standardized effect plot, all factors are found to be non-significant, so the option to find the result is not available in this plot. The adhesion is greatly affected by the product of Surface A and wash B, as clearly shown in the Pareto chart.

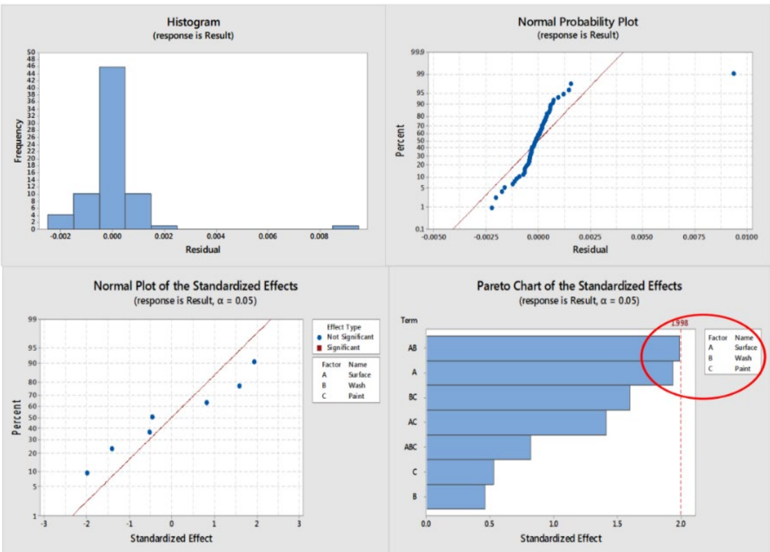


Figure 4. Face residual plots

The same procedure for level +1, which is edge, is being followed. The ANOVA results on the edge side are completely the same as on the side. The ANOVA results indicate that all P-values are greater than 0.05 and all factors are insignificant. However, a wash A value of 0.216, the smallest outcome, implies that the wash process has a more significant effect on painting adhesion. To confirm this, residual plots are visually analyzed in Figure 5. The original experiment evaluated the tank and spray wash processes, along with the P-Mix paint process and

Hot-Pot paint process. It was determined that the focus should be on the tank wash process. The new experiment utilizes a vendor's laboratory for the chemicals in the wash process. The response variable for tank 1 is the Water Break Free (percentage of cleanability), and for tank 3, it is the Coating Weight. By controlling and optimizing the wash parameters, we can improve the response variables, resulting in better paint adhesion and fewer customer quality issues. Therefore, the conclusion is that the "Washing Process" has more significance in paint adhesion testing. These tests are conducted using the copper hammer test.

