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An Application of Six Sigma for Optimality of Medium Density Fiberboard Production

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Abstract. During the production process of MDF, there is a high level of internal bond (IB) variation. This results in the waste of out-of-standard IB values that account for 0.38 % with damage value over 1 million baht/year. The company required products with fewer volatile compounds from formaldehyde adhesives, focusing on reducing the amount of adhesive but still being strong according to IB-specification which will reduce the cost of production by about 20 − 30 million baht/year. The results of wood sampling and IB testing were divided into 6 areas, namely IB1-IB6. It was found that most of the data were symmetrical except for the IB5 data as the area where the most variation occurs. The distributions of the IB1 and IB6 data showed relatively low variability compared to data from other areas. IB1 - IB6 values were normal distribution, expect for IB5. Process capacity in IB2 was relatively high compared to IB from other areas. From the Correlation Matrix and Correlation Map, it was found that the variables that influenced the IB were Press Factor, % Dosing Glue, Heat Circuit1, Primary Circuit Intel and % Mc After Gluing. To conduct the experiment and find the best variable conditions by 2^{5-2} - Factorial Design (Resolution: III). It was found that Glue = 7.4, Heat1 = 234.4, and Press = 6.5 would give IB = 0.88 which was closest to target (0.7). Glue = 7.1, Heat1 = 233.2, and Press = 6.48 would give IB = 1.15 which was the highest value. Results of production conditions at optimum or maximum that can be generalized from Rayleigh Method Dimensional Analysis was found that at the levels of 7.85, 254.28 and 257.70 of Glue, Heat1 and PrimCirIn, the target response (IB) was 0.7. and at the levels of 8.07, 233.35 and 281.60 of Glue, Heat1 and PrimCirIn resulted in a response value (IB) of 1.27.

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1. Introduction

In 2019, the Medium Density Fiberboard (MDF) produced had a high variation of Internal Bond (IB) with a standard deviation (StDev) of $0.15 - 0.18$ N/mm^2. This resulted in defects in the IB section not meeting the standards and loose-filled wood in the amount of 0.38 % from the production of $325,000$ m^3 per year. In addition, investigation of the cause causes the IB value to not meet the specification, companies also require products with zero emissions. Such volatiles come from formaldehyde glue used in the production process. If less glue is used, the volatiles will be reduced. Therefore, an additional consideration was to reduce the amount of adhesive while maintaining the required strength. IB-specification in order to reduce volatile substances to zero emission levels. In addition, reducing the amount of glue will reduce production costs as well. If the amount of glue can be reduced according to the target, the company will save production costs.

2. Experimental design

In this section, we shall recall some basic definitions that will be used in this paper.

2.1. **Materials.** This study aimed to investigate the MDF wood production process to find the optimum production conditions for MDF wood production that can reduce the formaldehyde. The quality inspector collects the MDF wood pieces produced from the production process each day, 7 pieces per day, distributed at all times of production each day (8:00 a.m.-4:00 p.m.). Then proceeded to study the nature of the IB value of Product 16 mm. E2 from the position spread over all areas of the wood, which is IB1-IB6 and tested the value of IB1 - IB6 compared with MDF Requirement.

2.2. **Research Methodology.** Due to the increasing competition in the market, many enterprises were required to improve the quality of their own products. Six sigma was one of the well-known and effective strategies for improving process quality to increase competitiveness. Six sigma therefore focused on reducing process variation and reducing the amount of waste generated by the process [11]. According to a study by Shanmugaraja et al. [10], it was found that in India, six sigma has been applied in small and medium enterprises (SMEs) by introducing the DMAIC process in the casting process to reduce the rejection rate that occurs. Desai and Prajapati [2] have implemented the six sigma DMAIC process in steel and plastic manufacturing industries, which face a high number of sorting problems. The implementation of the DMAIC process on the injection molding machine resulted in an enterprise savings of 10.8 lacs. The DMAIC process has been applied in conjunction with statistical process control (SPC) in the medical device manufacturing industry to also improve operational efficiency [3]. According to a study by Sajjad et al. [9], it was found that some organizations have applied the six sigma DMAIC process to effectively control the quality of their processes. Therefore, this research was conducted according to the six sigma DMAIC approach as follows.

Define

Cause and Effect Diagram

Based on MDF production data in 2019, it was found that the variation of Internal Bond (IB) was at a high level with standard deviation (StDev) between $0.15 - 0.18$ N/mm^2. This resulted in defects where the IB value did not pass the standard. In order to determine the cause of the non-compliance with the IB, the company also needed a product that contained very low volatile substances. Such volatiles come from the formaldehyde glue used in the manufacturing process. If a small amount of glue was used, the volatiles would be reduced. Therefore, the goal of the addition was to reduce the amount of adhesive which remained strong according to IB-specification. The study found that cause and effect diagrams (CED) have been applied by many researchers to find the cause of problems or defects such as belt manufacturing industry [5] and lamp manufacturing industry to obtain products that better quality and increase production efficiency [1]. Therefore, CED was applied for this study. By consider all possible causes that can be expected to affect the IB by collecting all possible variables. Then proceed to select and group them into different categories using the CED to find Key Process Input Variables (KPIVs).

Measure

Exploratory Data Analysis (EDA) & Visualization IB1 - IB6

To characterize the nature of the IB values of Product 16 mm. of E2 for KPIVs, in this study, the variables IB1-IB6 denoted Y1-Y6 by Exploratory Data Analysis (EDA) were presented as important statistical values. Visualization was performed to reflect the distribution or natural distribution of the IB1-IB6 relative to the MDF requirement.

Analyze

Process Capability Analysis

Analysis of the current process capability with the IB value. The first step was to determine whether the current production process was in control when preliminary sampling by $\overline{X} - R$ chart. If the process was stable or in control, a process capability analysis was performed. To be precise in determining processes, the current process must be subject to the requirement that processes have a normal distribution. Therefore, process capability was analyzed by Process Capability Indices (C_{pk}) and Process Performance Indices (P_{pk}). If the process is out of control or the process is not a normal distribution, data conversion must be performed data transformation and consider the process capability through the value P_{pk} only [7].

Correlation Analysis

To screening of variables that were expected to truly affect the IB value (at this stage, the mean of IB1-IB6 data was used as the result of the process) by multivariate analysis by constructing a correlation matrix to find effects and concordance between variables with Minitab ver. 16.0 program which selected pairs of variables with p-value < 0.05 and Rxy > 0.6. Then create a correlation map to describe the relationship between the variables.

