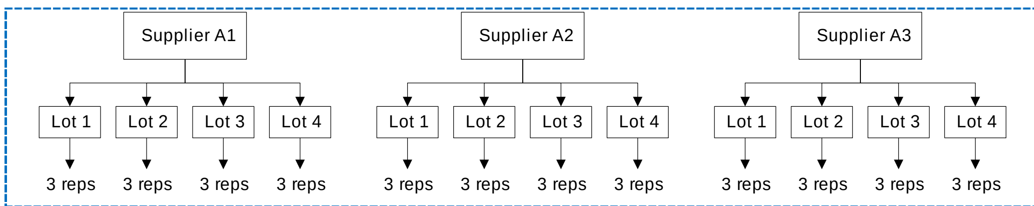
Nested General Factorial Tutorial

Information

In some experiments the levels of one factor (e.g., factor B) are similar but not identical for different levels of another factor (e.g. factor A). This arrangement is called a "nested" or "hierarchical" design. Analyzing a nested design is tricky, even for statisticians. It can be done on Design-Expert® software by properly designating effects in specific ways for subsequent analysis of variance. Proceed with care!

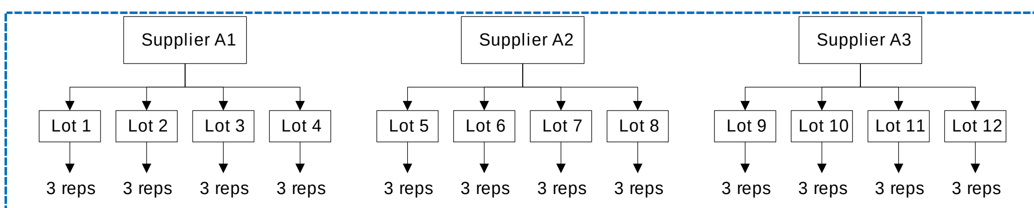
To illustrate how Design-Expert software can be used for a nested design, let's follow an example from Montgomery's *Design and Analysis of Experiments*. A company buys raw material from three different suppliers. The company wants to know if raw material purity is dependent on the supplier. Four lots of raw material are selected at random from each of the suppliers. Three independent measures of purity are made on each batch of raw material.

As shown in the diagram below, this is a nested design.



Flowchart of nested design on raw material supplier

The lots of raw material are nested within each supplier. Lot 1, under supplier A1, is not the same lot as lot 1 under supplier A2 or A3. Another (perhaps more correct) diagram of this design is therefore shown below. Note that the lots are now unique.



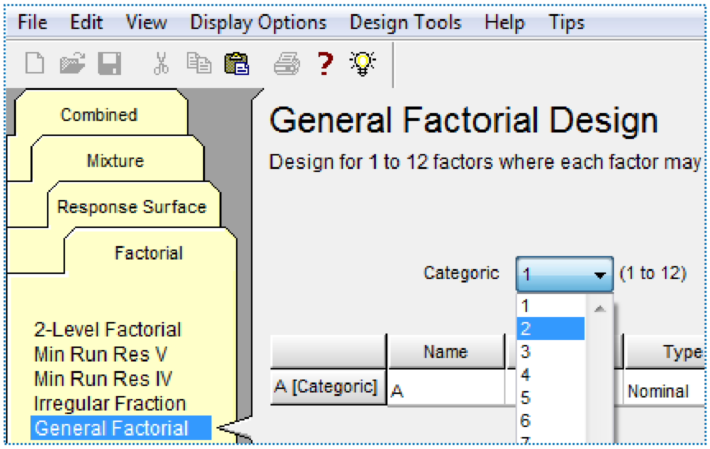
A more realistic way to view the lot-by-lot variation in nested design

Here we clearly see that each lot is dependent on supplier, that is, raw material lots are nested within each supplier. Another name for a nested design is "hierarchical" design. Think of the lots as children – and each supplier as a set of parents. Each lot is uniquely tied to its supplier, just as a child is to its parents.

Nested designs are a complex topic and this tutorial is intended to demonstrate only the mechanics. For theory see Montgomery's book.

