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Robust Design and Optimization of Production Wastes: An Application for Industries

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Abstract**—**This paper focuses on robust design and optimization of industrial production wastes. Past literatures were reviewed to case study Clamason Industries Limited (CIL) - a leading ladder-tops manufacturer. A painstaking study of the firm's practices at the shop floor revealed that Over-production, Waiting time, Excess inventory, and Defects are the major wastes that are impeding their progress and profitability. Design expert8 software was used to apply Taguchi robust design and response surface methodology in order to model, analyse and optimise the wastes cost in CIL. Waiting time and over-production rank first and second in contributing to the costs of wastes in CIL. For minimal wastes cost the control factors of over-production, waiting-time, defects and excess-inventory must be set at 0.30, 390.70, 4 and 55.70 respectively for CIL. The optimal value of cost of wastes for the months studied was 22.3679. Finally, a recommendation was made that for the company to enhance their profitability and customer satisfaction, they must adopt the Shingeo Shingo's Single Minute Exchange of Dies (SMED), which will immediately tackle the waste of waiting by drastically reducing their setup time.

Keywords**—**Excess-inventory, setup time, single minute exchange of dies, optimal value, over-production, robust design.

I. Introduction

LEAN Production System (LPS) is a manufacturing philosophy that is fashioned to respond quickly to the customer's requirements. It is aimed at the elimination of all wastes and non-value adding activities in manufacturing processes.

Apart from identifying and eliminating wastes, LPS enables organizations to be more profitable through the application of fewer resources to manufacture more quality products at a faster rate, thereby leading to competitive advantage and customer satisfaction.

The whole essence of LPS is targeted towards fast manufacturing of high quality products in an ever improving company. Reference [1] observed that Lean Production System "uses the less of everything compared with mass production – half the human effort in the factory, half the manufacturing space, half the investment in tools, half the engineering hours to develop a new product in half the time." To achieve these, LPS is therefore targeted at detection, isolation and elimination of all possible wastes in manufacturing through continuous improvement.

According to [2], in LPS every step of manufacturing necessitates the requirement for additional material at the following section downstream. He pointed out that its manufacturing cells make use of a system of inventory pull as well as control of manufacturing, as production only starts when there is a demand for additional inventory at the subsequent step. This is because the idea is to manufacture the exact amount of goods required by the customer at the exact time they are needed, which negates the traditional method of supplying products to the customers from the stock.

The role of LPS is to eliminate all the manufacturing activities that do not add value to the product and to also reduce the overall throughput of the product. On the other hand, Robust Design according [3] focuses on improving the fundamental function of the product or process, thus facilitating flexible designs and concurrent engineering, as it is the most powerful method available to reduce product cost, improve quality, and simultaneously reduce development interval. Reference [4] explained that Taguchi methods are statistical methods aimed to improve the quality of manufactured goods by consciously considering the noise factors (environmental variation during the product's usage, manufacturing variation, and component deterioration) and the cost of failure in the field, thereby leading to customer satisfaction.

Reference [5] used Taguchi robust design to establish optimal process parameters for an oil blending process. Reference [6] defines RSM as a collection of mathematical and statistical techniques useful for the modeling and analysis of problems in which a response of interest is influenced by several variables. It can also be defined as collection of statistical and mathematical techniques for developing, improving and optimizing processes. More information on RSM is found in [7]-[12].

II. Overview of LPS and Robust Design

In the 1980s, Genichi Taguchi introduced robust design on quality engineering through the statistical design of experiments as presented in [13] and [14]. The concepts of robust design and its realization methods are significant contributions to modern quality and process improvement.

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Reference [15], observed that the major focus of Lean Production System is to: achieve customer satisfaction, enhance value through the elimination of wastes, reduce cycle time through response to speed, improve flow, and flexibility to ensure customer satisfaction.

According to [16] the role of LPS is to eliminate all the manufacturing activities that do not add value to the product and to also reduce the overall throughput of the product. He listed its main elements as the management of "processes and the integrated logistics flow, relationship with employees, teams and suppliers, and the change from traditional mass production."

Reference [17], observed that "Today the ultimate goal of quality improvement is to design quality into every product and process and to follow up at every stage from design to final manufacture and sale. An important element is the extensive and innovative use of statistically designed experiments." Based on this Taguchi robust design that targets all forms of wastes and response surface method that fits high order polynomial function to experimental data were employed to model wastes of CIL.