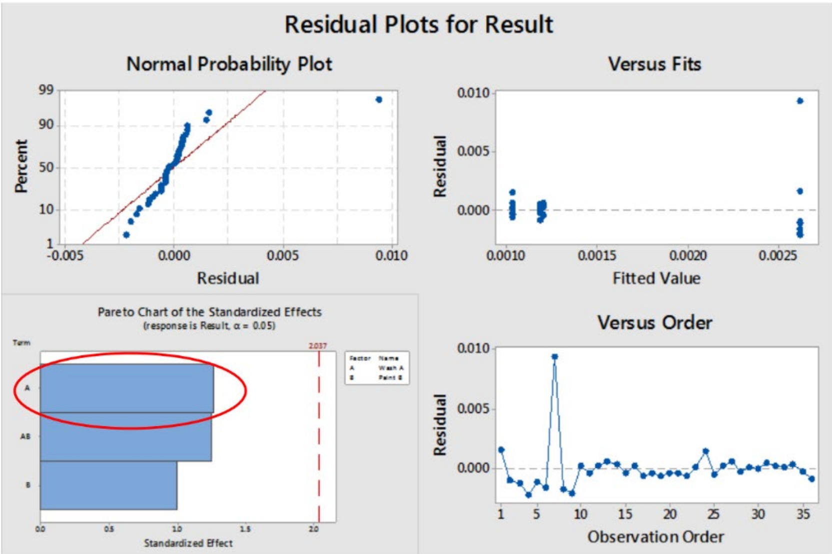


Figure 5. Edge residual plots

3.5 Economic Impact:

The total expected revenue reduction (cost reduction) on the washing process is \$3,638 monthly and \$43,650 annually. A good amount of savings can be achieved after developing the washing process effectively. The next task is to identify the tank responsible for unsatisfactory paint adhesion. In the 5 Dip Tank process, tanks 1 and 3 are the chemical tanks that can affect the part, while the other 3 tanks are rinse water tanks, with tank 5 being heated. The result of the ANOVA test conducted on Tank 1 provides the necessary information. If the problem is caused by Tank 1, it will need to be changed. Otherwise, if Tank 1 is not the cause, it implies that tank 3 could be responsible for the poor paint adhesion. Table 9 depicts the 8 scenarios examined, presenting machine specifications at varying temperatures along with dipping times of 2 and 5 minutes. The ANOVA reveals the significance of Factor B (Tank 3).

Table 9. ANOVA test

Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	1	2.890	2.8900	2.8900	0.86	0.382
B	**1**	**76.562**	**76.5625**	**76.5625**	**22.71**	**0.001**
C	1	2.103	2.1025	2.1025	0.62	0.452
A*B	1	0.090	0.0900	0.0900	0.03	0.874
A*C	1	0.040	0.0400	0.0400	0.01	0.916
B*C	1	0.423	0.4225	0.4225	0.13	0.732
A*B*C	1	0.360	0.3600	0.3600	0.11	0.752
Residual Error	8	26.970	26.9700	3.3712		
Pure Error	8	26.970	26.9700	3.3713		
Total	15	109.437				

No interaction exists between the factors; thus paint quality is not significantly affected by Tank 1; only tank 3 (factor B), specifically Zirconium, is responsible for the problems. Through the utilization of six-sigma and design of experiments as tools, the causative factor was identified. By employing Lean methodologies and ISO procedure design, a procedure can be developed for addressing the factor and achieving improvement.

3.6 Future process proposal:

Following problem identification and process improvement through the use of existing equipment, the proposal for an advanced washing process is presented as shown in Figure 6. The tank process, which is a method of washing that requires more operator interaction, was reviewed due to its space-saving benefits and suitability for custom products and low volumes. However, considering the growing business and technological advancements, a continuous upgrade with new technology to support processes is necessary. The parts are loaded from one side and pass through each room with chemical sprayers, similar to a car wash, before returning to the same location for unloading, as depicted in the above chart. The hanger design and dimensions can be found in the accompanying drawing. Although advanced automated wash processes are being explored, they cannot serve as a substitute for all products processed through the current tank wash process. Therefore, larger items such as big boxes and other types of products that cannot be hung on this advanced wash system would require pressure washing.

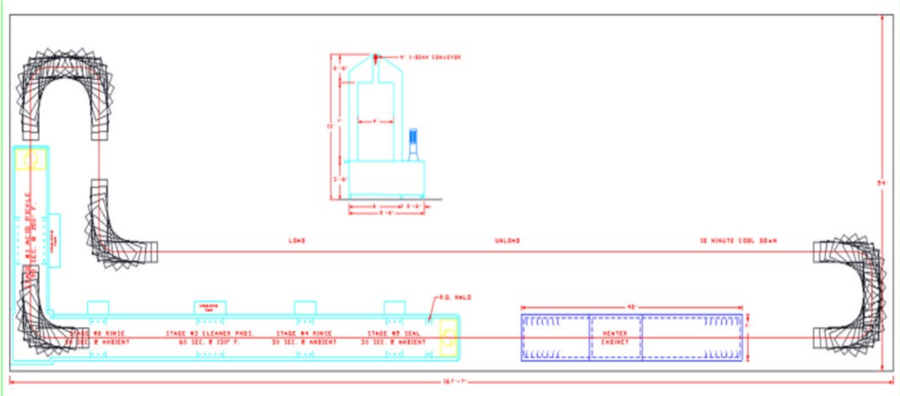
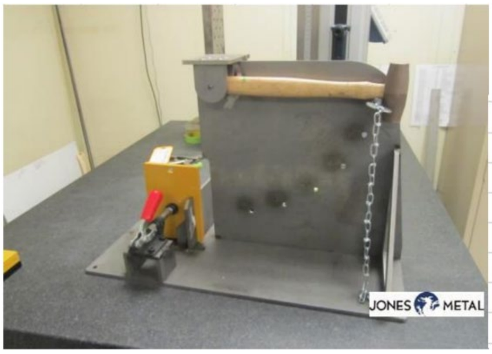