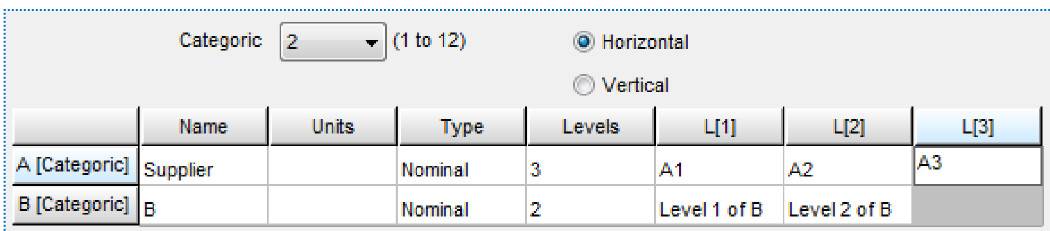
Design the Experiment

Click the blank-sheet icon 🗋 on your toolbar (or choose **File, New Design**). Then from the default Factorial tab click **General Factorial**. Choose **2** as the number of factors.



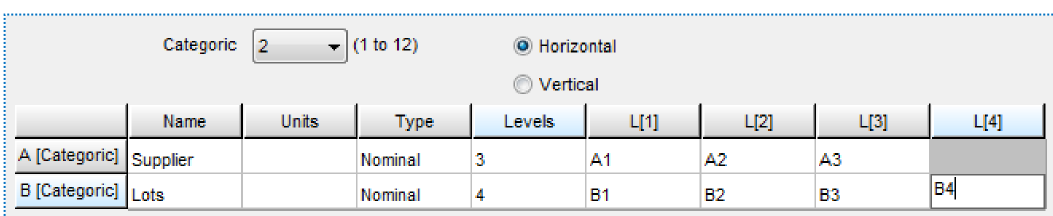
Setting up a two-factor general factorial design

Enter **Supplier** as your Factor A name. **Tab** to the **Levels** column and type **3** for the number of levels. **Tab** again and enter **A1**, **A2**, and **A3** as your **L(1)**, **L(2)**, and **L(3)** treatment names. If in Horizontal mode, your screen should look like that below.



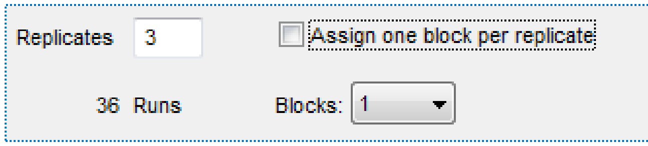
Entering first factor (A)

Carry on with this screen by entering **Lots** as your Factor B name, and **4** for the number of levels. Change the treatment names to **B1**, **B2**, **B3**, and **B4** as shown below.



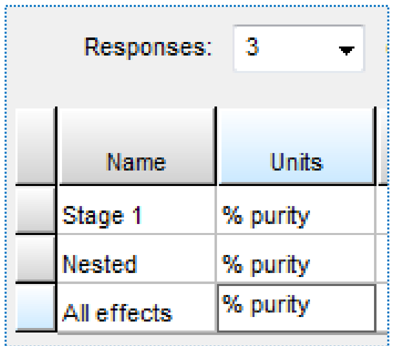
Details about the second factor (B)

Press **Continue.** For **Replicates,** enter the number **3** (representing the three independent measures of purity). Press the **Tab** key to update the number of runs.



Specifying three replicates

Press **Continue**. Change the number of responses to **3**. For **Name**, enter **Stage 1** (for assessing supplier effect), **Nested** (for analysis of lot-to-lot variation), and **All effects** (to be used on graphs). For **Units**, enter **% purity**. If you are adept with Windows, use its copy (Ctrl-C) and paste (Ctrl-V) functions to save keystrokes.



Response names

Don't bother with the option for calculating power – simply press **Continue** to complete the design-building wizard. Design-Expert now displays, in random run order by supplier and lot, the samples to test for purity.

Analyze the Results

To avoid potential data-entry errors, simply read in the responses via the folder icon or by **File, Open Design** from the main menu. Select the file named **Purity.dxp**. You should now see the data depicted in the table below. Purity values are based on a nominal value of 93 percent. For example, a value of 4 indicates a purity of 97 (93 + 4). Presumably, this response rescaling makes it easier for people to interpret the results.

