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Effect of Packing Density of Particles on RFID Penetration

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ABSTRACT

Radio frequency identification device (RFID) technology has risen to become a drastic aspect in supply chain management which is not just a replacement for barcodes. RFID maintains accurate inventory control and also real time product information is available to make decisions. It makes the supply chain significantly more accurate and improves efficiency and reliability. Also, due to real-time information is made available for administration, the planning processes can be significantly improved as well.

The problem with successful RFID execution is the lack of application specific optimization. In any manufacturing location the variation of factors such as type of material, speed of the conveyor, tag position, distance of antenna from tag cannot be generalized. Therefore, to gain the best performance of an RFID system in supply chain, these factors should be optimized. Previous researchers' [4] proved that the signal penetration readability of RFID through liquids of different concentration had variation. This research paper focuses on the readability of RFID penetration in different particulate solid products with varying particle sizes. In addition simulation during transportation is performed on a conveyor belt at different speeds. Variable factors in this experiment were different types of particulate solids of different particle sizes, packing density, and tag position.

PROBLEM STATEMENT

Packaging industries using RFID technology are facing the problem of missing the item count of products during processing due to different product characteristics such as chemical composition, density etc. This research examines the use of RFID in packaging industry where the items are of different particulate solids of different packing densities [2]. This is important in supply chain because transportation can change the product's physical characteristics. In this paper particle shape, size and packing density are investigated to determine its effects on RFID tag readability. Particle size is considered as an important characteristic since it affects the properties such as surface per unit volume and rate of settling of particles. The shape of the particle may have an effect on packing characteristics as well.

Variable factors in this experiment were, different types of particulate solids of different particle sizes, packing density, and tag position. Signal penetration tag readability readings are noted for 20 seconds to meet FCC regulation [6] which will be analyzed using 2^5 Factorial design (2-level, 5-factors) by performing design of experiments (DOE) to observe the significance of the main factors [3].

EQUIPMENT

Equipment used in this research are the rectangular standardized container of size 6in x 10in x 1.25in, fabricated using 0.25in thick Lexan material supported on a HDPE frame as shown in figure 1. This holds the particulate solid and the volume of the container is 934ml (934 CC).

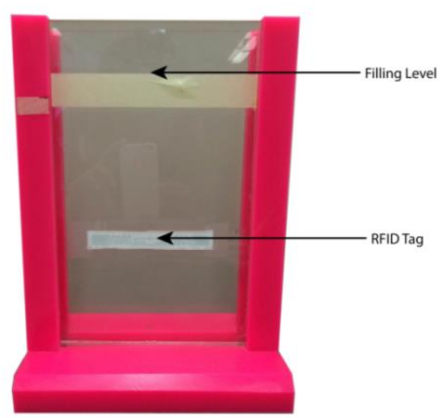

Figure 1. Container to hold particulate solids

An Alien RFID reader is used and model number is ALR-9800 (figure 2a). The reader is based on an Intel XScale processor, along with digital signal processor (DSP) (Roberti, 2006). The DSP enables the rapid interleaving of different protocols with minimal switching overhead, resulting in fast performance to interrogate RFID tags [10]. Supported RFID tag protocols are ECP Class 1 Gen 2, ISO 18000-6c [10]. Alien reader protocol is autonomous mode which has upgradeable architecture for future EPC reader protocols. An RFID tag reader uses antennas (figure 2b) to communicate with the RFID chip. RFID tags are so small and require so little power that they don't even need a battery to store information and exchange data with readers [10]. This makes it easy and cost effective to apply tags to different materials to identify or track. Tag used in this experiment was a passive tag (figure 2c). Passive RFID requires stronger signals from the reader, and the signal strength returned from the tag is constrained to very low levels. Active RFID allows very low-level signals to be received by the tag (because the reader does not need to power the tag), and the tag can generate high-level signals back to the reader. These tags have a useful life of twenty years or more and also not expensive to manufacture [8]. Also vibrating table Syntron Power Plus #225484A [6] is used to handle tough material to condense, settle, de-airing and packing [5].