Multiple Linear Regression Analysis

To find the significant variables that make the IB value meet the target value, which is 0.7, by applying multiple linear regression analysis using a general equation or 1st order model [7] as the equation below.

$$y = \beta + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \epsilon_0.$$

Improve

Process-Mean Shift Simulation

In order to get the IB value to meet the target value, which was 0.7, the variables expected to affect the IB value were studied to find suitable conditions for production with Excel called Solver, which was an Add-in of Excel. In Solver, there were many methods to choose forms. The method that can quickly find the optimum production conditions was the Generalized Reduced Gradient or GRG method [6].

Factorial Experiment

Study for new production conditions that result in the IB value being in accordance with the specification an appropriate experimental plan must be considered for conducting experiments with variables of interest k variables when $k > 1$. In each variable, there were 2 levels. Each replicate had the number of experiments equal to 2^k experiments or runs. This experimental design was called 2^k factorial design [8].

When the number of variables of 2^k factorial design increases, the number of runs also increases. To study the interaction of variables, at least two replications were required. Due to time, budget, resource, and environmental control constraints, it was impossible to conduct all experiments. A study by Jayness et al. [4] found that the fractional factorial design is one of the most widely used experimental designs in both scientific and industrial studies. Therefore, to reduce the number of runs and get an effective experimental design. 2^{k-2} fractional factorial design [8] was used in this study by Minitab ver. 16.0.

Response surface methodology (Steepest ascent)

Improving quality by analyzing an experiment designed to be effective in action will require repeatability of the experiment. For this research, the researcher wanted to study the new production conditions or the optimum point of the process efficiently that can improve the response or IB value according to the specification and can be effectively combined with the aforementioned 2^{k-2} fractional factorial design by replicating the experiment at the center point, i.e., the steepest ascent method. In cases where the process had a quadratic effect, the steepest ascent method was not suitable to be used to determine the new production conditions [8]. Therefore, before starting the steepest ascent, a quadratic effect test must be performed.

Dimensional analysis

Although an optimum or maximum production condition has been obtained, in fact the condition was valid only for the filtered set of variables and also applied only to the region or extent of that factor value. They cannot be generalized so a mathematical model describing the true relationship between the variable and the response was required. However, there was another tool that allows to consider a group of variables related to the response as a simple mathematical relationship. $(Y = f(X_1, \ldots, X_p))$ Such a tool was known as Dimensional Analysis, which was a mathematical analysis based on the principle that any physically related equation, quantity, must be isometric on both sides.

Control

Fault-tree diagram

In addition to finding the optimum production conditions, controlling the production process to achieve results according to specification was the key of quality control or process control with many kinds of control tools. One such tool was Root Cause Analysis, which consists of two tools. The first type was a bottom-up root cause tool. The second type was a later top-down root cause tool. From the analysis of problem conditions together with the production department, it was found that the model of problem analysis and root cause finding that was suitable for this project was a top-down root cause search called Fault Tree Analysis (FTA). The goal was to find the root cause and identify the Minimal Cut-Set for process control. Minimal Cut-Set refers to a group of major events that contribute to the manufacturing process error.

3. Results and Discussion

Define

Cause and Effect Diagram

By collecting all the possible causes that can be expected to affect IB, they can be selected and grouped according to different categories as shown in Figure 1.

Measure (M)

Exploratory Data Analysis (EDA) & Visualization IB1 - IB6

To characterize the nature of the IB value of Product 16 mm. E2 by Exploratory Data Analysis (EDA) were shown as significant statistics and visualization to reflect the distribution or the natural distribution of IB1-IB6 relative to the MDF requirement. It was found that the values of IB1 - IB6 were different mean values (adjusted for small/large values) between $0.8 - 1.1$, which exceeded the

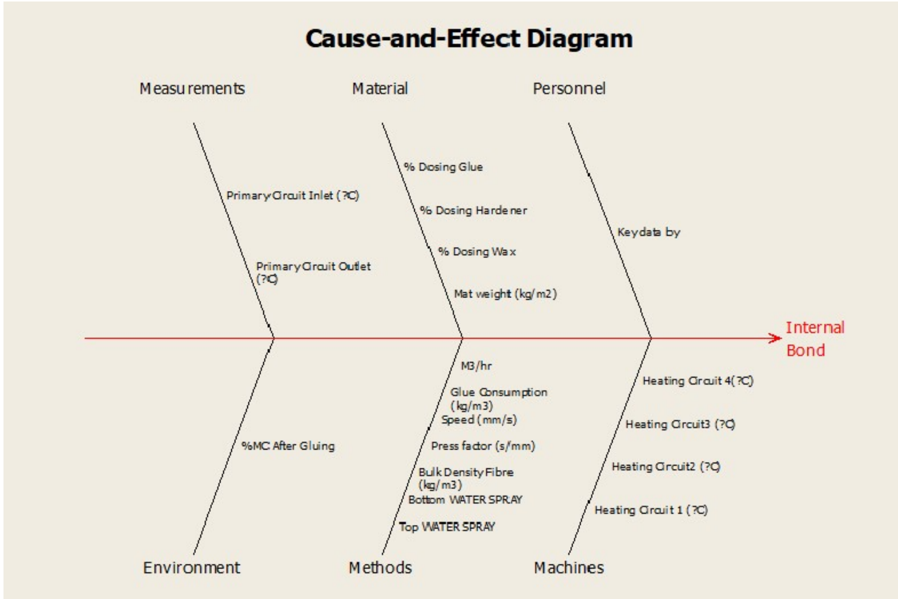

Figure 1. Cause and Effect Diagram

specification even if the IB1 and IB6 minimums were higher than the specification. Considering the lower bound of the preliminary distribution of data, it was found that this production process had a relatively high IB. When considering the mean values, both Trim Mean and Median are between $0.8 - 1.1$ N/m^2 which is beyond specification. However, it should be noted that IB1 and IB6 have Quartile 1, Trim Mean, Median, Quartile 3, and maximum value was lower than the IB2, IB3, IB4 and IB5 values, indicating that the left edge and right edge of the workpiece gave a significantly lower IB than the other areas. The distribution of the standard deviation (StDev)-described data, IB1, IB2 and IB6, were relatively lower than other areas. These showed that the production stability at the left and right margins is slightly higher than the rest, as shown in Figure 2.