Figure 6 . Advanced wash process proposal

3.7 Adhesion testing with copper hammer:

The adhesive testing procedure is important in determining paint quality. This procedure is derived from the lean six-sigma coupon testing. A hammer test equipment is constructed to address the issue of variable joules of pressure caused by individual variation in swinging the hammer. The test fails, necessitating the development of a specialized fixture and equipment capable of distributing equal force upon impact on the painted sample by the hammer. The equipment enables testing at 6 different angles, each resulting in a distinct impact on the specimen. The maximum impact of 1.40 Joules is achieved at a 900 angle, while the least pressure of 0.035 Joules is exerted at a 150 angle. Table 10 illustrates these impacts along with the design of the hammer test.

Table 10. Copper hammer adhesive test



SYSTEM ENERGY		
DEGREES	JOULES	FT/LBS
90°	1.40255	1.03446
75°	1.03954	0.76672
60°	0.70127	0.51723
45°	0.41079	0.30298
30°	0.1879	0.13858
15°	0.04779	0.03524

The hammer needs to be dropped from a 900-angle position that impacts the surface, after which the adhesive testing tape should be applied to the area and pulled strongly. The paint loss from the sample is analyzed. The test can also be conducted by hatching the surface with blade six times perpendicularly, as shown in the picture. Then, the adhesive testing tape should be applied and pulled strongly. Each time, the paint loss observed provides valuable information. The loss of paint needs to be measured to determine the strength of adhesiveness. This procedure improves the quality of the paint process and helps identify non-conforming paint lots, wash process issues, and adhesion problems.

3.8 Process improvement for quotation:

A new project's quotation can involve a lengthy process that considers numerous cost and process factors. Quoting an international project with new materials and vendors, comprising hundreds of assemblies, is extremely challenging. Months are required for this process to disassemble each assembly and determine the number of bends, hole thickness, and materials. The length of the process increases when there are multiple assemblies. The first method used for working on continuous improvement of the quoting process is product design mapping. A key role is played by design mapping in making the products easier and faster to process, particularly when there are assemblies, sub-assemblies, parts, and hardware. The tree chart as shown in Figure 7 provides details of all sub-assemblies for this project, including 3 major sub-assemblies, which fall under one package. With this map, communication with the customer becomes easy, answers to questions can be found, and a method for engineers to use on the quotes is provided.

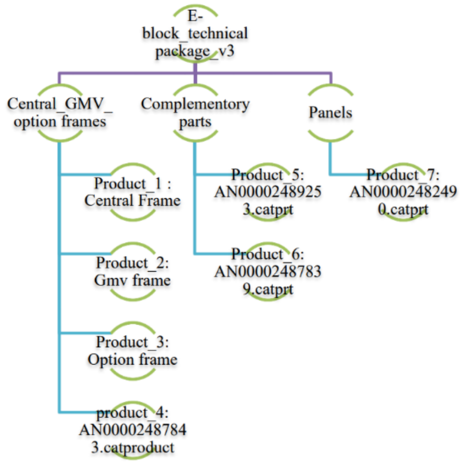


Figure 7. Sub-assemblies' chart

3.8 Material selections and estimations:

The material estimation for complete assemblies is provided by the estimation calculator, which is custom-tailored for each customer's requirements. The metal thickness can be selected, and the sheets for each assembly are added. The total cost for metal sheets is automatically generated by the calculator, enabling quicker quotes and flexibility to accommodate customer changes. A significant process improvement for the lean office has been achieved. Utilizing bar graphs, a comparison of different material costs allows for easy selection of low-cost materials or presenting material options and associated costs to customers. Pie charts display the percentage of different material thicknesses, offering clear visibility on the project and enabling multiple quotes without added complexity or time consumption. Table 11 shows a sample product estimation calculator with bar graph and pie chart. Customized products often pose challenges in procuring materials, especially when they are not readily available in the USA, necessitating substitutions while maintaining engineering requirements.

