Energy and Sustainability Topics – Performance Characteristic Lines (PCL) for energy management

TANGRAM TECHNOLOGY | **Consulting Engineers**

Energy and Sustainability Topics – Performance Characteristic Lines (PCL) for energy management

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Part 1: Single variables (drivers)

1.   Activity and condition drivers

Energy use can be related to either 'activity' or 'condition' drivers.

- An 'activity' driver is where the energy use varies with an internal activity, such as production volume.

- A 'condition' driver is where the energy use varies with an external influence, such as the weather.

In most cases where there is a single driver for an energy use then it is possible to relate the energy use directly to this driver.

2.   Single drivers

For a site with a single main process that uses electricity then it is possible to relate the electricity use to the single activity driver of production volume. This is shown in Figure 1 and is the normal case for many plastics processing sites which use only a single process.
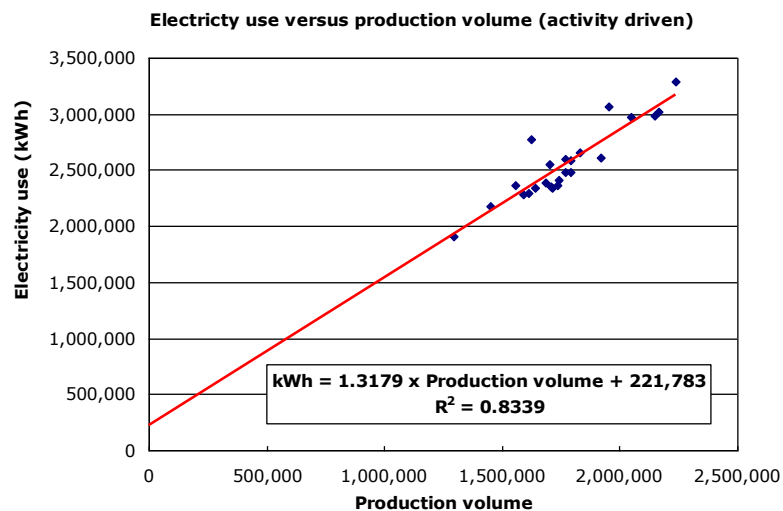

Electricty use versus production volume (activity driven)

$kWh = 1.3179 \times Production\ volume + 221,783$
$R^2 = 0.8339$

Figure 1: Single activity driver for electricity use

The amount of electricity used is directly related to the activity taking place. In this case, the production volume is the relevant activity.

For a site which uses gas only for heating then it is possible to relate the gas use to the single condition driver of Heating Degree Days (HDD = a measure of how cold it is). This is shown in Figure 2 and is the normal case for site heating where gas is used only for heating.

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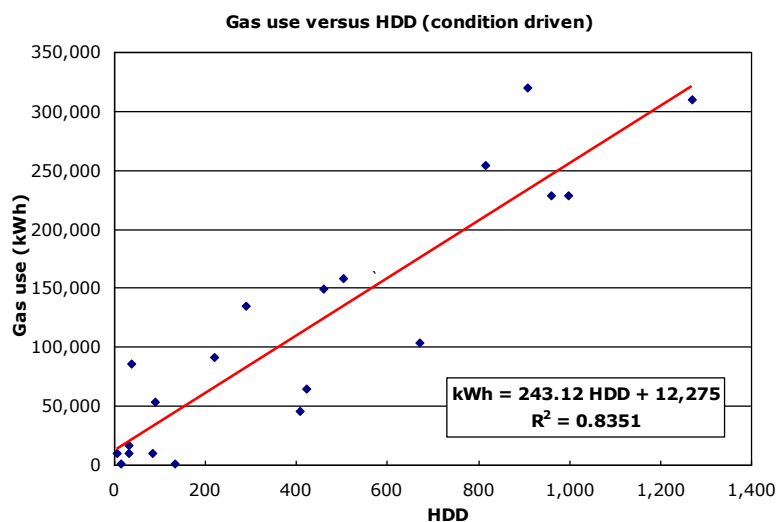

Figure 2: Single condition driver for gas use

The amount of gas used is directly related to the external condition. In this case, the HDD is the relevant condition.

In both of these cases, the energy use is related to the driver (activity or condition) by the equation:

kWh = A x Driver value + C

It is then relatively easy to predict the energy use by knowing the equation and the value of the relevant driver. It is also relatively easy to show the relationship using a simple graph.