Run	A: Supplier	B: Lots	Purity Percent
1	A1	B1	-1
2	A3	B2	2
3	A2	B2	0
4	A1	B3	0
5	A3	B3	2
6	A1	B3	-2
7	A2	B1	-3
8	A3	B4	3
9	A3	B2	-2
10	A2	B3	-1
11	A3	B4	2
12	A1	B2	-4
13	A3	B3	-1
14	A1	B4	0
15	A2	B3	-2
16	A3	B3	1
17	A1	B4	1
18	A3	B1	0
19	A2	B2	2
20	A2	B3	0
21	A1	B3	1
22	A3	B1	4
23	A2	B2	4
24	A1	B1	1
25	A1	B2	-2
26	A3	B1	2
27	A2	B1	1
28	A1	B2	-3
29	A1	B1	0
30	A1	B4	4
31	A3	B4	1
32	A2	B4	0
33	A3	B2	0
34	A2	B1	-2
35	A2	B4	3
36	A2	B4	2

Response data for paper tensile strength

Because this is a nested design, Design-Expert's analysis is not as straight-forward as usual. You must therefore create a separate ANOVA for each top-level (stage 1) treatment because supplier is a fixed factor. Then you need to fit the full model in order to get meaningful diagnostics and model graphs (but you must ignore the full model ANOVA!). To keep these various analyses straight, the purity results have been copied three times.

Statistical Details

Feel free to skip the following statistical details and resume the tutorial at Stage One ANOVA (Supplier) below.

In order to perform the correct F-test, you must determine which terms belong in the model and in the error. (Remember that $F=MS_{model}/MS_{error}$.) In this example, B is a random factor (a sample from a population of lots) that is nested within A, which is a fixed factor (there are only three suppliers of interest). The expected mean squares (EMS) are shown in the table below. (For more statistical details, see Montgomery's chapters on "Experiments with Random Factors" and, "Nested and Split-Plot Designs".)

Source	df	Expected MS	Calculated MS
A - Supplier	2	$\sigma^2 + 3\sigma^2_B + 6\Sigma A^2$	$(SS_A)/(df_A)$
B - Lots	9	$\sigma^2 + 3\sigma^2_B$	$(SS_B + SS_{AB})/(df_B + df_{AB})$
Error	24	σ^2	$MS_{Pure\ Error}$
Total	35		

Expected mean squares

From the expected MS column it can be inferred that A (Supplier) should be tested against the nested factor, B (Lots). The appropriate test for significance of A is then:

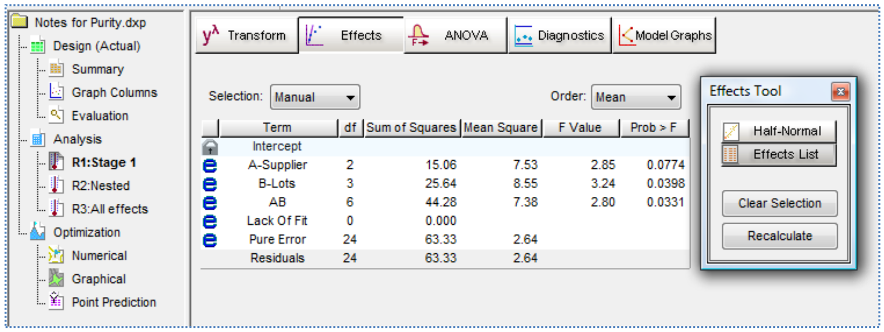
$$F = (\sigma^2 + 3\sigma^2_B + 6\Sigma A^2)/(\sigma^2 + 3\sigma^2_B)$$

From the calculated MS column it can be seen that the correct sum-of-squares for B is created by adding the sum-of-squares for factor B and the AB interaction. You must add these sums of squares manually using the procedure outlined in the formula below. Because lots are nested within supplier, there can be no true supplier by lot interaction (AB). Therefore the sum of squares (SS) is:

$$SS_{(B\ within\ A)} = SS_B + SS_{AB}.$$

Stage One ANOVA (Supplier)

Supplier (A) is tested against the lots within supplier (B + AB). To perform this analysis, click the analysis node **Stage 1** and press ahead to ***Effects***. Note that nothing stands out on the default view of the half-normal plot so Design-Expert picks no terms for a model. Via the floating **Effects Tool** change the view to the **Effects List** – all terms remain at their default of error ("e").