Descriptive Statistics: IB1, IB2, IB3, IB4, IB5, IB6

Variable	Mean	TrMean	StDev	Minimum	Q1	Median	Q3	Maximum
IB1	0.8759	0.8831	0.1566	0.3834	0.7816	0.8772	1.0048	1.1596
IB2	0.9790	0.9834	0.1573	0.5975	0.8768	0.9952	1.0874	1.2846
IB3	0.9318	0.9345	0.1758	0.5307	0.8224	0.9527	1.0530	1.2844
IB4	0.9478	0.9513	0.1815	0.5077	0.8307	0.9639	1.0767	1.3569
IB5	1.0024	1.0087	0.1828	0.5336	0.9165	1.0455	1.1084	1.4082
IB6	0.8662	0.8729	0.1566	0.3078	0.7657	0.8728	0.9828	1.1555

Figure 2. Exploratory Data Analysis of IB1 - IB6

From Figure 3, it can be seen that IB1 and IB6 have a significantly lower range of data spread than IB2, IB3, IB4 and IB5. IB1 and IB6 were also found to have slightly narrower confidence intervals than IB2, IB3, IB4 and IB5. This was consistent with the results shown in Figure 2. The StDev values

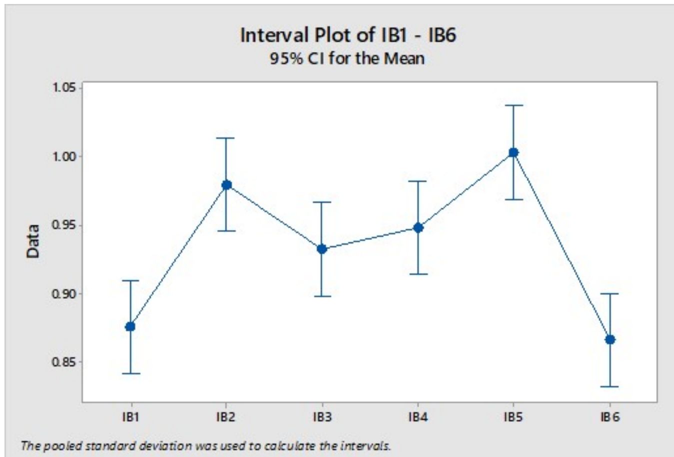

Figure 3. Interval Plot of IB1 - IB6

of IB1 and IB6 are less than those of IB2, IB3, IB4 and IB5. When considering the mean value of IB in each area by analysis of variance, the analysis results were shown in Figure 4.

One-way ANOVA: IB1, IB2, IB3, IB4, IB5, IB6

Method

Null hypothesis	All means are equal
Alternative hypothesis	At least one mean is different
Significance level	$\alpha = 0.05$

Equal variances were assumed for the analysis.

Analysis of Variance

Sourece	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Factor	5	1.414	8.09%	1.414	0.28281	9.92	0.000
Error	564	16.075	91.91%	16.075	0.02850		
Total	569	17.489	100.00%				

Figure 4. ANOVA of IB1 - IB6

Figure 4 showed that the P-value from one-way analysis of variance was lower than the defined significance level by 0.05. Therefore, it can be concluded according to alternative hypothesis that at least one mean was different, which must be considered whether it was IB1, IB6 or not by multiple comparisons. (Figure 5)

Figure 5 showed that IB1 and IB6 do not belong to the other groups (do not use the same letters with other groups). This showed a significant difference between other IB1 and IB6 groups. There were also differences in IB5 compared to other groups. However with the Lower Specification Limit of the IB value, it focused on IB1 and IB6 with some data lower than the lower specification limit. Therefore, it can be concluded based on the assumption that the left and right areas of the specimen can make the IB values significantly lower than other areas.

Figure 6 showed the distribution of IB1 - IB6 data. It was found that data from most areas were symmetrical except that data from IB5 were clearly left skewed. It also found the most extremely low data from other areas, and the only area where extremely high data were found. These led to

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping
IB5	95	1.0024	A
IB2	95	0.9790	A B
IB4	95	0.9478	A B
IB3	95	0.9318	B C
IB1	95	0.8759	C
IB6	95	0.8662	C

Means that do not share a letter are significantly different.

Figure 5. Multiple Comparisons of IB1 - IB6

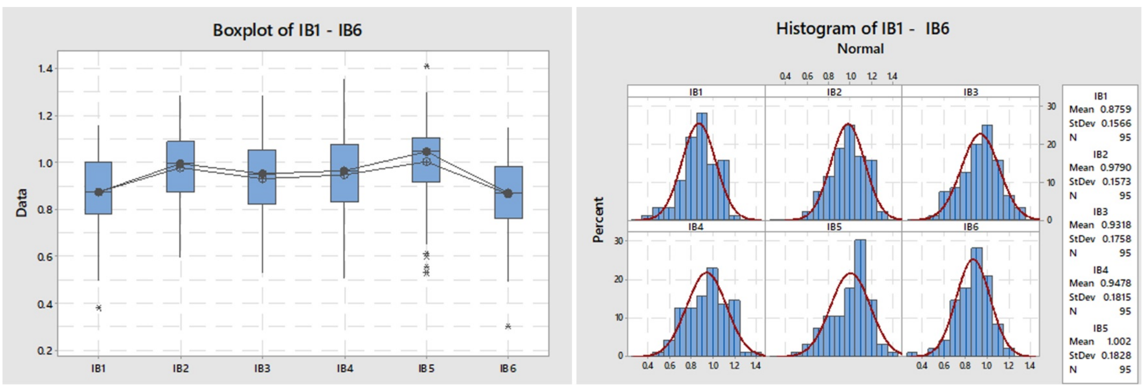

Figure 6. Boxplot and Histogram of IB1 - IB6

further assumptions about the IB5 data that might be the area of greatest variation (corresponding to the StDev value in Figure 4). It was also found that the distributions of the IB1 and IB6 data not only were symmetrical, but also had relatively low variation compared to data from other areas. This confirmed that the process performance was good in terms of dispersion, but it was still poor in terms of location downward.

Analyze (A)

Process Capability Analysis

The preliminary analysis of the distribution of data found that the data from all areas had a relatively normal distribution (p-value < 0.05), except for IB5. When testing the normality test, it was found that IB5 was not the normal distribution. Therefore, the process capability analysis was performed through the values of IB1, IB2, IB3, IB4 and IB6, assuming that the data were normal distribution. In addition, the sample size or (rational) subgroup size of IB1-IB6 must be considered. If considered according to Lot No., it will be found that some works (to be tested for the IB value) were randomly drawn from any Lot No. only once (or one lot). While some pieces were drawn from any Lot No. more than once (or more than one piece). If the process was followed with a control chart, there were two possible cases: a I-MR chart and a $\overline{X}$-R chart. In order to avoid such problems, the process was followed up with a I-MR chart considering each piece to be tested as if it came from a different Lot

No. Even though many pieces come from the same Lot No., they were cut from different areas of the large pieces in that lot.