(a) Alien ALR9800 RFID reader

(b) External Circular Polarized Antenna

(c) ALN-9640/9740 Tag

Figure 2. RFID components

METHODOLOGY

Experiments were conducted by varying the factors, type of particulate solid (salt and sugar), packing density (free flow and tapped), and speed of conveyor (6ft/min and 12ft/min), antenna placement (side and top) and tag placement front facing and back facing.

The antennas are connected to Alien RFID reader where one slot is connected for the RF transmission and one slot as the receiver. Following is the fixed setup used for the complete experiment.

1. Ant0 - Transmitter, Ant1 - Receiver
2. Select both Generation 1 and 2 (Gen1 and Gen2)
3. RF-Attenuation - 40dB
4. Preset – 30seconds

The above power settings were fixed after experimenting with the required adjustments and limitations for the proper read range. It is important for the experiment that we select the correct hardware and to have optimum settings setup for the experiment.

Two different particulate solids, sugar (organic compound) and salt (inorganic compound) was tested for its particle shape and different packing densities, to understand the impact of tag readability of RFID signal penetration. Experiments were performed, with tag placed on near side and far side of the cell, antennas are placed at the sides and top of the product. A typical set-up is shown in figure 3. The cell containing the solids are kept at constant distance from the antenna, in this experiment the distance is 18 inches apart.

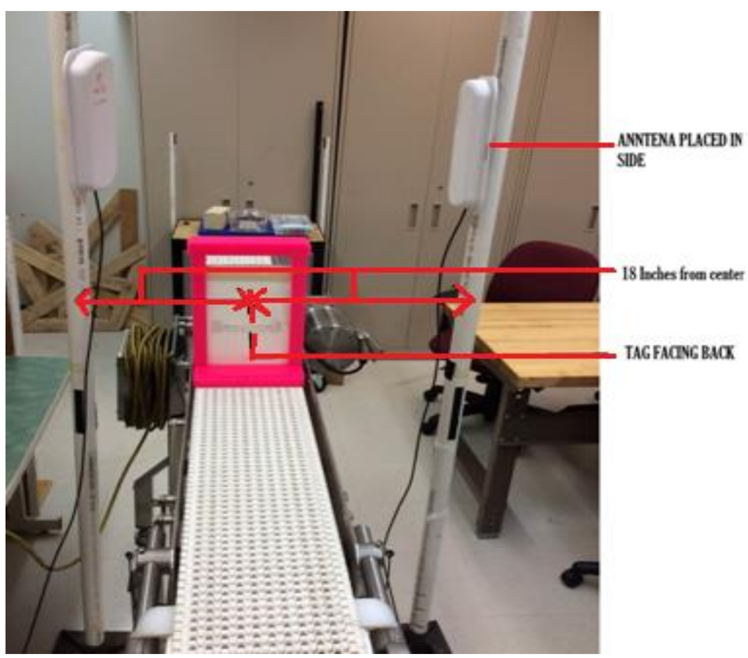

Figure 3. Example container on conveyor tag facing back and antenna placed side

To fill the material to the container with proper consistency, the material is loaded using a funnel. This funnel method used is similar to a volumeter. Volumeter is an apparatus to fill the particle by uncompressing, onto a container. This allows free flow of material into the container without excessive packing. The amount of material in the container was measured by weight. Tag readability readings were noted for both sugar and salt under this condition. The container with material has to be vibrated for two minutes on the vibrating table, such that the space created due to packing was replenished and continued vibration until no weight change was observed. Tag readability is checked again for the packed product. Table 1 are the weights pre and post vibration.

Table 1: The weight of the particulate solid pre and post vibration

	Pre vibration		Post vibration	
	Salt	Sugar	Salt	Sugar
weight, g	1150	764	1211	836
Volume, cm^3	934	934	934	934
Pack. Den g/cm^3	1.231	0.818	1.297	0.895

DATA COLLECTION AND ANALYSIS

The factors were analyzed using Design of Experiments methodology, there were five factors, each at two levels and hence the experiment is 2^5 factorial experiment. The experiments that was performed with the factors and their levels is listed in the Table 2 and data in table 3.