3.   Calculating the values for single drivers

There are two methods for calculating the 'A' and 'C' values in the single driver case. Both of these methods use Microsoft Excel to varying degrees so the method will be explained using standard Excel functions (the exact methods may vary with your specific version of Excel). The two methods are:

Simple method:

This method uses simple Excel charting functions.

- Plot an XY scatter chart of energy usage (in kWh) versus the relevant activity or condition driver.

- Add a trend line to the scatter chart using the standard Excel function.

- Format the trend line to display the equation and the R-squared value on the chart.

- This will give a visual display of the trend line as well as the values of A, C and R^2.

- The value of R^2 is the correlation coefficient and is a measure of how good the data fits to the trend line. When R^2 = 1.0 there is a perfect correlation between the data and the trend line and when R^2 = 0 then there is no correlation between the data and the trend line. As a general rule, R^2 should be > 0.70 for a reliable relationship.

This is a simple 'least-squares line of best fit' method and is nice visual method of treating the numbers.

Complex method

This method uses the Excel 'Analysis ToolPak'. This is generally available but must be installed with Excel. It can be activated by Tools > Add-Ins and checking the Analysis ToolPak box. This will activate the ToolPak.

- Go to Tools and this should now show the Data Analysis option. Scroll down to 'Regression' and click to open the Options Box.

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- Select the 'Input Y Range' to match the required data (typically kWh).

- Select the 'Input X Range' to match the required data (typically production volume or HDD).

- Select the 'Output Range' as somewhere in the relevant spreadsheet.

- Click 'OK' and a table of numbers will appear where the Output Range was selected.

The resulting table look very similar to that shown in Figure 3:

SUMMARY OUTPUT	
Regression Statistics	
Multiple R	0.91320415
R Square	**0.8339**
Adjusted R Squar	0.82639372
Standard Error	134241.6659
Observations	24
ANOVA	
	df
Regression	1
Residual	22
Total	23
	Coefficients
Intercept	**221,783**
X Variable 1	**1.3179**

Figure 3: Output from Excel regression analysis

The R Square, Intercept and X Variable 1 values are the same as for the simple method (see Figure 1).

This gives in numbers the same information that resulted from the simple method. In this case the relevant numbers are the R Square, Intercept and X Variable 1. These can be compared to the values from the simple method (see Figure 1).

4.   What do A and C mean?

The 'least-squares line of best fit' for the data points in either Figure 1 or Figure 2 can be termed the Performance Characteristic Line (PCL) and this line shows how the system will respond to the relevant driver.

- The slope of the PCL (the A value) is the 'process load', i.e. the amount of energy used for each incremental increase in the driver. For an activity driver such as production volume, this gives the amount of extra energy that will be used for each extra kg processed. This can be referred to as the Specific Energy Consumption or SEC (kWh/kg) for the process, i.e. the actual energy being used to produce the product.

- The intersection of the PCL with the 'kWh' axis (the C value) indicates the 'base load' for the site, i.e., the energy usage when no activity or condition is present. For an activity driver such as production volume, this gives the amount of energy that will be used when no production is taking place but machinery and services are available.

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Part 2: Multi-variate analysis

1.   Complex sites

When energy use has a single activity or condition driver then analysis is easy and straightforward.

However, there are some sites where the energy use is more complex and where a single source of energy is used for two distinct purposes that are not metered separately. Some typical examples are:

- Injection moulding sites where electricity is used not only for the process heating and machines but also for significant air conditioning loads. How do you separate the activity (process heating and machines) from the condition (air conditioning) if you only have one electricity meter?

- Rotational moulding sites where gas is used not only for the process heating but also for the site heating. How do you separate the activity (process heating) from the condition (site heating) if you only have one gas meter?

Sites which have two processes taking place and where the processes have very different SEC values. An example of this might be a site where both injection moulding and extrusion take place. Extrusion has a much lower SEC than injection moulding and the energy use will be very different depending on the relative volumes of material processed.

2.   Multiple drivers

For sites with multiple drivers the energy use is related to the drivers (activity or condition) by the equation:

kWh = A x Driver 1 + B x Driver 2 + C

In this case the it is also easy to predict the energy use by knowing the equation and the value of the relevant drivers but it is not easy to show the relationship using a simple graph.