1. Process Capability of IB1

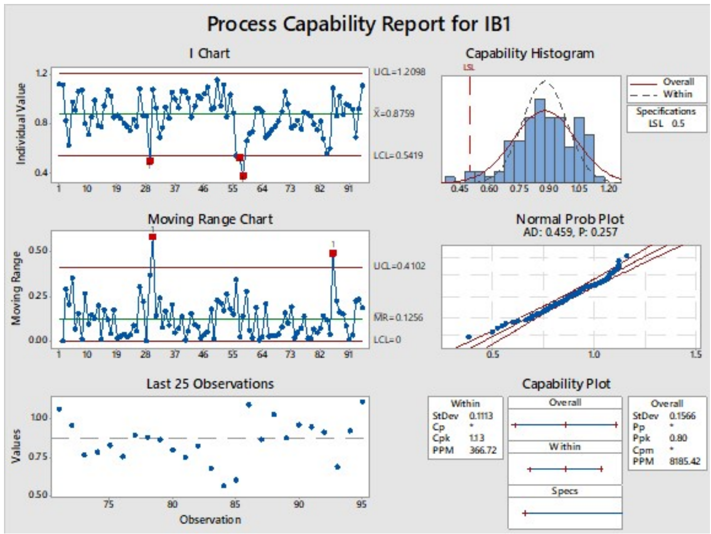

Figure 7. Process Capability of IB1

From Figure 7, it was found that the capability of the process considered through the Internal Bonding data from the test of the specimen in area 1 was out of control or had points falling outside to control limits in specimens 29, 57 and 58. The IB1 values were normal distribution based on the histogram and the p-value of the AD-Test greater than the 0.05 significance level. However the IB1 distribution was slightly skewed, although the short-term process capability is relatively high considering the C_{pk} value of 1.13. Nevertheless the slightly skewed distribution of IB1 reflected the process capability. It causes more defects than the symmetrical distribution here is approximately 367 ppm. When considering the P_{pk} value, it was found that in the long term, if allowed to continue the process may result in more frequent out of control or result in defects that may go up to approximately 8185 ppm.

2. Process Capability of IB2

From Figure 8, it was found that the capability of the process considered through Internal Bonding data from the test specimen in area 2 was not out of control. The value of IB2 was a normal distribution. The histogram and p-value of the AD-Test were considered to be greater than the significance level of 0.05 and the distribution of IB2 was almost symmetrical. The short-term process capability was quite high. When considering the C_{pk} value equal to 1.25, there were defects at approximately 89 ppm. When considering the P_{pk} value, it was found that in the long term, allowing the process to continue could result in more frequent out of control or resulting in defects that could rise up to approximately 1161 ppm.

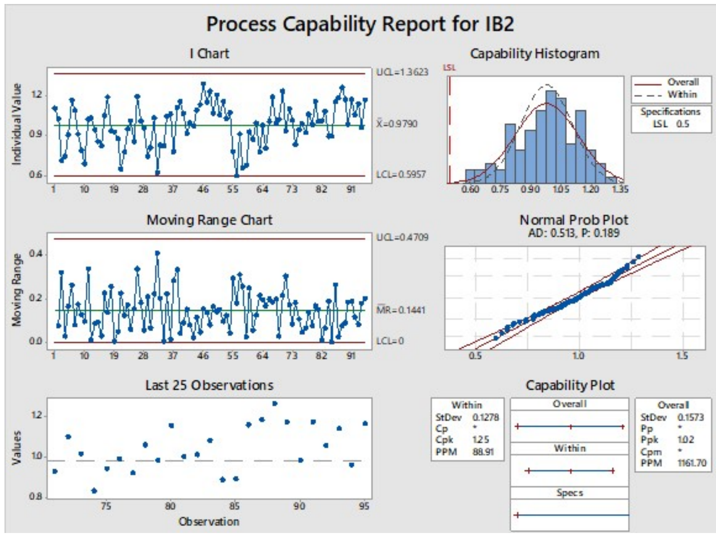

Figure 8. Process Capability of IB2

3. Process Capability of IB3

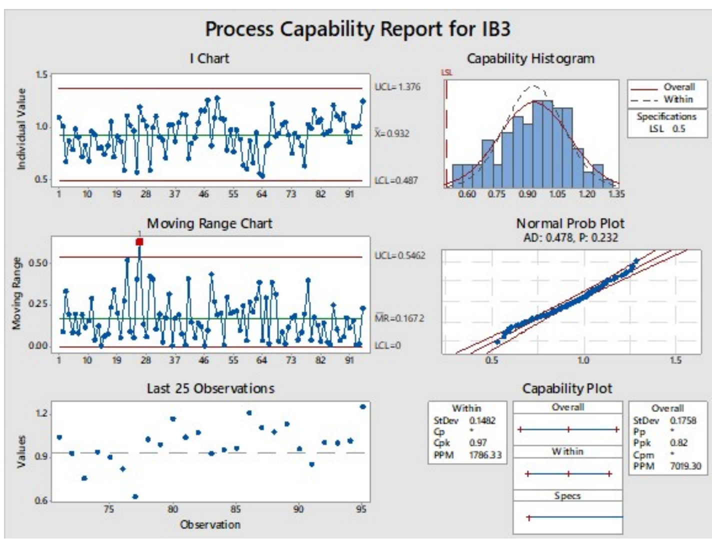

Figure 9. Process Capability of IB3

From Figure 9, it was found that the capability of the process considered through the Internal Bonding data from the test of the specimen in area 3 was not out-of-control. The IB3 was a normal distribution based on the histogram and the AD-Test's p-value greater than the 0.05 significance level, and the IB3 distribution was almost symmetrical. Short-term process ability was relatively low considering a C_{pk} value of 0.97, reflecting the poor process capability causing defects at approximately 1786 ppm. When considering the P_{pk} value, it has been found that in the long term, allowing the process to continue may result in lower process capability, resulting in defects that can reach as high as approximately 7019 ppm.

4. Process Capability of IB4

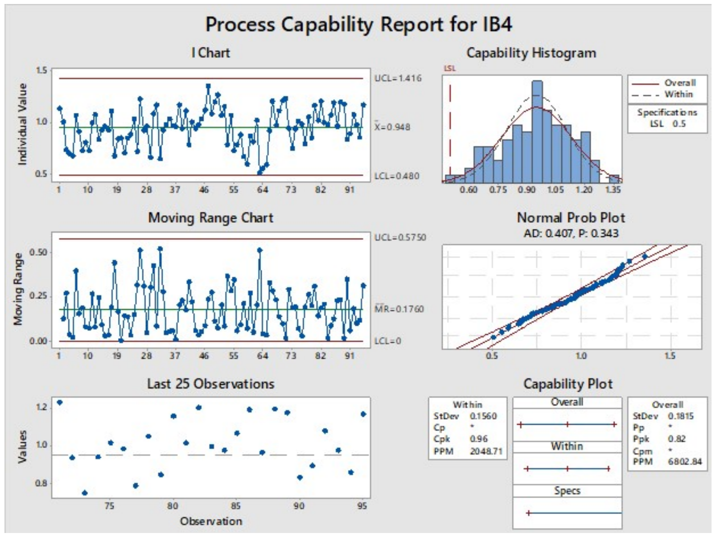

Figure 10. Process Capability of IB4

From Figure 10, it was found that the process capability considered through the Internal Bonding data from the test specimen in area 4 was not out-of-control. The IB4 was a normal distribution based on the histogram and the p-value of the AD-Test greater than the 0.05 significance level, and the distribution of IB4 was almost symmetrical. Short-term process capability was relatively low, with a value C_{pk} of 0.96 reflecting poor process capability, causing defects at approximately 2048 ppm. When considering the P_{pk} value, it has been found that in the long term, allowing the process to continue may result in lower process capability resulting in defects that can reach as high as approximately 6802 ppm.