Table 2: List of 5 factor and their respective 2 levels

Factors which are subject to change	Low Level (-)	High Level (+)
Material used (M)	Sugar	Salt
Density (D)	Free	Tap
Antenna placement (AP)	Side	Top
Speed of conveyor (S)	6ft/min	12ft/min
Tag position (TP)	Front	Back

Table 3: The summary of tag readability data and average of all the 32 combinations

M	D	AP	S	TP	Expt No	1	2	3	4	Average
-	-	-	-	-	1	36	37	37	35	36.25
+	-	-	-	-	2	58	55	54	54	55.25
-	+	-	-	-	3	35	31	33	39	34.5
+	+	-	-	-	4	29	36	33	33	32.75
-	-	+	-	-	5	33	30	38	30	32.75
+	-	+	-	-	6	25	20	23	24	23
-	+	+	-	-	7	36	35	37	42	37.5
+	+	+	-	-	8	22	21	23	22	22
-	-	-	+	-	9	55	56	57	59	56.75
+	-	-	+	-	10	65	63	64	65	64.25
-	+	-	+	-	11	50	49	46	49	48.5
+	+	-	+	-	12	49	51	50	51	50.25
-	-	+	+	-	13	56	53	53	54	54
+	-	+	+	-	14	48	47	50	47	48
-	+	+	+	-	15	56	52	56	57	55.25
+	+	+	+	-	16	51	47	49	53	50
-	-	-	-	+	17	43	42	46	45	44
+	-	-	-	+	18	59	55	60	57	57.75
-	+	-	-	+	19	43	42	40	39	41
+	+	-	-	+	20	45	44	43	45	44.25
-	-	+	-	+	21	46	44	43	45	44.5
+	-	+	-	+	22	48	48	45	45	46.5
-	+	+	-	+	23	49	50	47	44	47.5
+	+	+	-	+	24	42	39	43	43	41.75
-	-	-	+	+	25	62	59	58	61	60
+	-	-	+	+	26	63	64	64	61	63
-	+	-	+	+	27	54	55	57	58	56
+	+	-	+	+	28	54	56	55	58	55.75
-	-	+	+	+	29	48	48	48	43	46.75
+	-	+	+	+	30	34	38	40	36	37
-	+	+	+	+	31	46	48	48	41	45.75
+	+	+	+	+	32	35	34	36	33	34.5

Data Analysis – Main and Interaction Effects:

For all treatments the resultant values are used to find the main effects, often the impact of levels are described as an effect. A Main Effect is the difference between the factor average and the grand mean. Effect size determines which factors have the most significant impact on the results. The vales are then plotted as Main Effect Plot which is a quick and efficient way to visualize the extent of effect. Factors with steeper slopes have larger effects and thus, larger impact on tag readability.