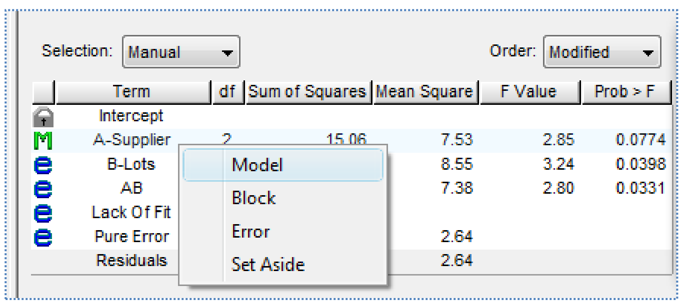


Effects list (floating Effects Tool moved next to this view)

There are four states an effect can have:

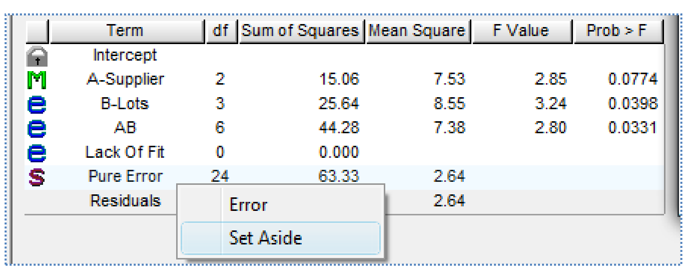
- Model ("M")
- Block ("b")
- Error ("e")
- Set Aside ("S").

Right-click on term **A** and choose **Model**, which will allow you to test it statistically. (Note: Another way to toggle a term to model is by double-clicking it. Feel free to try this now.)



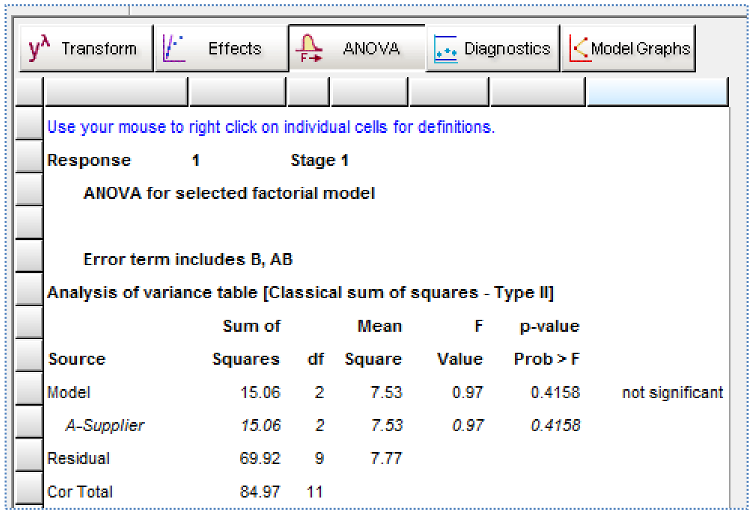
Designating the effect of A for model

Right click on term **Pure Error** and choose **Set Aside**. Leave **B**, **AB** and **Lack Of Fit** set as **e** for error (the default). Your screen should now match that shown below.



Completed effects screen in preparation for ANOVA on effect of A

Click on the ***ANOVA*** button. You can now see that the supplier (factor A) is not significant (p-value for Prob > F is greater than 0.10).



Use your mouse to right click on individual cells for definitions.

Response 1 Stage 1

ANOVA for selected factorial model

Error term includes B, AB

Analysis of variance table [Classical sum of squares - Type II]

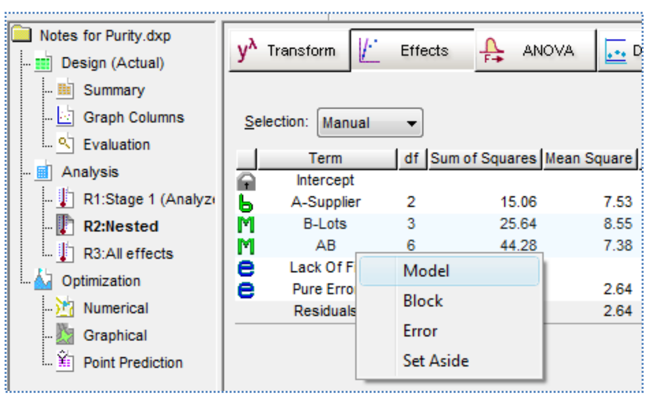
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	15.06	2	7.53	0.97	0.4158	not significant
A-Supplier	*15.06*	*2*	*7.53*	*0.97*	*0.4158*	
Residual	69.92	9	7.77			
Cor Total	84.97	11				