5. Process Capability of IB5

From Figure 11, it was found that the capability of the process was considered through the Internal Bonding data from the testing of the specimens in area 5 was out of control or had points falling outside to control limits in specimen 47. The IB5 value was not a normal distribution based on the histogram and the p-value of the AD-Test that was less than the 0.05 significance level. After that, identification was performed to find the optimal distribution. It was found that the smallest extreme value distribution had the highest p-value. When estimating a distribution of characteristics other than the normal distribution, it only considers the long-term capability of the process. It was found to be very low considering the P_{pk} values equal to 0.55, reflecting the poor capacity of the process. This, together with the extremely low skewed distribution (left skew), was the cause of the defection as high as 22136 ppm, approximately.

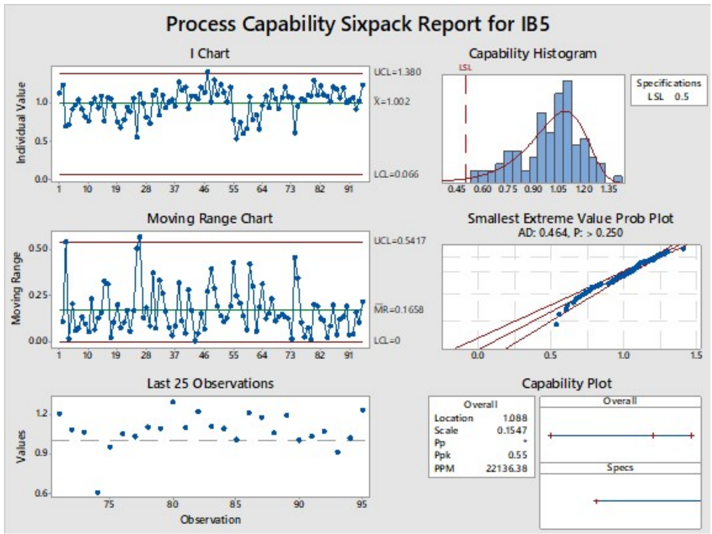

Figure 11. Process Capability of IB5

6. Process Capability of IB6

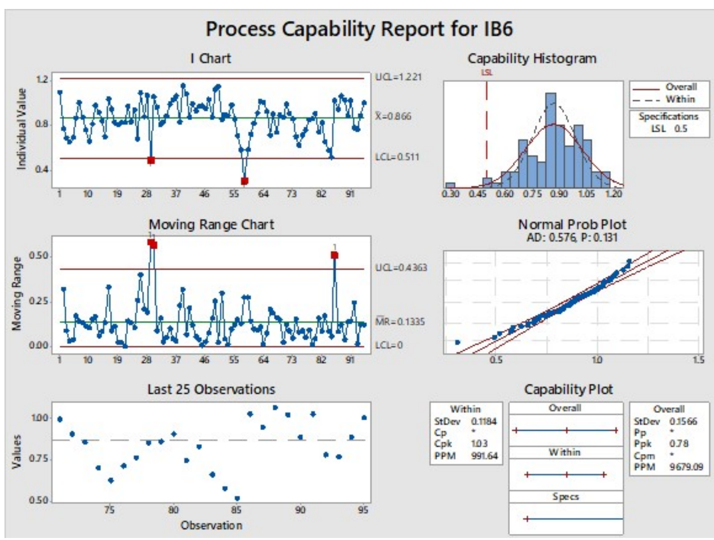

Figure 12. Process Capability of IB6

From Figure 12, it was found that the capability of the process considered through the Internal Bonding data from the test specimen in area 6 was out of control or had points falling outside to control limits in specimens 29, and 58 (in IB1 case was specimens $29, 57, 58$). IB6 was a normal distribution base on histogram and p-value of the AD-Test were considered to be greater than the significance level of 0.05, but the IB6 distribution was slightly skewed. The short-term process capability is relatively low considering a C_{pk} value of 1.03, reflecting the poor process capability. This, together with the slightly skewed nature of the distribution, caused defection at approximately 992 ppm. When considering the

P_{pk} value, it was found that in the long term, allowing the process to continue would result in severely deteriorating process capability and resulting in defects that could reach as high as approximately 9679 ppm.

Correlation Analysis From the correlation matrix, we can see the relationship of each variable, so we can create a correlation map (Figure 13) to explain the relationship between the variables. It was found that Glue was at 4th level, which is influential with PrimCirIn (3rd level). Therefore, the main variables, both Glue and PrimCirIn, were also included in the model because the Glue variable is the target variable that needs to be adjusted. Although it was not significant at early levels, the Glue variable must be added to the model. Including considering the combined influence of Glue* PrimCirIn and Heat* PrimCirIn. In addition, from the Correlation Map, it was found that the number of variables in PrimCirIn was only one, McAfGlue, so had to move to select variables from Secondary, which would get Heat, Press and Speed with the relationship between Heat1-Press, Press-Speed.

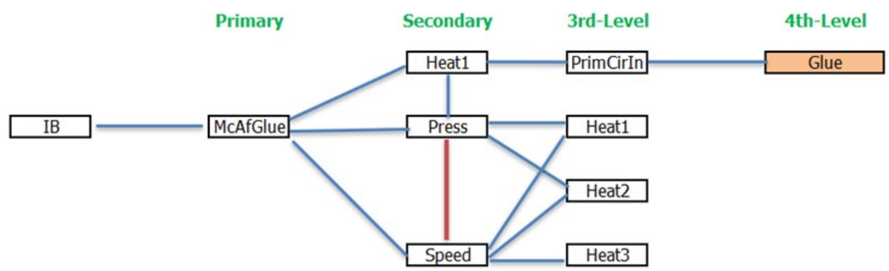

Figure 13. Correlation Map of Main Factors

Multiple Linear Regression Analysis Figure 13 showed the relationship between the response value and the significant factor. Therefore, the proper model for regression for this situation is

$$Y = f(\text{McAfGlue, Heat1, Press, Speed, PrimCirIn, Glue,}$$
$$\text{Heat1*Press, Press*Speed, Heat1*PrimCirIn, PrimCirIn*Glue})$$

Then perform regression analysis with initial model.

$$Y = \beta_0 + \beta_1\text{McAfGlue} + \beta_2\text{Heat1} + \beta_3\text{Press} + \beta_4\text{Speed} + \beta_5\text{PrimCirIn} + \beta_6\text{Glue}$$
$$+\beta_7\text{Heat1} * \text{Press} + \beta_8\text{Press} * \text{Speed} + \beta_9\text{Heat1} * \text{PrimCirIn} + \beta_1 0\text{PrimCirIn} * \text{Glue}.$$

The final model that contains all significant variables as shown in Table 1, which will be used as the equation for process mean shift.