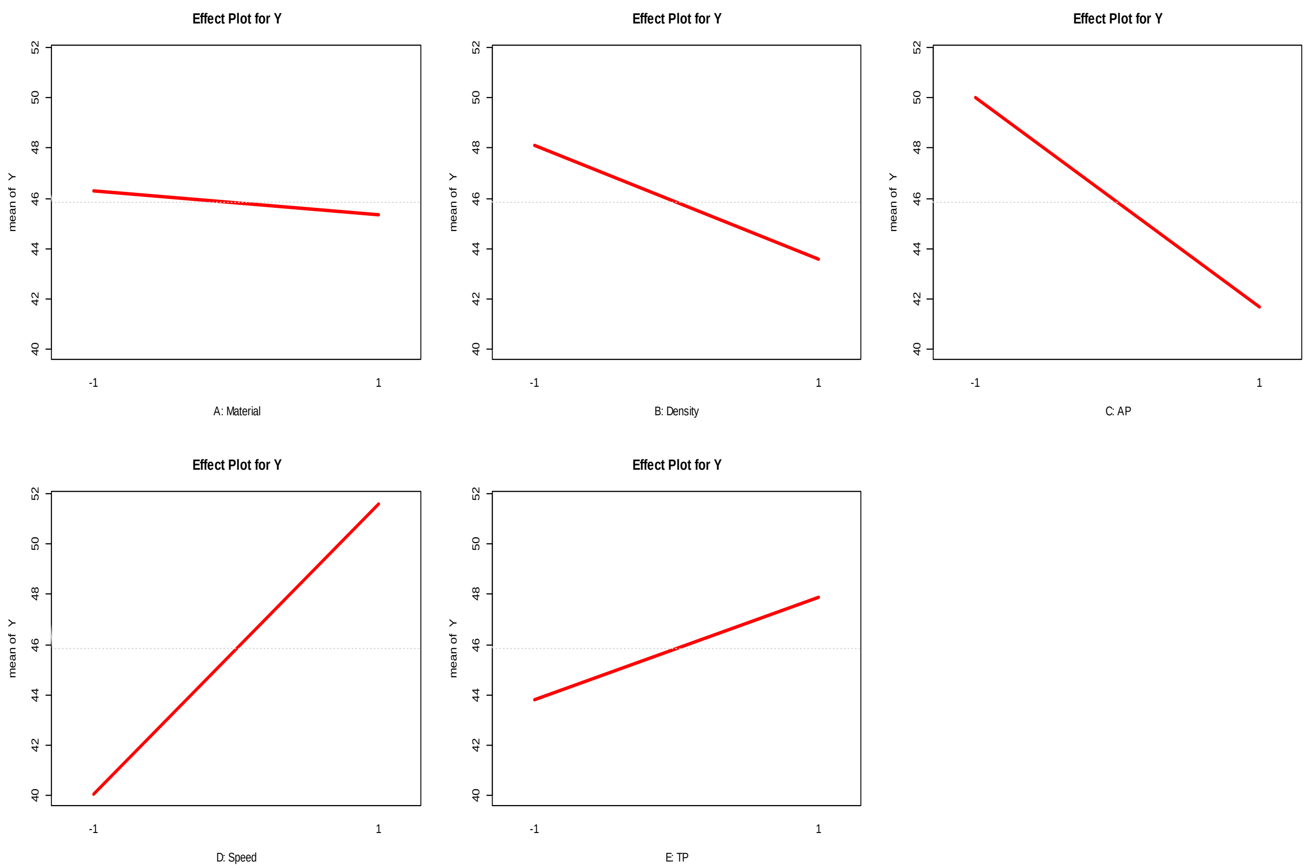

Figure 5.Main effects of full factorial design

Figure 5 is the main effects plot which is a diagrammatic representation of the most significant and the least significant factors. From this it is evident that there is a significant rise in the number of reads when factor D (speed of the conveyor) is changed from low level (6 ft/min) to the high level (12 ft/min).