It is important to realise the Driver 1 and Driver 2 can be either activity or condition drivers and typical examples might be:

kWh = A x Production volume$_{Process\ 1}$ + B x Production volume$_{Process\ 2}$ + C.

kWh = A x HDD Site + B x Production volume + C.

kWh = A x CDD Site + B x Production volume + C. (where CDD = Cooling Degree Days)

Visualising the relationship

The visual graph for a single driver is shown in Figure 4 and this is the type of graph that has been seen for many situations.
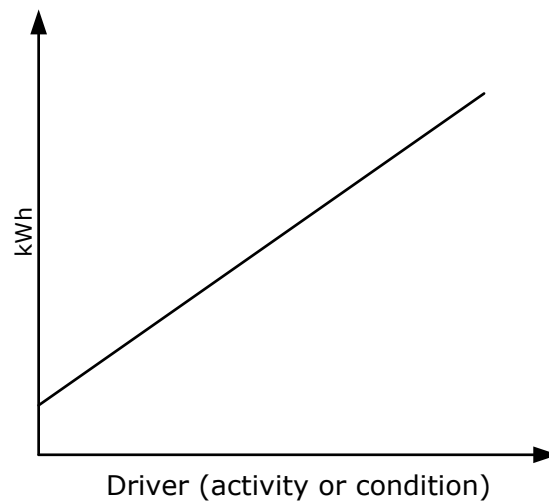
Figure 4: Graph of single activity driver

Visualising a single driver can be done on a simple 2D chart.

For multiple drivers the visual representation is more accurately shown by Figure 5, i.e. the relationship is in 3D and it is not possible to draw a simple chart to show the relation.

Figure 5: Graph of multiple activity drivers
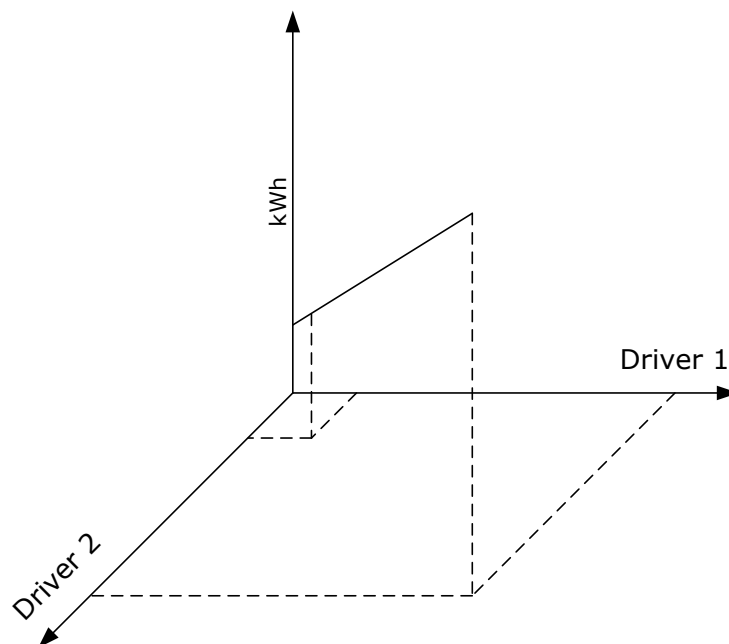
Visualising multiple drivers is difficult on a simple 2D chart because the relationship is actually in 3D.

3.   Calculating the values for multiple drivers

There is no visual methods for calculating the 'A', 'B' and 'C' values in the multiple driver case. It is only possible using the Microsoft Excel 'Analysis ToolPak' it is assumed that the ToolPak has been activated.

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- Go to Tools and this should now show the Data Analysis option. Scroll down to 'Regression and click to open the Options Box.

- Select the 'Input Y Range' to match the required data (typically kWh).

- Select the 'Input X Range' to match the required data. In this case the range needs to be extended to cover both of the drivers so it is easiest if they are next to one another in the spreadsheet.

- Select the 'Output Range' as somewhere in the relevant spreadsheet.

- Click 'OK' and a table of numbers will appear where the Output Range was selected.

- The resulting table look very similar to that shown in Figure 6:

SUMMARY OUTPUT	
Regression Statistics	
Multiple R	0.838914241
R Square	**0.7038**
Adjusted R Squar	0.685263172
Standard Error	250257.6899
Observations	35
ANOVA	
	df
Regression	2
Residual	32
Total	34
	Coefficients
Intercept	**22,118**
X Variable 1	**7458.367**
X Variable 2	**2.112**

Figure 6: Output from Excel regression analysis

The R Square, Intercept, X Variable 1 and X Variable 2 values are read from the table.