ANOVA for effect of A

Don't bother going any further with analysis because the model is incomplete at this point. However, to preserve your ANOVA on the stage 1 factor of supplier, select **File**, **Save As** and modify the name to **Purity-a.dxp** (or anything else you'd like that will leave the original tutorial file as-is).

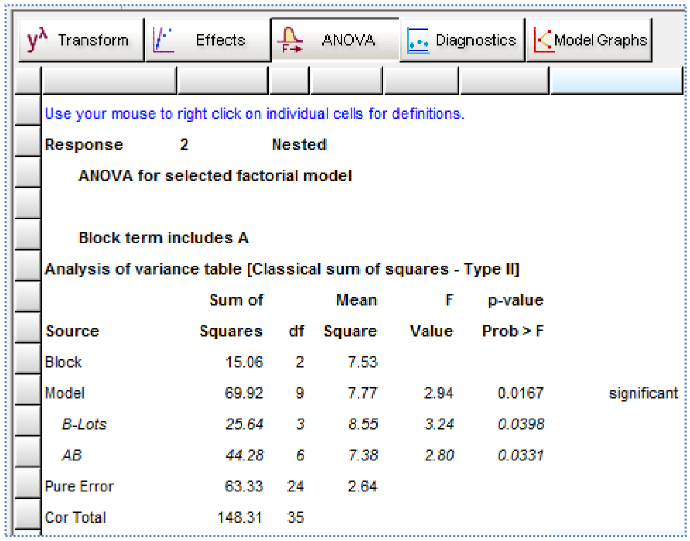
ANOVA on Nested Factor (Lots)

To analyze the variance caused by lots, click the node named **Nested**, then ***Effects***, and via the floating **Effects Tool** change the view to the **Effects List**. The lots within supplier should be tested against the pure error. Via the right-click menu, set this up as follows: **A** as **Block**, and **B** and **AB** as **Model**. Leave the **Lack of Fit** and **Pure Error** terms as **e** for error. Your screen should now match the illustration below. (Notice that by dragging over multiple terms, they all can be designated the same with one operation.)



Designating effects for ANOVA on nested variable (lots)

Click on the ***ANOVA*** button. The results show that lots within supplier (the Model line) created a significant effect on purity (p = 0.0167).



Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Block	15.06	2	7.53			
Model	69.92	9	7.77	2.94	0.0167	significant
B-Lots	*25.64*	*3*	*8.55*	*3.24*	*0.0398*	
AB	*44.28*	*6*	*7.38*	*2.80*	*0.0331*	
Pure Error	63.33	24	2.64			
Cor Total	148.31	35				

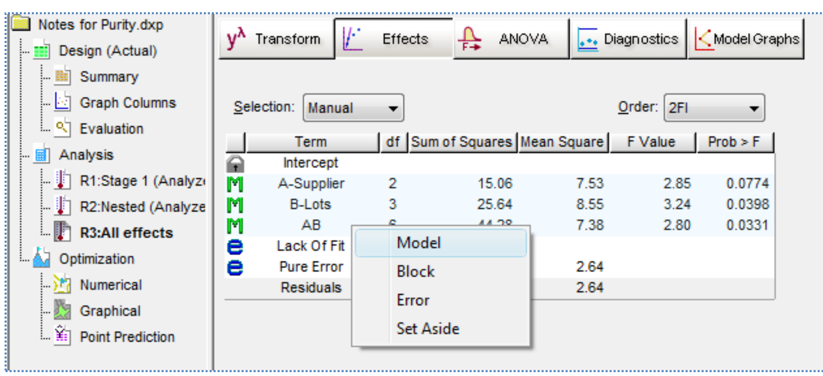
ANOVA for lots within supplier

Do not look at the Diagnostics or the Model Graphs because the model is incomplete at this point. However, to preserve your ANOVA, select **File**, **Save** or simply click the save icon 🖫.