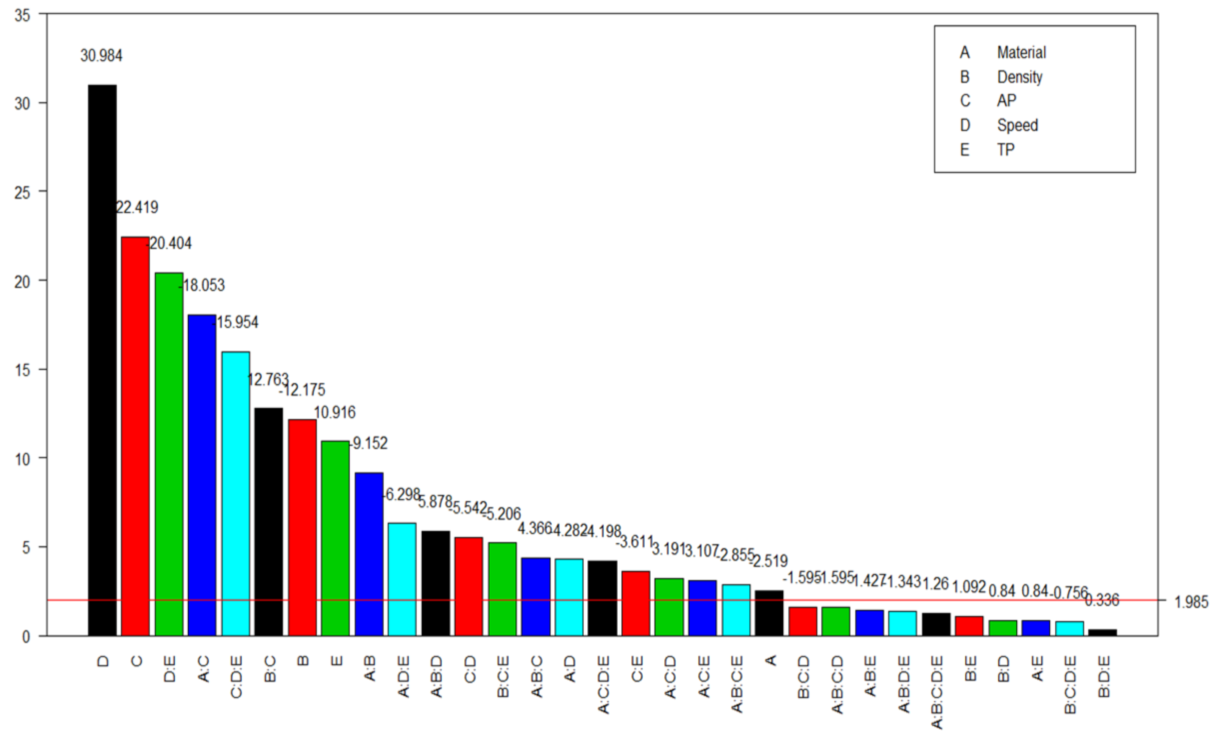

Figure 6. Pareto chart (Standardized Main Effects and Interactions)

Pareto distribution diagram, is a vertical bar graph in which values are plotted in decreasing order of relative frequency from left to right. Pareto charts are extremely useful for analyzing what factors contribute most, the bars on the chart representing frequency. From figure 6 it is evident that the factors, speed of the conveyor and antenna placement have significant effect on tag readability. Decision limit (DL) for the 95% confidence interval is 1.985. Any bar above the DL has an impact on the tag readability.

Table 3 clearly shows the significant factors. For 95% confidence interval, any p-value which is below the 0.05 level is significant. Therefore from the above table the p-value greater than 0.05 are many interactions, which are insignificant (highlighted).

Table 3 - Estimated Effects and Coefficients

Source	DF	Adj SS	AdjMS	F-Value	P-Value
Model	31	14279.4	460.63	103.92	0.000
Linear	5	7696.1	1539.22	347.27	0.000
M	1	28.1	28.13	6.35	0.013
D	1	657.0	657.03	148.24	0.000
AP	1	2227.8	2227.78	502.63	0.000
S	1	4255.0	4255.03	960.01	0.000
TP	1	528.1	528.12	119.15	0.000
2-Way Interactions	10	4669.8	466.98	105.36	0.000
M*D	1	371.3	371.28	83.77	0.000
M*AP	1	1444.5	1444.53	325.91	0.000
M*S	1	81.3	81.28	18.34	0.000
M*TP	1	3.1	3.12	0.71	0.403
D*AP	1	722.0	722.00	162.90	0.000
D*S	1	3.1	3.13	0.71	0.403
D*TP	1	5.3	5.28	1.19	0.278
AP*S	1	136.1	136.13	30.71	0.000
AP*TP	1	57.8	57.78	13.04	0.000
S*TP	1	1845.3	1845.28	416.33	0.000
3-Way Interactions	10	1770.4	177.04	39.94	0.000
M*D*AP	1	84.5	84.50	19.06	0.000
M*D*S	1	153.1	153.12	34.55	0.000
M*D*TP	1	9.0	9.03	2.04	0.157
M*AP*S	1	45.1	45.12	10.18	0.002
M*AP*TP	1	42.8	42.78	9.65	0.002
M*S*TP	1	175.8	175.78	39.66	0.000
D*AP*S	1	11.3	11.28	2.55	0.114
D*AP*TP	1	120.1	120.12	27.10	0.000
D*S*TP	1	0.5	0.50	0.11	0.738
AP*S*TP	1	1128.1	1128.12	254.52	0.000
4-Way Interactions	5	136.1	27.21	6.14	0.000
M*D*AP*S	1	11.3	11.28	2.55	0.114
M*D*AP*TP	1	36.1	36.13	8.15	0.005
M*D*S*TP	1	8.0	8.00	1.80	0.182
M*AP*S*TP	1	78.1	78.13	17.63	0.000
D*AP*S*TP	1	2.5	2.53	0.57	0.452
5-Way Interactions	1	7.0	7.03	1.59	0.211
M*D*AP*S*TP	1	7.0	7.03	1.59	0.211
Error	96	425.5	4.43		
Total	127	14704.9			