III. Production Wastes: Clamason Manufacturing Company

CIL has two transfer press lines with up to six presses located together to enable robotic movement of the pressed part between each press station. This allows the production of highly complex parts, with no carry strip, automatic insertion of other components, and the capability for multiple burr reversals. Some of their products include set top boxes, ladder tops, and radio components.

Customer demand and the ever present need to improve productivity were the major factors that influenced the company's decision to adopt lean production system. Other factors include: High inventories, financial losses, low productivity, customer complaints, ease of implementation, and poor resource utilisation. With continuous improvement, the company has been able to address the various limitations thereby increasing its efficiency and productivity which were the criteria for choosing LPS projects in the company.

IV. Applying Taguchi Robust Design to CIL

As CIL had been implementing LPS for the past fifteen years, it is expected that they must have eliminated all the wastes in their manufacturing processes, however, although LPS had helped them tremendously to drastically reduce the wastes over the years, a careful study of their nine months ladder-tops production chart showed that the wastes of defects, inventory, and over-production has not been adequately tackled.

As could be observed from Table I where Mnt stands for month, AI stands for available inventory, MLT stands for manufactured ladder top, SLT stands for sold ladder top, A, B, C and D stands for defects, excess inventory, overproduction and over processing respectively, in the month of September 2010, the company had a total of seven defective ladder-tops, four hundred and thirty five excess inventory, zero over-processing, and from the number that was manufactured and the number that was sold, nine pieces were over-produced.

TABLE I
Clamason's Ladder-Tops Nine Months Production Chart

Mnt	AI	MLT	SLT	A	B	C	D
Sep. 2010	17004	16569	16560	7	435	9	0
Oct. 2010	24012	23800	23796	2	212	4	0
Nov. 2010	15896	15896	15888	1	0	8	0
Dec 2010	31000	31000	30996	3	0	4	0
Jan.2011	16433	16430	16428	0	3	2	0
Feb.2011	29807	29643	29640	2	164	3	0
Mar. 2011	25000	24713	24708	4	287	5	0
April 2011	12307	12093	12108	1	214	-15	0
May 2011	26008	26003	25992	2	5	11	0

Although the management of the company explained that only defects, excess inventory, and over-production were the only wastes that they are contending with, the author's acknowledgement of set-up time and the works of Shingeo Shingo on Single Minute Exchange of Dies (SMED) made the probe further on the efforts to reduce their set-up time.

SMED plays a prominent role in lean production, as achieving set-up time reduction is very important in transforming a company from mass production to lean. Reference [18] explained that the application of SMED results in remarkable set-up time reductions as well as increase in productivity even in its inception. With quick changeover, SMED contributes immensely to increase in flexibility, production capacity and the maintenance of very low inventory in Optimum production, as one-piece flow and streamlining operations can easily be achieved.

The company explained that they spend an average of a quarter of a minute to set-up a dozen units of the ladder-tops on the pressing machine. This shows that for every twelve ladder-tops that are manufactured, that the machines are stopped for 0.25 minutes, thereby making the shop floor workers to wait until it is mounted. As LPS aims to eliminate all wastes in manufacturing processes, the waste of waiting cannot be ignored as it is not insignificant. This is because the company can reduce it to the barest minimum if they realize how much time that is wasted by adopting the principles of SMED.

A. Calculating the Waste of Waiting

As an average of a quarter of a minute is used to set-up twelve ladder-tops, it implies that the amount of time spent monthly for waiting can be calculated with (1).

$$Monthly\ Waiting = 0.25\ (minute) * \frac{number\ of\ manufactured\ ladder\ tops}{12} \tag{1}$$

Substituting in (1)

For September 2010: $Waiting = 0.25 * \frac{16569}{12} = 345.19$

The values obtained by performing similar calculations for the remaining months are summarized in Table II, where **D** stands for waiting time.

TABLE II
CALCULATED TIME IN MINUTES

Mnt	AI	MLT	SLT	A	B	C	D
Sep. 2010	17004	16569	16560	9	435	9	345.19
Oct. 2010	24012	23800	23796	2	212	4	495.83
Nov. 2010	15896	15896	15888	1	0	8	331.17
Dec. 2010	31000	31000	30996	3	0	4	645.83
Jan. 2011	16433	16430	16428	0	3	2	342.29
Feb. 2011	29807	29643	29640	2	164	3	617.56
March 2011	25000	24713	24708	4	287	5	514.54
April 2011	12307	12093	12108	1	214	-15	251.94
May 2011	26008	26003	25992	2	5	11	541.73

From Table II, it could be deduced that the four wastes that are adversely affecting the company's LPS efforts are: defects, Excess inventory, Over-production, and waiting.