Viewing Diagnostic and Model Graphs

To get meaningful diagnostics and model graphs you need to fit the full model. Of course you must then ignore the ANOVA, because the estimate of error will be incorrect.

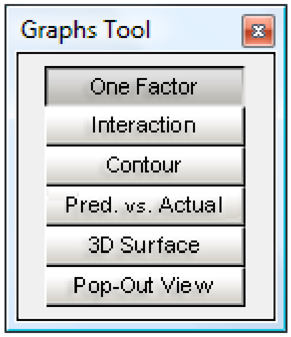
Click the **All effects** node under the Analysis branch of your Design-Expert software. Go to the ***Effects***, bring up the **Effects List** view and do a mouse-drag over **A**, **B**, and **AB**. Then, via the right-click menu, set these terms to **Model**. Leave **Lack of Fit** and **Pure Error** at **e** for error. Your screen should now match that illustrated.



Modeling all the effects

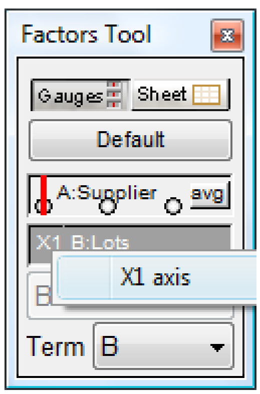
Skip by the ANOVA button (not correct for this complete model) to the ***Diagnostics***. Examine the normal plot of residuals, which comes up by default. The residuals fall roughly in line, so assume there's no gross abnormality. If you like, look at the other graphs available on the floating Diagnostics Tool. For advice on each one, press the Screen Tips icon – a light-bulb.

Now click on the ***Model Graphs*** button. On the floating **Graphs Tool** press **One Factor** (or from the main menu bar choose View, One Factor).



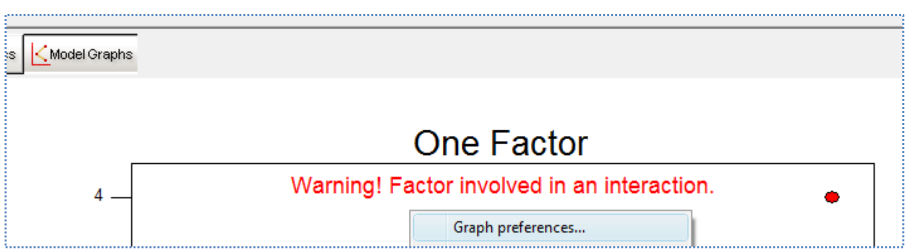
Graphs tool

The default graph shows the effect of supplier on purity, but since it was shown earlier to be statistically insignificant, do not dwell on it. Also, pay no attention to the warning about factors being involved in an interaction because, as explained earlier in the statistical details, the nesting makes this irrelevant. Instead, go to the **Factors Tool**, right click over the **Lots** factor, (which is significant) and make it the **X1 axis**. Another way to do this is to press the down-list arrow (⮟) on the term list and change to factor B. Try this route if you like.



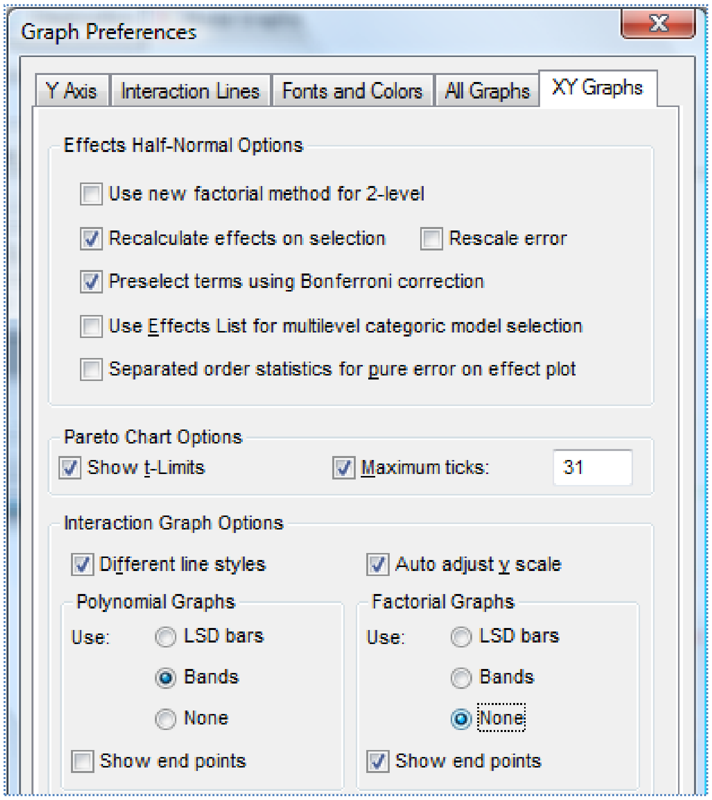
Putting lots (factor B) on the X1 (bottom) axis