Improve Process-Mean Shift Simulation Solver results by GRG method from the Excel program when setting the target value at 0.7 can find the conditions that will make the target value by McAfGlue, Heat1, Press, PrimCirIn, and Glue were $8.00, 240.34, 9.01, 263.60$ and 7.29 respectively. Factorial Experiment As a 5 factors experimental plan requires at least 32 runs under different treatment combinations. In practice, it was very difficult to adjust the conditions for each experiment, so a

Table 1 Final Model Coefficients

	Coeffcients	Standard Error	t Stat	p-value
McAfGlue	-0.0582	0.0199	-2.9256	0.0044
Heat1	-0.0842	0.0230	-3.6689	0.0004
Press	-2.6842	0.7365	-3.6447	0.0005
PrimCirIn	0.0805	0.0204	3.9528	0.0002
Glue	2.6287	0.7036	3.7360	0.0003
Heat1*Press	0.0112	0.0031	3.6259	0.0005
PrimCirIn*Glue	-0.0098	0.0026	-3.7731	0.0003

fractional factorial design scheme must be considered. Considering the regression coefficient of main influence from Table 1, it was found that Press, Glue was greater than McAfGlue, Heat 1, and PrimCirIn. Therefore, the main variables are Press, Glue will be considered first, followed by Heat 1, PrimCirIn, and McAfGlue. Because there were 5 factors which would be difficult to carry out the experiment as mentioned above, it was turned to use fractional factorial design: 25-2 Resolution: III by specifying the following conditions are:

- Runs $= 8 + 5$ (Center point)
- Design Generator: $D = AB, E = AC$
- Alias Structure

  $I + ABD + ACE + BCDE$

  $A + BD + CE + ABCDE \rightarrow$ A: Press

  $B + AD + CDE + ABCE \rightarrow$ B: Glue

  $C + AE + BDE + ABCD \rightarrow$ C: Heat1

  $D + AB + BCE + ACDE \rightarrow$ D: PrimCirIn

  $E + AC + BCD + ABDE \rightarrow$ E: McAfGlue

  $BC + DE + ABE + ACD$

  $BE + CD + ABC + ADE$

Then construct the design matrix table for the 2^{5-2} fractional factorial experiment design, and determine the different levels of each factors. Then, the experiments were conducted according to each variable level. The experimental results were shown in Table 2.

Response surface methodology (Steepest ascent) Then the quadratic effect was tested which found that $F_0 = 0.017 < F_{\text{critical}} = 7.708$. This indicates that the range of the selected variable does not have a quadratic effect. That is, it is plane-bound to the actual process response, indicating that can be found the optimum process by the steepest ascent method. Regression coefficients were performed and found that intercept, Press, Glue, and Heat1 had regression coefficients of $0.978, 0.004, -0.092$ and 0.036 respectively. Then the rate of change was calculated from the equation.

$$\Delta X_i = \frac{\beta_i}{\beta_{\text{largest}}/\Delta X_{\text{largest}}}$$

Table 2 2^{5-2} fractional factorial experiment design

Coded values			Natural values			
Press	Glue	Heat1	Press	Glue	Heat1	IB
-1	-1	-1	6.0	7.0	230	1.06
-1	-1	1	6.0	7.0	240	1.10
-1	1	-1	6.0	8.0	230	0.82
-1	1	-1	6.0	8.0	240	0.93
1	-1	-1	7.0	7.0	230	1.08
1	-1	1	7.0	7.0	240	1.05
1	1	-1	7.0	8.0	230	0.82
1	1	1	7.0	8.0	240	0.99
0	0	0	6.5	7.5	235	0.98
0	0	0	6.5	7.5	235	1.06
0	0	0	6.5	7.5	235	0.75
0	0	0	6.5	7.5	235	1.03
0	0	0	6.5	7.5	235	1.04

By setting Glue as the leading variable (due to the high regression coefficient), followed by Heat1 and Press. Set Glue (coded) to decrease by 0.3, which will cause Heat1 and Press to decrease by 0.118 and 0.012 respectively. Once the rate of change is obtained, the coded values are converted to natural values and the step size (ΔX_i) is calculated as shown in Table 3.

Table 3 Coded Values, Natural Values and Steps

	Coded values			Natural values		
	X_1	X_2	X_3	Glue	Heat1	Press
Step	0.30	-0.12	-0.01			
1	0.00	0.00	0.00	7.50	235.00	6.50
2	-0.30	-0.12	-0.01	7.35	234.41	6.49
3	-0.60	-0.24	-0.02	7.20	233.82	6.49
4	-0.90	-0.35	-0.04	7.05	233.24	6.48
5	-1.20	-0.47	-0.05	6.90	232.65	6.48
6	-1.50	-0.59	-0.06	6.75	232.06	6.47
7	-1.80	-0.71	-0.07	6.60	231.47	6.46
8	-2.10	-0.82	-0.09	6.45	230.88	6.46

Then conduct further experiments according to different levels of variables. The experimental results were shown in Table 4. When plotted between step and response, the optimum levels were found as shown in Figure 14.

From Figure 14, it was found that the optimum levels of each variable were possible in two cases:

- In the optimum case, it means that the response value is closest to the target. In this case, it was found that at step 2, the process variable value was set at Glue = 7.4, Heat1 = 234.4, and Press = 6.5, resulting in IB = 0.88, which had the value closest to target (0.7).
- In the case of maximum, it means that the response value was the highest. In this case, found at step 4, the process variable values were set at Glue = 7.1, Heat1 = 233.2 and Press = 6.48, resulting in IB = 1.15 which was the highest value.