B. Objective Function, Experimentations, and Quality Characteristics

The main aim of LPS is to minimise or possibly eliminate all forms of wastes in production processes. The four wastes identified in CMC are defects (A), excess inventory (B), over-production (C), and waiting (D). The total cost of wastes (C_T) is the objective function to be optimized and can be expressed as follows:

$$C_T = C_A + C_B + C_C + C_D \tag{2}$$

where
C_A=cost of defects production, C_E =cost of excess inventory, C_C =cost of over-production, C_D = cost of waiting

Equation (2) is used for the computation of the nine months of production and recorded as in Table III.

TABLE III
PRODUCTION WASTES AND ASSOCIATED COSTS

Experiment Number	A	B	C	D	Average cost
1	9	435	9	345.19	39.87
2	2	212	4	495.83	52.40
3	1	0	8	331.17	36.53
4	3	0	4	645.83	50.07
5	0	3	2	342.29	35.20
6	2	164	3	617.56	48.47
7	4	287	5	514.54	46.33
8	1	214	-15	251.94	30.33
9	2	5	11	541.73	46.00

V. ANALYSIS OF PRODUCTION WASTES WITH DESIGN EXPERT8 SOFTWARE

A. Application of Taguchi Robust Design

To successfully apply the Taguchi robust design from the Design Expert8 software to model the wastes that are inherent in the ladder-tops production processes in Clamason Industries Limited, the average values of the wastes are required. They are calculated as shown in Table IV.

TABLE IV
AVERAGE VALUES OF THE FACTORS IN CLAMASON INDUSTRIES LIMITED

Average of Experiment Numbers	Average of Defects (A)	Average of Excess Inventory(B)	Average of Over-production(C)	Average of Waiting (D)
1,2, and 3	4	215.7	7	390.7
4,5, and 6	1.7	55.7	3	535.2
7,8, and 9	2.3	168.7	0.3	436.1

Using the calculated average values as inputs, the software produced the design layout as can be seen on Table V and Fig. 1-6, where response1 represents the optimized costs of wastes.

TABLE V
THE DESIGN LAYOUT

Standard	Run	Factor 1 (A)	Factor 2 (B)	Factor 3 (C)	Factor 4 (D)	Response 1
1	1	4	215.7	7	390.7	39.9
2	3	4	55.7	3	535.2	52.4
3	7	4	168.7	0.3	436.1	36.5
4	9	1.7	215.7	3	436.1	50.1
5	4	1.7	55.7	0.3	390.7	35.2
6	2	1.7	168.7	7	535.2	48.5
7	6	2.3	215.7	0.3	535.2	46.3
8	5	2.3	55.7	7	436.1	30.3
9	8	2.3	168.7	3	390.7	46.0