The least-significant-difference (LSD) bars on this graph will be incorrect due to the nested design for the experiment, so they should be turned off before publication. Do this by a right-click over the plot and selecting **Graph preferences**. (Y`ou can ignore the warning on the graph, as before)



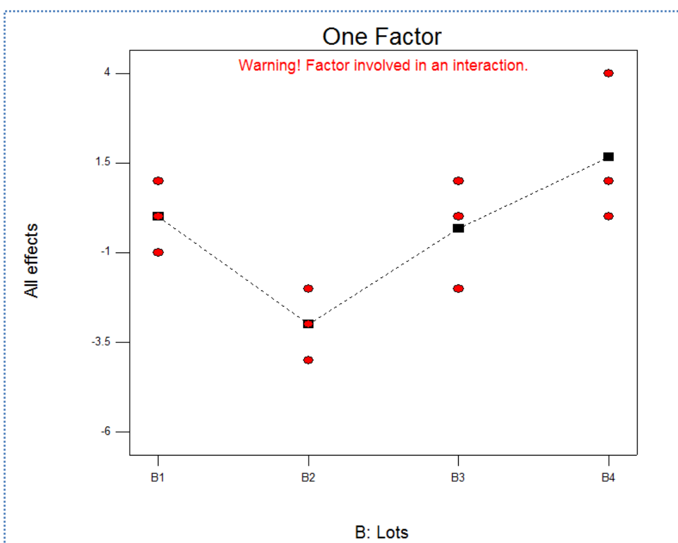
Graph preferences

Then click **XY Graphs** and under **Factorial Graphs** press the option for **None**.



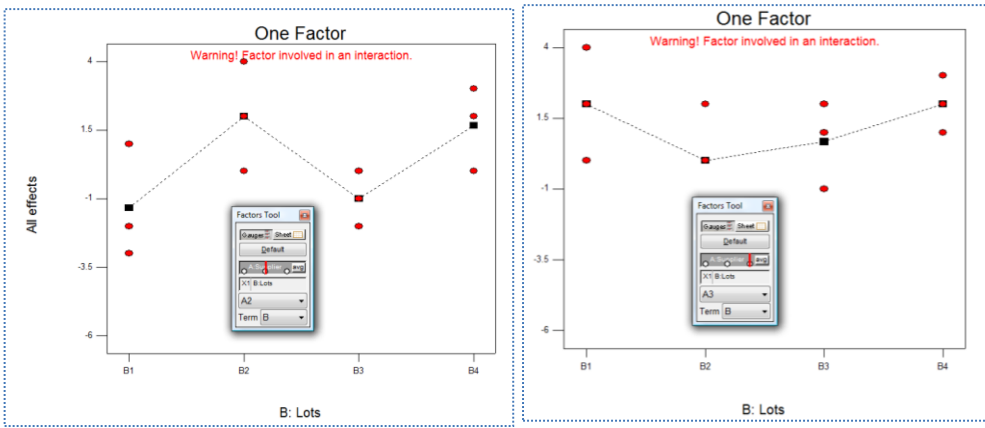
Turning off the LSD bars

OK this change (remember to reverse it back to LSD bars in future when analyzing completely randomized designs). You should now see the graph of lot purity for the first supplier.



Effect graph of lot-to-lot variation from the first supplier

On the factors tool palette, click on the other two buttons for A:Supplier to see how lots vary within suppliers A2 and A3. The patterns change in random fashion, but the amount of variation is considerable.