- Figure 6 gives in numbers the same information that resulted from the simple method. In this case the relevant numbers are the R Square, Intercept (C), X Variable 1 (A) and X Variable 2 (B) values. These can then be fed into the equation:

kWh = A x Driver 1 + B x Driver 2 + C.

4. What do A, B and C mean?

This is simply a multi-variate approach to the same problem as for a single variable and generates a 'least-squares line of best fit' for the data points.

- The 'A' value is the 'process load' for Driver 1, i.e., the amount of energy used for each incremental increase in the driver.

- The 'B' value is the 'process load' for Driver 2 i.e., the amount of energy used for each incremental increase in the driver.

- The 'C' value indicates the 'base load' for the site, i.e., the energy use when no activity or condition is present. For an activity driver such as production volume, this gives the amount of energy that will be used when no production is taking place but machinery and services are available.

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Part 3: Multi-variate analysis - Worked example

1.   Combined production and air conditioning loads

This is a worked example for assessing the effect of large air conditioning loads (driven by how hot it is) on the energy use of an injection moulding site.

Air conditioning loads are best assessed using Cooling Degree Days (CDD = a measure of how hot it is) and the process loads are best assessed by production volume.

2.   Method

- Set up a spreadsheet with the monthly data inserted (see Figure 7):

Month	Electricity (kWh)	Cooling Degree days (21°C)	Production volume
1	3,760,314	3	1,738,418
2	3,222,694	0	1,629,615
3	3,244,175	0	1,541,568
4	3,318,627	0	1,643,109
5	3,312,452	0	1,644,856
6	3,891,257	2	1,907,922
7	3,388,316	4	1,845,965
8	3,622,373	24	1,778,819
9	3,888,471	47	1,722,895
10	3,742,843	67	1,691,129
11	4,061,520	56	1,654,623
12	3,262,715	34	1,640,351
13	4,024,341	14	1,724,739
14	3,286,382	0	1,519,979
15	3,552,958	0	1,557,222
16	3,787,276	0	1,775,241
17	3,762,962	0	1,628,597
18	4,040,556	0	1,883,256
19	4,084,577	2	1,832,562
20	4,168,801	5	1,814,114
21	4,533,844	31	1,873,790
22	4,283,209	64	1,813,177
23	4,396,315	50	1,889,990
24	3,920,902	21	1,664,804
25	4,100,024	3	1,851,210
26	2,742,427	1	1,350,366
27	3,831,322	2	1,628,831
28	3,861,558	0	1,926,595
29	3,839,794	0	1,885,229
30	4,238,619	0	2,042,907
31	4,109,057	2	1,859,320
32	4,118,107	8	1,986,519
33	4,661,775	44	1,836,948
34	4,473,181	31	1,886,091
35	4,580,393	57	1,915,745

Figure 7: Data for energy use, CDD and production volume

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- The production volume data should come from the site data.

- The Cooling Degree Days can come from external data (see www.degreedays.net).

- In Excel, go to Tools, click on Data Analysis, scroll down to 'Regression and click to open the Options Box.

- Select the 'Input Y Range' to match the required data. In the example data this is the yellow area.

- Select the 'Input X Range' to match the required data. In the example data this is the red area.

- Select the 'Output Range' as somewhere in the relevant spreadsheet.

- Click 'OK' and a table of numbers will appear where the Output Range was selected (see Figure 8 for the output data).

SUMMARY OUTPUT	
Regression Statistics	
Multiple R	0.838914241
R Square	**0.7038**
Adjusted R Square	0.685263172
Standard Error	250257.6899
Observations	35
ANOVA	
	df
Regression	2
Residual	32
Total	34
	Coefficients
Intercept	**22,118**
X Variable 1	**7458**
X Variable 2	**2.1121**

Figure 8: Output from Excel regression analysis

The R Square, Intercept, X Variable 1 and X Variable 2 values are read from the table.

- The equation for the contribution of the two drivers is then:

kWh = 7458 x CDD + 2.11 x Production volume + 22,118.