Table 4 Response for Steepest Ascent

	Coded values			Natural values			
	X_1	X_2	X_3	Glue	Heat1	Press	IB
Step	0.30	-0.12	-0.01				
1	0.00	0.00	0.00	7.50	235.00	6.50	0.99
2	-0.30	-0.12	-0.01	7.35	234.41	6.49	0.88
3	-0.60	-0.24	-0.02	7.20	233.82	6.49	1.04
4	-0.90	-0.35	-0.04	7.05	233.24	6.48	1.15
5	-1.20	-0.47	-0.05	6.90	232.65	6.48	1.12
6	-1.50	-0.59	-0.06	6.75	232.06	6.47	1.08
7	-1.80	-0.71	-0.07	6.60	231.47	6.46	0.95
8	-2.10	-0.82	-0.09	6.45	230.88	6.46	0.91

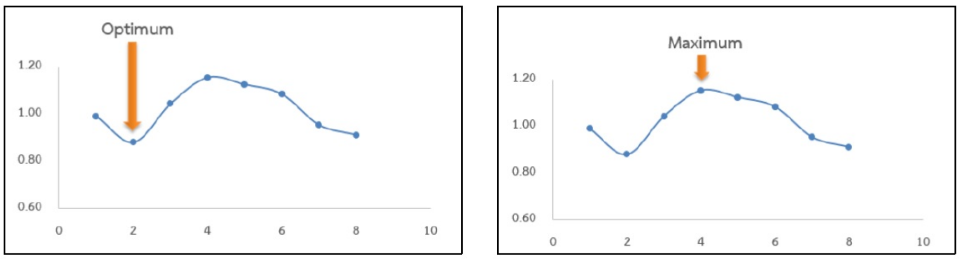

Figure 14. Response from Each Step: Optimum, Maximum

Dimensional analysis Although an optimum or maximum production condition has been obtained, it was in fact valid only for the filtered set of variables and was valid only for the area or extent of such variable values. It cannot be generalized in that it requires a mathematical model that describes the true relationship between the variable and the response. However, there was another tool to consider a group of variables related to the response as a simple mathematical relationship ($Y = f(X_1, \ldots, X_p)$). Such tools were called dimensional analysis, which was a mathematical analysis based on the principle that any equation with physical relations and quantities must be isometric on both sides. In this case, the model of the relationship between inputs and responses is:

$$Y = f(\text{Press, Glue, Heat1, PrimCirln, McAfGlue})) \quad (1)$$

By considering the unit of % Dosing Glue as a unit of adhesive force, which has the same unit as pressure1 instead of the original unit of mass. Rayleigh Method dimensional analysis is used to determine the relationship pattern from the correlation analysis to find the relationship of IB with the screened variables. The dimensions of all variables and response values are shown in Table 5. Then group the basic dimensions of both the response and the variable as follows:

$$Y = f(X_1, X_2, X_3, X_4, X_5) \quad (2)$$

$$Y = C * (X_1)^a * (X_2)^b * (X_3)^c * (X_4)^d * (X_5)^e \quad (3)$$

$$ML^{-1}T^{-2} = C * (TL^{-1})^a * (ML^{-1}T^{-2})^b * (\theta)^c * (\theta)^d * M^e \quad (4)$$

$$ML^{-1}T^{-2}\theta^0 = C * M^{(b+e)} * (L)^{-a-b}(T)^{(a-2b)} * (\theta)^{c+d} \quad (5)$$

Consider the exponents on both sides of the equation.

Table 5 Parameter and Dimension

	Parameter	Dimension
Internal Bond (Force/Area)	Y	$ML^{-1}T^{-2}$
Press Factor (Time/Length)	X_1	TL^{-1}
%Dosing Glue (Pressure)	X_2	$ML^{-1}T^{-2}$
Heat Curcuit1 (Temperature)	X_3	θ
Primary Circuit Inlet (Temperature)	X_4	θ
%MC After Glue (Mass)	X_5	M

- $M : b + e = 1$
- $L : -a - b = -1$
- $T : a - 2b = -2$
- $\theta : c + d = 0$

Solve the aforementioned system of equations to find the values of a, b, c, d and e. Found to be equal to $0, 1, -d, d$ and 0, respectively. From $Y = C * (X_1)^a * (X_2)^b * (X_3)^c * (X_4)^d * (X_5)^e$

It can be said $Y = C * (X_1)^0 * (X_2)^1 * (X_3)^{(-d)} * (X_4)^d * (X_5)^0$ (6)

or $Y = C * X_2 * (X_4/X_3)^d$ (7)

(where C and d constants that will be determined in further actual experimental operations) Find the C and d constants, starting by framing Equation (7) in the $\pi_1 = C\pi_2^d$ form. Then transformed into a linear equation using logarithm

$\ln(\pi) = \ln(C) + d\ln(\pi_2)$ (8)

Equation (8) was equivalent to a linear equation $Y = AX + B$. To find the coefficients using regression analysis. The regression coefficients were obtained as shown in Table 6, that is $\ln(C) = -2.4611$,$C = e^{-2.4611} = 0.0853$ and $d = 3.2571$. Therefore, the relationship equation between the variables and the response value was:

$Y = 0.0853X_2(\frac{X_4}{X_3})^{3.2571}$ (9)

Then use Equation (9) to calculate the level of the most suitable variable of production. Both optimum and maximum cases were taken into account. It was found that at the levels of 7.85, 254.28 and 257.70 of Glue, Heat1 and PrimCirIn, the target response (IB) was 0.7. At the 8.07, 233.35 and 281.60 levels of Glue, Heat1 and PrimCirIn, the maximum response (IB) value was 1.27 as shown in Table 7.

Table 6 Regression Coefficients of $ln(\pi) = ln(C) + d\ ln(\pi_2)$

	Coefficients	Standard Error	t Stat	P-value
Intercept	-2.4611	0.2042	-12.0550	0.0000
$\ln(\pi_2)$	3.2571	1.5681	2.0772	0.0446

The approach to find the optimum production level by the Dimensional Analysis method can start by considering all variables before screening by Correlation Analysis and Regression Analysis, but with a large number of variables (in this case, 20 initial variables), making the structure of the system equation

Table 7 Optimum and Maximum condition for IB

	Glue	Heat1	PrimCirIn	IB
	X_2	X_3	X_4	Y
Optimum	7.85	254.28	257.70	0.70
Maximum	8.07	233.35	281.60	1.27

to solving for a constant that describes the relationship between all variables, and the response was so complex that it can be analyzed using the Bukingham Pi method. Therefore, if the initial variables were large, the selection of KPIVs was still very important.

Control (C) Fault-tree diagram To find the root cause and identify the Minimal Cut-Set for process control. In the first step of the FTA, a diagram showing the relationship between the main problems and their causes in hierarchical levels is shown in Figure 15.