Table 11. Sample product estimation calculator

Estimated weights

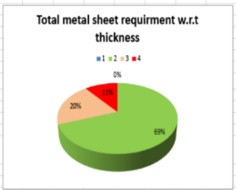
Product	weight of 1 mm	weight of 2 mm	weight of 3 mm	weight 4 mm	Total weight of each product
Central frame	** Can not caluculate **				
GMV frame		259.9283138	111.7817539	328.1	699.8100677
option frame	** Can not caluculate **				
AN00002487843.catproduct		9.903120093	8.777152645		18.68027274
AN00002487839.catprt	0.327760015	44.94141105	3.518114903		48.78728596
AN00002489253.catprt		149.7818325	311.5526497	8.925	470.2594822
AN00002482490.catprt		487.5399793			487.5399793
Total	**0.33**	**952.0946567**	**435.6296712**	**337.025**	**1725.077088**

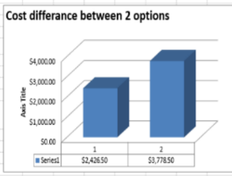
Budget plan for metal sheets: **(Option: 1)** As ZAM steel : 1.5$ per pound Galvanized Mild steel : 1$ per pound

Product	Costs for 1 mm	Costs for 2 mm	Costs for3 mm	Costs for 4 mm	Total cost of each product
Central frame	** Can not caluculate **				
GMV frame		$390.00	$168.00	$329.00	$887.00
option frame	** Can not caluculate **				
AN00002487843.catproduct		$15.00	$13.50		$28.50
AN00002487839.catprt	$0.50	$67.50	$6.00		$74.00
AN00002489253.catprt		$225.00	$468.00	$9.00	$702.00
AN00002482490.catprt		$735.00			$735.00
Total	**$0.33**	**$1,432.50**	**$655.50**	**$338.00**	**$2,426.50**

Budget plan for metal sheets: **(Option: 2)** As ZAM steel : 1.5$ per pound ATI special alloys : 5$ per pound

Product	Costs for 1 mm	Costs for 2 mm	Costs for3 mm	Costs for 4 mm	Total cost of each product
Central frame	** Can not caluculate **				
GMV frame		$390.00	$168.00	$1,645.00	$2,203.00
option frame	** Can not caluculate **				
AN00002487843.catproduct		$15.00	$13.50		$28.50
AN00002487839.catprt	$0.50	$67.50	$6.00		$74.00
AN00002489253.catprt		$225.00	$468.00	$45.00	$738.00
AN00002482490.catprt		$735.00			$735.00
Total	**$0.33**	**$1,432.50**	**$655.50**	**$1,690.00**	**$3,778.50**





When the material available in the USA is not provided by customers, a chart with yield strength requirements of the international material needed to be developed. Due to varying mixtures of metals, alloys, and codes in Europe, Asia, and the USA, an acceptable material for the parts had to be sought. A vast database was created, encompassing material codes, yield strength, young's modules, tensile strength, and density, making it easier and faster to cross-reference customer material requirements with available metals in the USA. Table 12 depicts a sample material database.