3.   Displaying the results

The easiest method of displaying multivariate results is to calculate the predicted energy use (using the equation developed above) and to compare this to the actual use. This is shown in Figure 9:

Energy and Sustainability Topics – Performance Characteristic Lines (PCL) for energy management
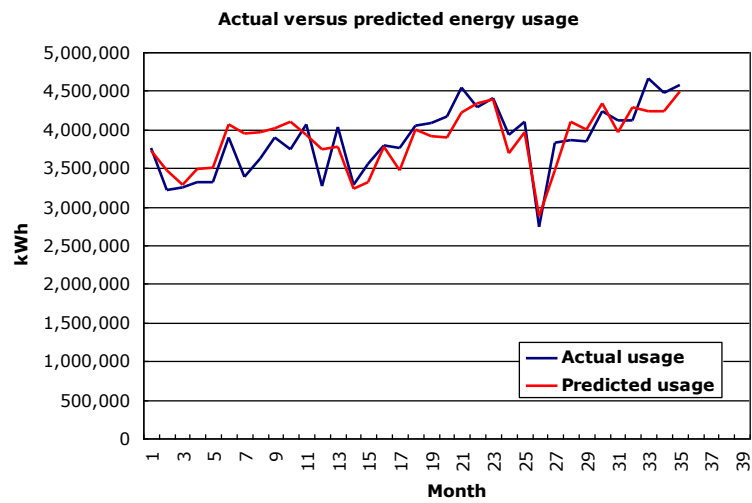

Figure 9: Actual versus predicted performance

This give some results but both numbers are large and it is hard to really assess the pattern.

it is much clearer to calculate the deviation from the predicted performance and to plot this. This is shown in Figure 10:
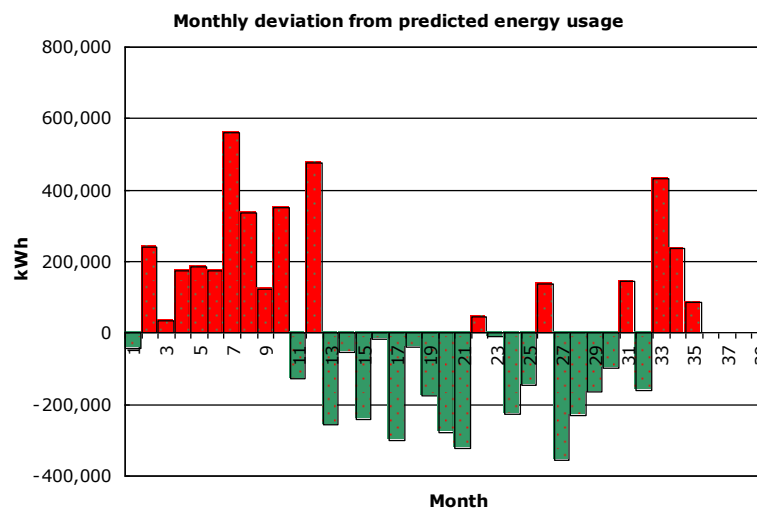

Figure 10: Deviation from predicted performance

It is obvious that there has been a good period but that this is now over and performance is currently poor.

It is also possible to calculate the relative contribution of each driver using a simple stacked bar chart and this is shown in Figure 11:

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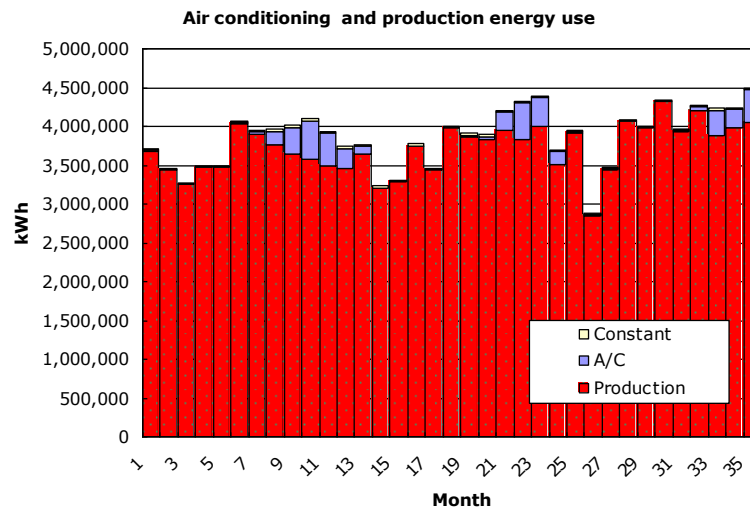

Figure 11: The contribution of multiple drivers

It is possible to assess the relative contributions of the multiple drivers. In this case the A/C and base loads are very minor.

It is obvious that the air conditioning and fixed loads are minor compared to the production load and in this case the site decided to ignore the air conditioning contribution to the energy use - this is not always the case.