Regression Equation for Full Factorial Design

Output Read = 45.844 - 0.469 Mat - 2.266 Den - 4.172 AnP + 5.766 Sp + 2.031 TgP - 1.703 Mat*Den - 3.359 Mat*AnP - 0.797 Mat*Sp + 0.156 Mat*TgP + 2.375 Den*AnP + 0.156 Den*Sp + 0.203 Den*TgP - 1.031 AnP*Sp - 0.672 AnP*TgP - 3.797 Sp*TgP + 0.813 Mat*Den*AnP + 1.094 Mat*Den*Sp + 0.266 Mat*Den*TgP + 0.594 Mat*AnP*Sp + 0.578 Mat*AnP*TgP - 1.172 Mat*Sp*TgP - 0.297 Den*AnP*Sp - 0.969 Den*AnP*TgP + 0.062 Den*Sp*TgP - 2.969 AnP*Sp*TgP - 0.297 Mat*Den*AnP*Sp - 0.531 Mat*Den*AnP*TgP - 0.250 Mat*Den*Sp*TgP - 0.781 Mat*AnP*Sp*TgP - 0.141 Den*AnP*Sp*TgP + 0.234 Mat*Den*AnP*Sp*TgP

Where Mat- Material Used (Factor A)
Den- Density (Factor B)
AnP- Antenna Position (Factor C)
Sp - Speed of the conveyor (Factor D)
TgP- Tag position (Factor E)

Reduced Regression Equation for Full Factorial Design:

a. From the estimated effects table where the factors below 0.05 p-value are not significant And can be reduced in the regression equation shown below.

```
Output Read =  45.844 - 0.469 Mat - 2.266 Den - 4.172 AnP + 5.766 Sp
       + 2.031 TgP - 1.703 Mat*Den - 3.359 Mat*AnP - 0.797 Mat*Sp
       + 2.375 Den*AnP- 1.031 AnP*Sp - 0.672 AnP*TgP -3.797 Sp*TgP
       + 0.813 Mat*Den*AnP + 1.094 Mat*Den*Sp  + 0.594 Mat*AnP*Sp
       + 0.578 Mat*AnP*TgP - 1.172 Mat*Sp*TgP  - 0.969 Den*AnP*TgP -
        2.969 AnP*Sp*TgP - 0.531 Mat*Den*AnP*TgP - 0.781 Mat*AnP*Sp*TgP
```

b. The Pareto chart provides a graphic depiction of the Pareto principle, a theory maintaining that 80% of the output in a given situation or system is produced by 20% of the input. Further,Pareto theory (80/20) was applied to select the main and interaction factors to be included in the reduced regression equation which is shown below

```
Output Read = 45.844 - 2.266 Den - 4.172 AnP + 5.766 Sp + 2.031 TgP - 1.703 Mat*Den -
        3.359 Mat*AnP + 2.375 Den*AnP - 3.797 Sp*TgP - 2.969 AnP*Sp*TgP-
 1.172 Mat*Sp*TgP+ 1.094 Mat*Den*Sp- 1.031 AnP*Sp- 0.969 Den*AnP*TgP
```