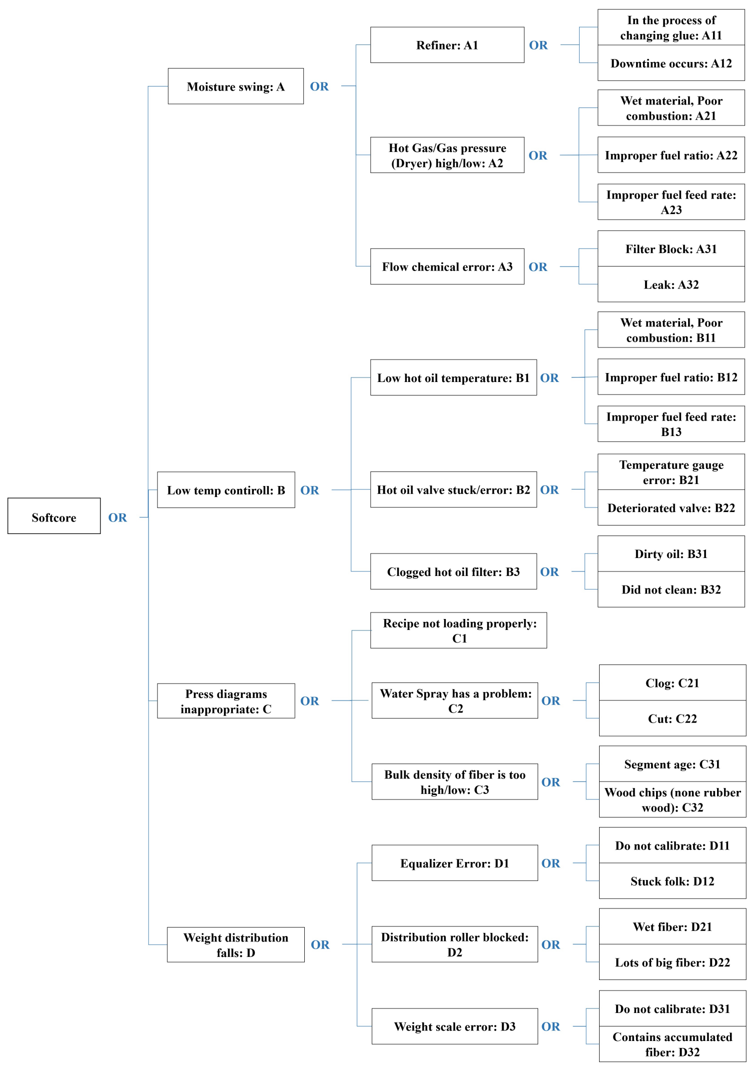

Figure 15. Fault Tree Analysis of Softcore

From considering the problems and causes together through the FTA diagram, it was initially found that the causes or events that occurred at each level are mutually exclusive. If these events occur together, they will severely affect the response (the IB value will drop significantly). In the past, there was no such severe problem occurring. Therefore, when considering the linkage of the causes, the linkage point was replaced by the FTA gate symbol: OR gate as shown in Figure 15, which was the Minimal Cut-Set as Equation (11).

$$\begin{aligned} \text{Softcore} &= (A_{11} \cup A_{12}) \cup (A_{21} \cup A_{22} \cup A_{23}) \cup (A_{31} \cup A_{32}) \\ &(B_{11} \cup B_{12} \cup B_{13}) \cup (B_{21} \cup B_{21}) \cup (B_{31} \cup B_{31}) \\ &(C_{21} \cup C_{21}) \cup (C_{31} \cup C_{31}) \cup (D_{11} \cup D_{11}) \cup (D_{21} \cup D_{21}) \cup (D_{31} \cup D_{31}) \end{aligned} \tag{10}$$

$$\begin{aligned} \text{Minimal Cut-Set} &= A_{11} + A_{12} + A_{21} + A_{22} + A_{23} + A_{31} + A_{32} + \\ &B_{11} + B_{12} + B_{13} + B_{21} + B_{21} + B_{31} + B_{31} + \\ &C_{21} + C_{21} + C_{31} + C_{31} + D_{11} + D_{11} + D_{21} + D_{21} + D_{31} + D_{31} \end{aligned} \tag{11}$$

where the $A_{11}, \ldots, D_{31}$ event had a meaning as in Table 8.

Table 8 Description of Causes of Softcore

Code	Description	Code	Description	Code	Description
A11	In the process of changing glue.	B12	Improper fuel ratio	C31	Segment age
A12	Downtime occurs	B13	Improper fuel feed rate	C32	Wood chips (none rubber wood)
A21	Wet material, Poor combustion	B21	Temperature gauge error	D11	Do not calibrate
A22	Improper fuel ratio	B22	Deteriorated valve	D12	Stuck folk
A23	Improper fuel feed rate	B31	Dirty oil	D21	Wet fiber
A31	Filter Block	B32	Did not clean	D22	Lots of big fiber
A32	Leak	C21	Clog	D31	Do not calibrate
B11	Wet material, Poor combustion	C22	Cut	D32	Contains accumulated fiber

4. Conclusions

Because the company wanted to investigate the cause of the IB value not meeting the requirements and wanted to reduce the amount of formaldehyde in the production process. From the study of the current production process through the IB, dividing the test areas into 6 areas including IB1-IB6, it was found that most of the data were symmetrical, except IB5, which had the greatest variation of data, and the short-term process capability of IB2 was quite high compared to other regions with $C_{pk} = 1.25$. But in the long term, if the process is allowed to continue, it may result in a decrease in process capability in all areas. By considering the correlation matrix and multiple linear regression analysis, it was found that the factors that significantly influenced the IB were Press Factor, % Dosing Glue, Heat Circuit1, Primary Circuit Intel and % Mc After Gluing. Optimal factor conditions were performed using 2^{5-2} - Factorial Design (Resolution: III) with Steepest Ascent Method, and it was found that at Glue, Heat1 and Press were 7.4, 234.4 and 6.5 respectively, the IB = 0.88 which was closest to the target value of 0.7 and Glue, Heat1 and Press of 7.1, 233.2 and 6.48 respectively, giving the IB = 1.15 which was the highest value. The results of production terms optimum or maximum can be generalized from the Rayleigh method of dimensional analysis. It was found that at the levels of 7.85, 254.28 and 257.70 of Glue, Heat1 and PrimCirIn, the target IB value was 0.7, and at the levels of 8.07, 233.35 and 281.60 of Glue, Heat1 and PrimCirIn, the maximum IB value would be 1.27. When the new production conditions were suitable, then the production process was controlled to achieve the desired results. Specification using the Fault-tree diagrame (FTA) method. It was found that the causes or events that occurred at each level were not mutually exclusive so they did not have a severe effect on the IB value and the Minimal Cut-Set was obtained as Equation (11).

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