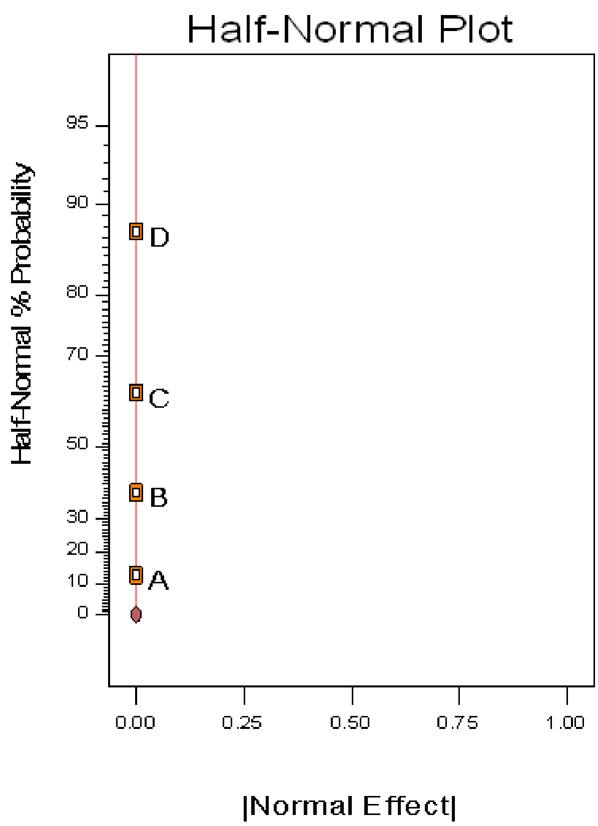

Fig. 1 Normal effects plot with selected wastes

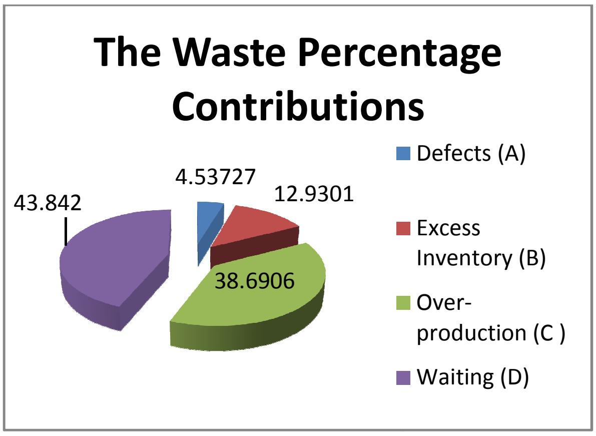

Fig. 2 The Waste percentage contributions

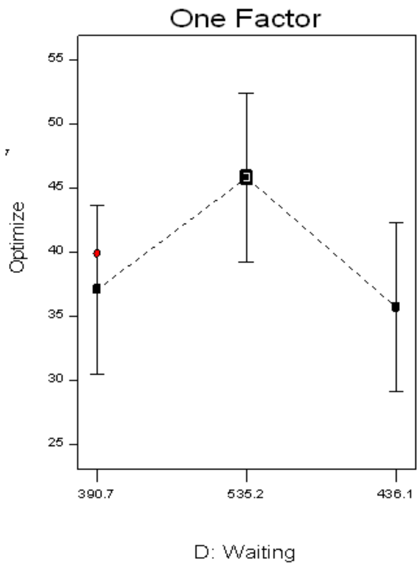

Fig. 3 Model graph for Waiting (When the waiting time is 436.1 seconds)

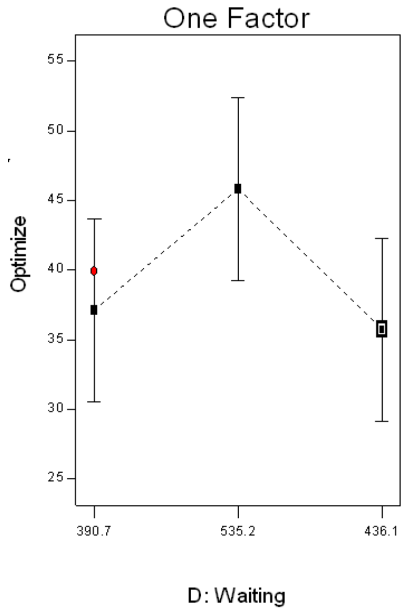

Fig. 4 Model graph for Waiting (When the waiting time is 535.2 seconds)

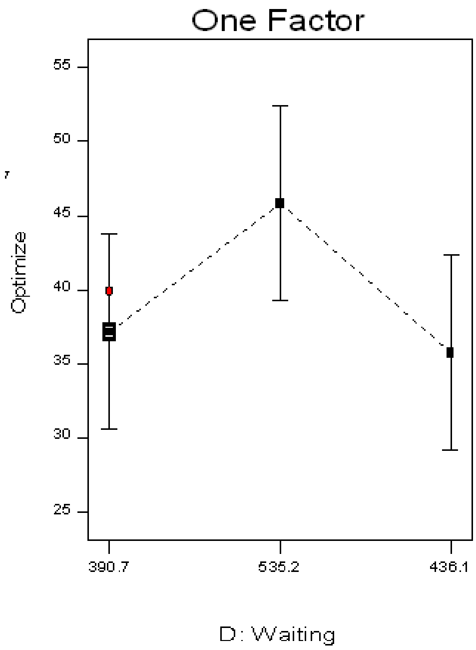

Fig. 5 Model graph for waiting (When the waiting time is 390.7 seconds)