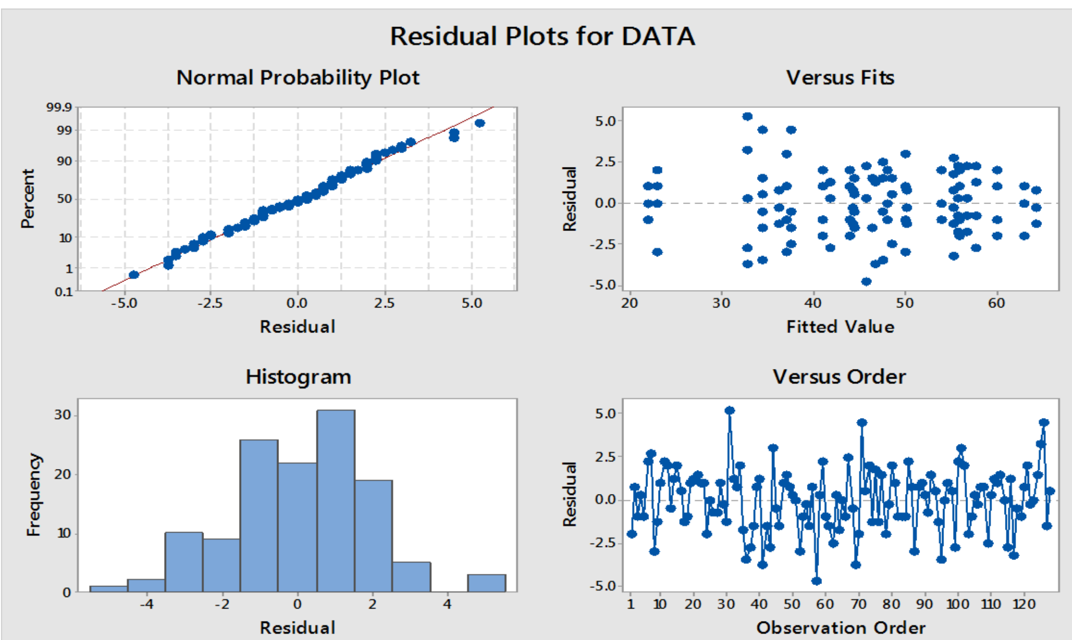

Figure 7. Full factorial (a) Normal probability plot (b) Histogram (c) Full factorial probability plot (d) full factorial probability observation order

The probability plots (figure 7) shows different ways to represent the residuals, that most of the data lies around the normal value indicating normality. From the above figures we can also identify possible outliers which lie far from the center. Figure 12c shows that the data is random because there is no pattern evident, typically it is funnel shape.