Table 12. Sample material database

Material Name	Family	Material Class	Density ρ (kg/m^3)	Yield Strength Sy (MPa)	Tensile Strength Su (MPa)
AISI 1340 steel	Metal & alloy	Steel	7870	434	703
AISI 1006 Steel, cold drawn	Metal & alloy	Steel	7872	285	330
AISI 1010 Steel, cold drawn	Metal & alloy	Steel	7870	305	365
AISI Grade 18 Ni (200)	Metal & alloy	Steel	8000	1710	1750
AISI 1010 Steel, hot rolled bar, 19-32 mm (0.75-1.25 in) round or thickness	Metal & alloy	Steel	7870	180	325
AISI Grade 18Ni (250)	Metal & alloy	Steel	8000	655	965
AISI 1020 Steel, cold rolled	Metal & alloy	Steel	7870	350	420
AISI Grade 18Ni (300)	Metal & alloy	Steel	8000	1693	1771
AISI Grade 18Ni (350)	Metal & alloy	Steel	8080	827	1140
AISI 1030 Steel, as rolled	Metal & alloy	Steel	7850	345	550
AISI 2330 Steel	Metal & alloy	Steel	7750	689	841
AISI 1042 Steel, Cold Drawn Bar (UNS G10420)	Metal & alloy	Steel	7850	517	614
AISI 1040 Steel, as rolled	Metal & alloy	Steel	7845	415	620
AISI 2515 Steel	Metal & alloy	Steel	7750	648	779
AISI 1050 Steel, as rolled	Metal & alloy	Steel	7850	415	725
AISI 4023 Steel	Metal & alloy	Steel	7850	415	724
AISI 1060 Steel, as rolled	Metal & alloy	Steel	7850	485	814
AISI 1080 Steel, as rolled	Metal & alloy	Steel	7850	585	965
AISI 4027 Steel, annealed	Metal & alloy	Steel	7850	325	515
AISI 1095 Steel, as rolled	Metal & alloy	Steel	7850	570	965
AISI 1118 Steel, as rolled	Metal & alloy	Steel	7850	315	525
AISI 4053 Steel	Metal & alloy	Steel	7750	1538	1724
AISI 1137 Steel, as rolled	Metal & alloy	Steel	7870	380	625
AISI 1144 Steel, as rolled	Metal & alloy	Steel	7870	420	705
AISI 1541 Steel, Cold Drawn Bar (UNS G15410)	Metal & alloy	Steel	7850	600	706.7
AISI 4063 Steel	Metal & alloy	Steel	7750	1593	1855
AISI 4118 Steel	Metal & alloy	Steel	7850	365	517
AISI 4130 Steel	Metal & alloy	Steel	7850	460	560
AISI 4140 Steel, annealed	Metal & alloy	Steel	7850	415	655
202 Stainless Steel, Annealed Bar	Metal & alloy	Steel	7860	275	515

3.8 Spec sheets for fast quotation process:

A very long process of quoting 450-piece parts within 3 days had been undertaken. More than 2 months were spent on understanding and reviewing each piece part, necessitating faster quoting methods due to their non-value-added nature for any company. The need to improve the process arose as not every quote resulted in a purchase order. The ultimate calculator as shown was sought to provide quotes for 450 parts within 3 days without complications, saving 30 days and increasing the chances of winning the project. The sample piece of the calculator is depicted in Table 13, designed to accommodate every factor of the part. Entries for length, width, thickness of the sheet, number of bends, setup times, weight, and material cost were required. However, most options were already pre-selected in the calculator, making it faster than dealing with the actual sheet. These calculators were not universally tailored to individual customers' process time, but rather considered the processes at Jones Metal and followed current estimating standards.