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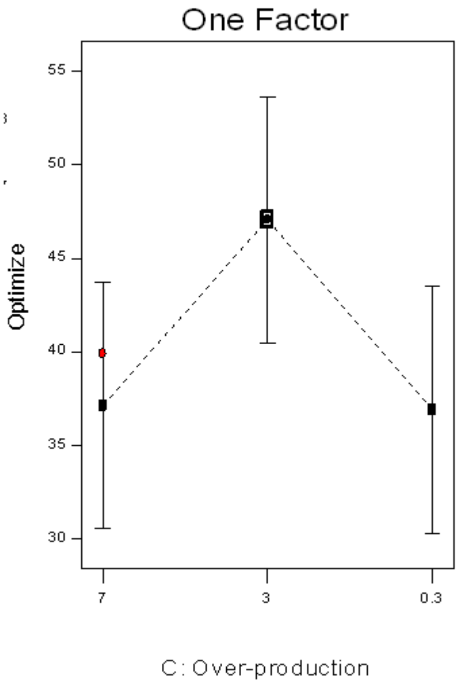

Fig. 6 Effect plot of factor C

B. Response Surface Optimization of Wastes

A power law model of Table V in terms of four factors of wastes and responses were obtained as

$$R = 0.30903 * A^{-0.27} * B^{0.121} * C^{0.0203} * D^{0.710} \quad (3)$$

TABLE VI
CONTROL FACTOR LEVELS

Factor	Low(-)	High(+)
A:Defects (Ladder-tops)	1.7	4
B:Excess Inventory (Ladder-tops)	55.7	168.7
C:Over-production (Ladder-tops)	0.3	7
D:Waiting (Ladder-tops)	390.7	535.2

The power law model is used with Table VI to obtain the following RSM graphics of design expert8 software on implementation of central composite design (CCD) with CCD matrix.

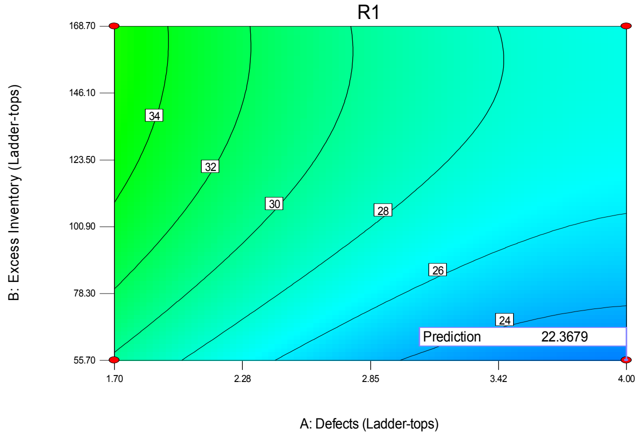

Fig. 7 Design expert8 contour depiction of optimum (MINIMUM) cost of wastes when C=0.3, D=390.70

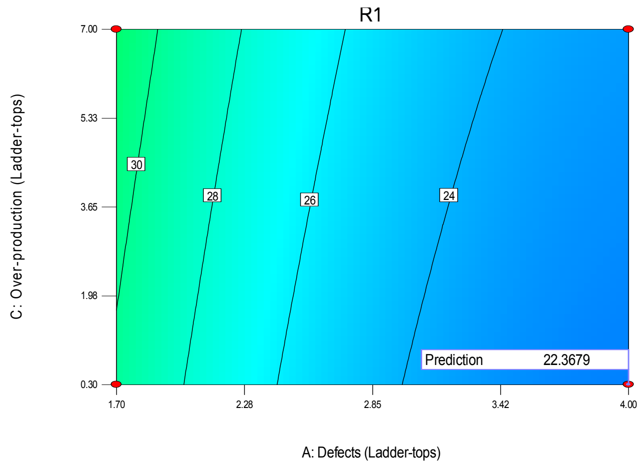

Fig. 8 Design expert8 contour depiction of optimum (MINIMUM) cost of wastes when B=55.70, D=390.70