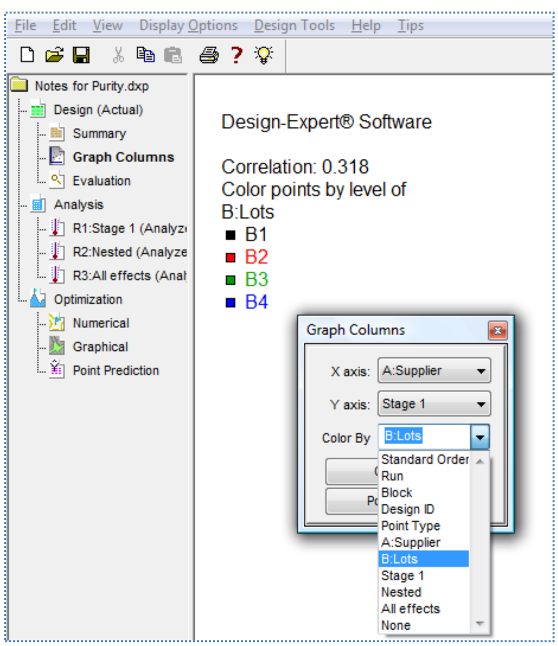


Lot-by-lot variation for the two other suppliers

To preserve the modeling used to produce the plot of lot-by-lot effects, select **File**, **Save** or click the save icon 🖫.

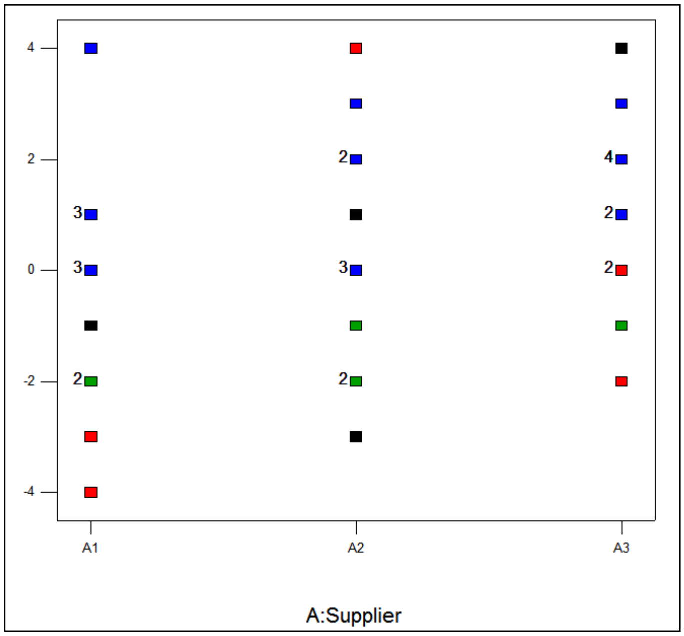
Montgomery summarizes this case study by saying:
"*The practical implications of this experiment and the analysis are very important. The objective of the experimenter is to find the source of the variability in raw material purity. If it results from differences among suppliers, then we may be able to solve the problem by selecting the "best" supplier. However, that solution is not applicable here because the major source of variability is the batch-to-batch purity variation within suppliers. Therefore, we must attack the problem by working with the suppliers to reduce their batch-to-batch variability.*"

To provide support for Montgomery's conclusions, click on the **Graph Columns** node under the Design branch of your Design-Expert software. Then on the Graph Columns tool click the down list ▼for **Color By** and select **B: Lots**.



Setting up a graph of purity by supplier, colored by lots

The correlation of purity versus supplier is positive in the direction of supplier A3, but only very weakly. There's too much lot-to-lot scatter within each supplier to see statistically significant differences between them.



Scatter plot of actual purity results

This is the end of the story, but as a postscript, you may wonder if it was worth all the bother to properly account for the split-plot nature of this experiment. Click back to the ANOVA for the "All effects" analysis and then back to the ones for "Stage 1" and "Nested". The difference for the supplier effect is dramatic – only by properly accounting for variances does one see that, due to variation by lots, the impact of this factor cannot be reliably estimated from this experiment. In other words, in this particular case, an experimenter who unwittingly ignored the restrictions in randomization caused by the nesting may have unfairly picked on a particular supplier who exhibited lower than normal purity.

Notice that for this particular design structure, the "All effects" ANOVA does provide an accurate test on the nested factor (B – Lots). However, it is best that you not count on this always being the case for nested designs in general.