Table 13 . Ultimate quote calculator

Part Number	Description	Quantity	Thickness (mm)	Thickness (gage)	Length (mm)	Length (inch)	Width (mm)	Width (inch)	Height (Pipes, tubes-mm)	Height (inch)	No. of bends	Bending Run
Red Color columns	Products	Quantity is NOT multiplyed with sheet dimensions	DATA IS MENTIONED FOR SPECIFICATIONS. TO BUILD A PRODUCT NEED TO MULTIPLY PARTS WITH QUANTITY									
Green Columns	sub assemblies											
White Columns	Parts											
CM00000064085	Semi -Structural											
CM00000064085	CIRCUIT BREAKER SUPPORT	1										
CM00000094232	LONGITUDINAL GIRDER 40X60X2202	1	3	11	40	1.57	60	2.36	2202	86.69	0	-
CM00001620190	LONGITUDINAL GIRDER 40X60X2202	1	3	11	40	1.57	60	2.36	2202	86.69	0	-
CM00001620148	LONGITUDINAL GIRDER 40X60X2202	1	3	11	40	1.57	60	2.36	2202	86.69	0	-
CM00000094201	FOLDED PLATE 3X273X1510	2	3	11	273	10.75	1510	59.45	0	0.00	8	50.2
CM00000094301	FOLDED PLATE 5X206.5X271	6	5	6	206.5	8.13	271	10.67	0	0.00	8	50.2
CM00000094336	MOUNTING PLATE 3X191X204	6	3	11	191	7.52	204	8.03	0	0.00	0	-
CM00000178812	SUPPORT	4	14.6	-	110	4.33	56	2.20	0	0.00	0	-
CM00000445984	FOLDED PLATE 2X192X954	1	2	14	192	7.56	954	37.56	0	0.00	3	25.2
DTR0000000083	STUD, RIVETING CU NU M10 D 19	4						Hardware				
DTR0009908100	SCREW H.ISO4017-M6X16-A2-70	8						Hardware				
DTR0009909266	NUT CLUFIX M8FO050-STEEL	3						Hardware				
DTR0009909265	NUT CLUFIX M6FO035-STEEL	2						Hardware				
DTR00211519AJ	RIVET.M-LOK MGLP-R8-E 6.4-2.03-15.8	198						Hardware				
CM00000807763	SCREW LOCKING STRONG LOCKING FLUID	10						Hardware				
CM00001853835	CABLE DUCT	1										
DTR0013214066	TUBE 20-2.5	1	2	14		Hardware			20	0.79	8	50.2
DTR0025280491	SLEEVE, HEAT-SHRINKABLE BBIT L=40	1						Hardware				
CM00001920501	EQUIPED FITTING SHEET	1										
CM00001920515	SHEET 11X836X1730	1	2	14	850	33.46	1750	68.90	-	-	-	-
CM00001922480	FOLDED SHEET 15X56X385	8	2	14	65	2.56	420	16.54	-	-	-	-
CM00001923135	FOLDED SHEET 15X56X1560	1	2	14	65	2.56	420	16.54	-	-	3	16.2
CM00001923453	BEARING SHEET	2	1.5	16	45	1.77	120	4.72	-	-	3	16.2
CM00002116500	EQUIPED BENT SHEET	2	1.5	16	520	20.47	600	23.62	-	-	6	22.2
CM00001560384	FELT 10X1	120						Hardware				
CM00001923633	BEARING SHEET	1	2.5	13	800	31.50	220	8.66	-	-	1	12.2

4. Results:

The quotation processes have been improved and cross-referencing for materials and the quoting calculator have saved a lot of time. The work is made easier, and Muda within the process is reduced. The product cost estimator displays the best-in-class product, and the mapping provides visual clarity and enhances flexibility and understanding. Quick quotes are generated by the quote calculator, representing a significant process improvement from lean thinking.

5. Conclusion:

Flexibility was increased, process speed was proven, and cost savings were provided by lean thinking. The use of both lean and six sigma in various projects played an instrumental role in creating a process and work environment that facilitated excellent outcomes on customer audits. Quality improvement within the paint process was achieved through the use of 5S methods and six sigma DOE projects. Procedural changes resulting from lean projects led to the documentation of procedures within the ISO framework and contributed to Jones Metal Inc.'s registration to ISO 9001-2015 standard. The combination of lean projects in paint and engineering estimating was crucial in acquiring a new customer, Alstom, a company that builds high-speed trains. Passing Alstom's company audits, especially their special process audit in the paint area, can be observed in the audit results.

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Biographies

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Naim Islam is a professional science master's student, pursuing engineering management under the Department of Industrial and Manufacturing Engineering at Minnesota State University, Mankato. He completed his bachelor's degree in communications engineering from International Islamic University, Malaysia. Upon completing graduation, he worked as an IT assistant in Sydney, Australia and as a performance marketer in Dubai, U.A.E. During his work experience, he has handled process improvement and waste reduction projects in different applications. He is actively involved and interested in various research topics including quality assurance, supply chain management, Lean manufacturing, Lean-Six-sigma applications, project management, new product development, design of experiments, data analysis and statistics. He has registered with IEOM as a student member to be actively involved and learn more from the industrial/manufacturing sector.