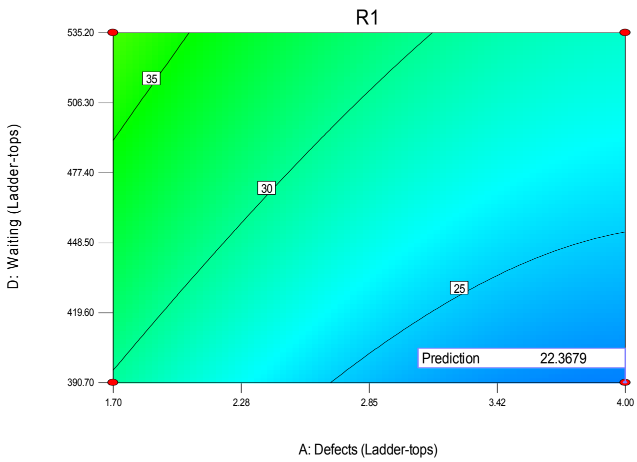

Fig. 9 Design expert8 contour depiction of optimum (MINIMUM) cost of wastes when B=55.70, C=0.30

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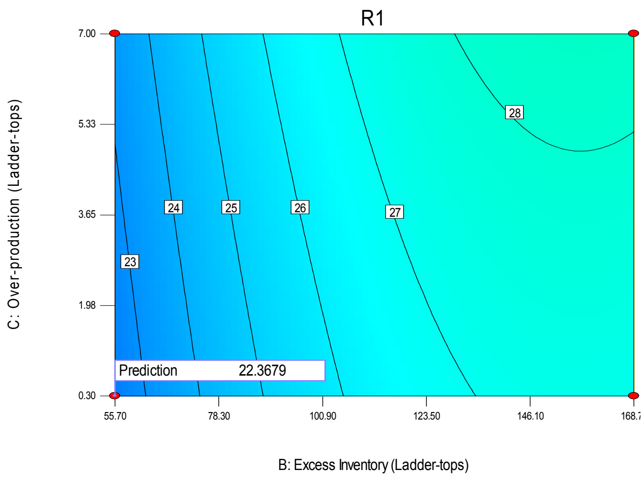

Fig. 10 Design expert8 contour depiction of optimum (MINIMUM) cost of wastes when A= 4.0, D = 390.70

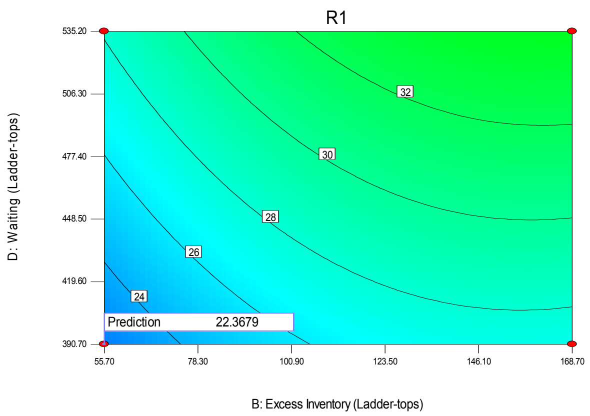

Fig. 11 Design expert8 contour depiction of optimum (MINIMUM) cost of wastes when A=4.0, C=0.30

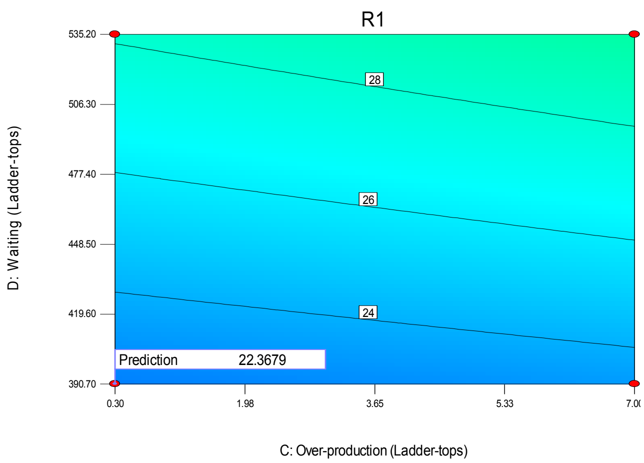

Fig. 12 Design expert8 contour depiction of optimum (MINIMUM) cost of wastes when A=4.0, B=55.7