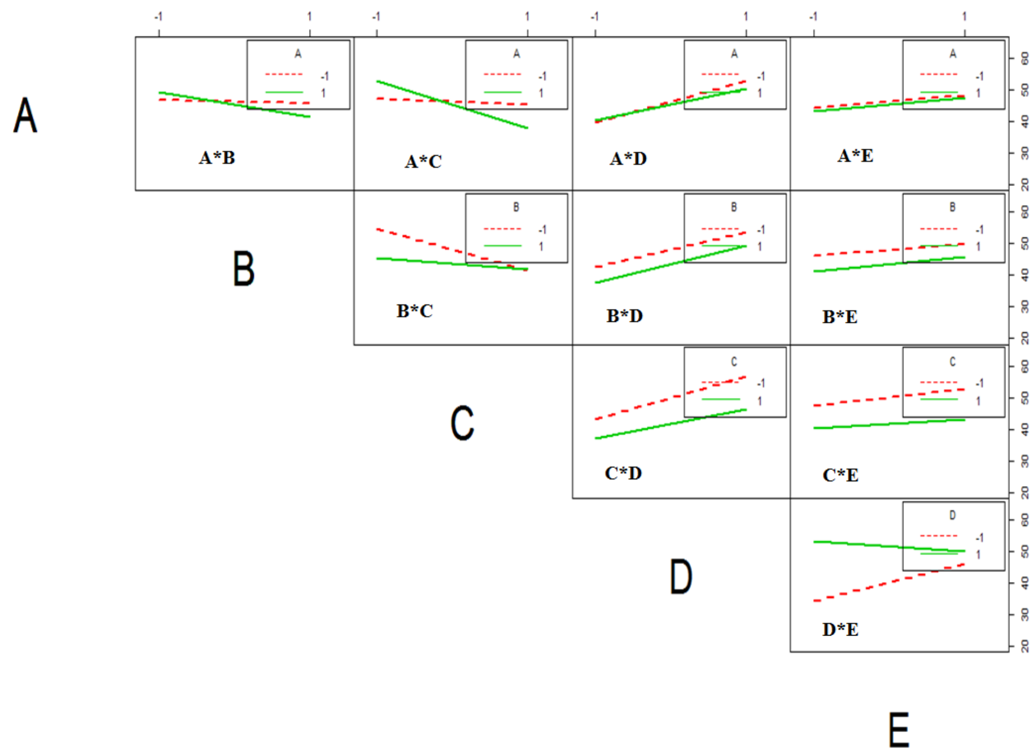

Figure 8. Interaction plots

Two way interaction plots are shown in the figure 8. The A*E, B*D, B*E, C*E, C*D interaction plots, the lines are almost parallel and therefore do not indicate interaction effects that are significant. However the other combinations A*B, A*C, B*C, A*D, D*E indicate that significant interaction exists. By looking at the main effects plot one would likely miss the interactions that are obvious here.

Fractional Factorial Design:

2^{5-2} design is 1/4 of a two level, five factor factorial design. Rather than the 32 runs that would be required for the full 2^5 factorial experiment, this experiment requires only eight runs.

Source	DF	Adj SS	AdjMS	F-Value	P-Value
Model	7	2313.00	330.43	96.12	0.000
Linear	5	2257.75	451.55	131.36	0.000
A	1	18.00	18.00	5.24	0.031
B	1	1378.12	1378.12	400.91	0.000
C	1	578.00	578.00	168.15	0.000
D	1	171.12	171.12	49.78	0.000
E	1	112.50	112.50	32.73	0.000
2-Way Interactions	2	55.25	27.63	8.04	0.002
B*C	1	10.13	10.13	2.95	0.099
B*E	1	45.13	45.13	13.13	0.001
Error	24	82.50	3.44		
Total	31	2395.50			

Regression Equation for Fractional Factorial Design

```
Output Read = 47.375 - 0.750 Mat - 6.563 Den - 4.250 AnP + 2.313 Sp - 1.875 TgP -
 0.563 Den*AnP - 1.188 Den*TgP
```

CONCLUSION

It confirms from the full factorial DOE analysis that speed of the conveyor contributes significant impact on tag readability. Therefore, to have better communication for product tracing and tracking it is important to have consistent speed thought out the supply chain. The results of full and fractional factorial design clearly shows the factors which are affecting the tag readability process. The material type alone has no significant impact, but the interaction effects of material type with the packing density and antenna placement are significant, i.e. salt (inorganic particles) at low density (free flow) have better tag readings. Similarly, salt with antenna placed at side has better tag readings. The packing densities of different particulate materials change during transportation along the supply chain, thus changing the product physical characteristics. One of the major problems within supply chain industry is the transportation due to the fact that the packing density varies during transportation. As recorded in table 1 the volume of product in the container changes after vibration simulating transportation. Therefore, the density is indirectly a factor causing significant interactions. Since it is proved that the density varies according to the intensity of vibrations, it is possible that the tag readability also changes with the antenna placement referred as interaction B*C.

The interactions between materials used and speed of conveyor, material used and tag types are not significant in full factorial design. On the other hand, fractional factorial design shows that the material used and speed of conveyor, material used and tag orientation are not significant. Higher coefficient of determination for fractional factorial design indicates that the fractional factorial design is more appropriate than the full factorial design. The model adequacy checked using the residuals indicate that the fractional factorial design performs better than the full factorial design with half the number of runs. The model developed here can be used to minimize failures, cost of implementation and predict outcomes with ease. It can be observed that in selecting an RFID system for a manufacturing application it is important to conduct design of experiments to identify the critical variables for optimum tag readability.

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