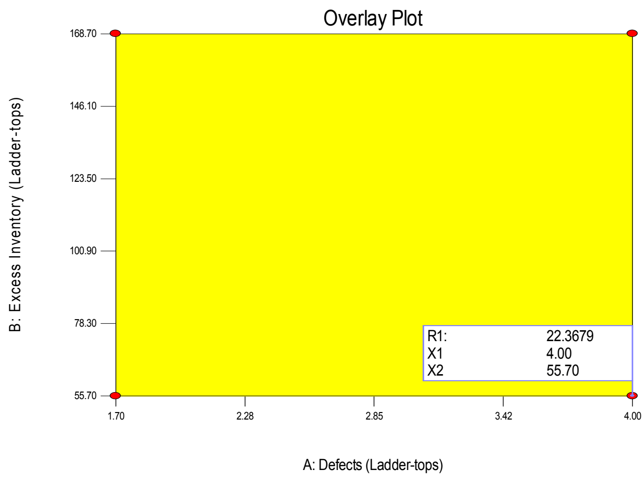

Fig. 13 Design expert8 overlay plot depiction of optimum (MINIMUM) cost of wastes when C=0.30, D =390.70

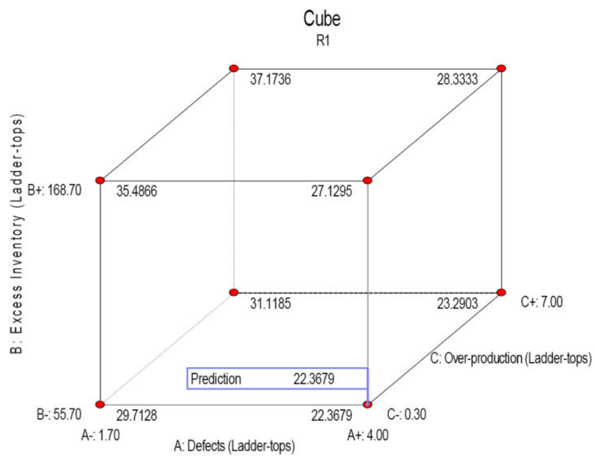

Fig. 14 Design expert8 cube plot depiction of optimum (MINIMUM) cost of wastes when D =390.70

TABLE VII
ANOVA FOR RESPONSE SURFACE QUADRATIC MODEL: [PARTIAL SUM OF SQUARES - TYPE III]

Response 1(R1)						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	1194.03	14	85.28787	23.6332	< 0.0001	significant
A	478.8656	1	478.8656	132.6933	< 0.0001	
B	208.7145	1	208.7145	57.83464	< 0.0001	
C	14.20099	1	14.20099	3.935083	0.0659	
D	322.5962	1	322.5962	89.39116	< 0.0001	
AB	1.024429	1	1.024429	0.283868	0.6020	
AC	0.23351	1	0.23351	0.064705	0.8027	
AD	2.829624	1	2.829624	0.784087	0.3899	
BC	0.079119	1	0.079119	0.021924	0.8843	
BD	0.95875	1	0.95875	0.265669	0.6138	
CD	0.218539	1	0.218539	0.060557	0.8090	
A^2	73.57247	1	73.57247	20.38688	0.0004	
B^2	66.67242	1	66.67242	18.47488	0.0006	
C^2	0.003127	1	0.003127	0.000867	0.9769	
D^2	0.597463	1	0.597463	0.165557	0.6898	
Residual	54.13223	15	3.608815			
Lack of Fit	54.13223	10	5.413223			
Pure Error	0	5	0			
Std. Dev.	1.899688					
Mean	33.00449					
C.V. %	5.755849					

Final Equation in Terms of Coded Factors:

$$R_1 = +33.05 - 4.47\,\mathrm{A} + 2.95\mathrm{B} + 0.77\mathrm{C} + 3.67\,\mathrm{D} -0.25\,\mathrm{A\,B} - 0.12\mathrm{A\,C} - 0.42\,\mathrm{A\,D} + 0.070\,\mathrm{B\,C} +0.24\,\mathrm{B} + 0.12\,\mathrm{C\,D} + 1.64\mathrm{A}^2 - 1.56\mathrm{B}^2 + 0.011\,\mathrm{C}^2 - 0.15 \quad (4)$$

Final Equation in Terms of Actual Factors:

$$R_1 = 7.63170 - 8.04852\,\mathrm{A} + 0.14377\,\mathrm{B} + 0.046819\,\mathrm{C} + 0.082857\,\mathrm{D} - 3.89435\mathrm{E} - 003\,\mathrm{A\,B} - 0.031358\,\mathrm{AC} + 0.082857\,\mathrm{D} - 3.89435\mathrm{E} - 003\,\mathrm{A\,B} - 0.031358\,\mathrm{AC} - 5.06138\mathrm{E} - 003\mathrm{A\,D} + 3.71525\mathrm{E} - 004\,\mathrm{B\,C} + 5.99662\mathrm{E} - 005\,\mathrm{B\,D} +4.82861\mathrm{E} - 004\,\mathrm{C\,D} + 1.23840\,\mathrm{A}^2 - 4.88399\mathrm{E} - 004\,\mathrm{B}^2 + 9.51495\mathrm{E} - 004\,\mathrm{C}^2 - 2.82734\mathrm{E} - 005\mathrm{D}^2 \quad (5)$$

VI. DISCUSSION OF RESULTS

The normal effect plot of Fig. 3 shows that waiting time constitutes the highest influence on the CIL production followed by over production, equally Fig. 4 gives the percentage contribution of each factor to CIL waste volume with 43.842%, 38.69065, 12.9305 and 4.53727% recorded for waiting, over-production, excess inventory and defects respectively.

Figs. 5-7 show the interaction effects of waiting time on the variation of cost of wastes, with the least wastes cost estimate of 35.7333 when the waiting time is set at 436.1seconds and the actual factors values are 4,215.7 and 7 for defects, excess inventory and over-production. Fig. 8 captures the effects of over-production on the cost of wastes with highest value recorded as 47.0667 when the factors are set at 3, 4, 215.7 and 390.7 for over-production, defects, excess inventory and waiting.

Figs. 7-12 clearly depict the optimal value of cost of wastes as 22.3679 at different factors interaction while Fig. 13 gives the optimal values of factors for optimal wastes cost in CIL as 0.30, 390.70, 4 and 55.70 for over-production, waiting, defects and excess inventory respectively.

The cube plot of Fig. 14 clearly describes optimal values of wastes when the value of waiting is set at its minimum of 390.7 while Table VII, the ANOVA table exhibits the significant model terms. Equations (4) and (5) are the response surface quadratic models in terms of coded and actual factors. When the significant model terms are considered (4) and (5) reduces to

$$R_1 = +33.05 - 4.47\mathrm{A} + 2.95\mathrm{B} + 3.67\mathrm{D} + 1.64\mathrm{A}^2 - 1.56\,\mathrm{B}^2 \quad (6)$$

$$R_1 = +7.63170 - 8.04852\,\mathrm{A} + 0.14377\,\mathrm{B} + 0.082857\mathrm{D} + 1.23840\,\mathrm{A}^2 - 4.88399\mathrm{E} - 004\,\mathrm{B}^2 \quad (7)$$

The models of (4)-(7) are further validated with the RSM statistical values as depicted in Table VIII**.** The "Pred R-Squared" of 0.7502 is in reasonable agreement with the "Adj R-Squared" of 0.9162."Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 20.561 indicates an adequate signal. This model can be used to navigate the design space.

TABLE VIII
RSM MODEL STATISTICS

Std. Dev.	**1.899688**	**R-Squared**	**0.95663**
Mean	33.00449	Adj R-Squared	0.916152
C.V. %	5.755849	Pred R-Squared	0.750191
PRESS	311.8016	Adeq Precision	20.56093

VII. CONCLUSION

The study concludes that,

1. Waiting time and over-production rank first and second in contributing to the costs of wastes in CIL
2. For minimal wastes costs the control factors over-production, waiting time, defects and excess- inventory must be set at 0.30, 390.70, 4 and 55.70 respectively

3. The optimal value of cost of wastes for the months is 22.3679
4. Although that Clamason Industries limited had made a lot of efforts in the past to be optimum, the results have however shown that if they are still desirous of maintaining their lead as the number one manufacturers of ladder-tops, that a lot still had to be done to tackle all the wastes that act as clogs in their wheel of progress.
5. As continuous improvement in all manufacturing processes is the major aim of LPS, constant efforts geared towards reducing the wastes and possible elimination will not only increase the profitability of the company but will also ensure that they will continue to beat their numerous competitors.
6. While the company should adopt all the principles of Just-in-Time (JIT) tool and technique of LPS which will enable them to work on their supply chain in order to reduce their rate of over-production and excess inventory, they should also source for suppliers with a high quality track record in order to reduce the rate of defective products. However, they must adopt and implement the entire concept of Shingeo Shingo's Single Minute Exchange of Dies (SMED) to enable them to tackle the waste of Waiting by drastically reducing their set-up time. This will make the company to be more competitive as the freed money can be ploughed back into the business for expansion, research and development, as well as for new product introduction.

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