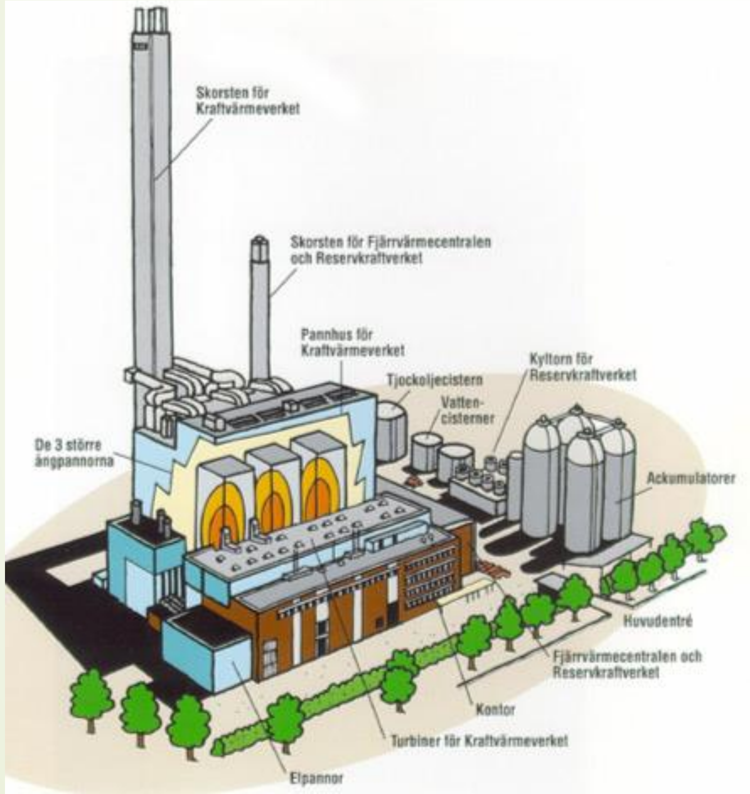
NOx – reduction by planned adjustment of 40 lance burners

Presentation of planning, execution and evaluation of a designed experiment performed at Malmö Heleneholm unit 12 1997 with SAS Institutes JMP 12 Pro Statistical Discovery Software

Heleneholm P12



P12 is a 150 MW thermal effect gas fired boiler with electric turbines and district heating heat sinks.

NOx emissions at project start 63 mg/MJ.

CO – operational limit 100 ppm.

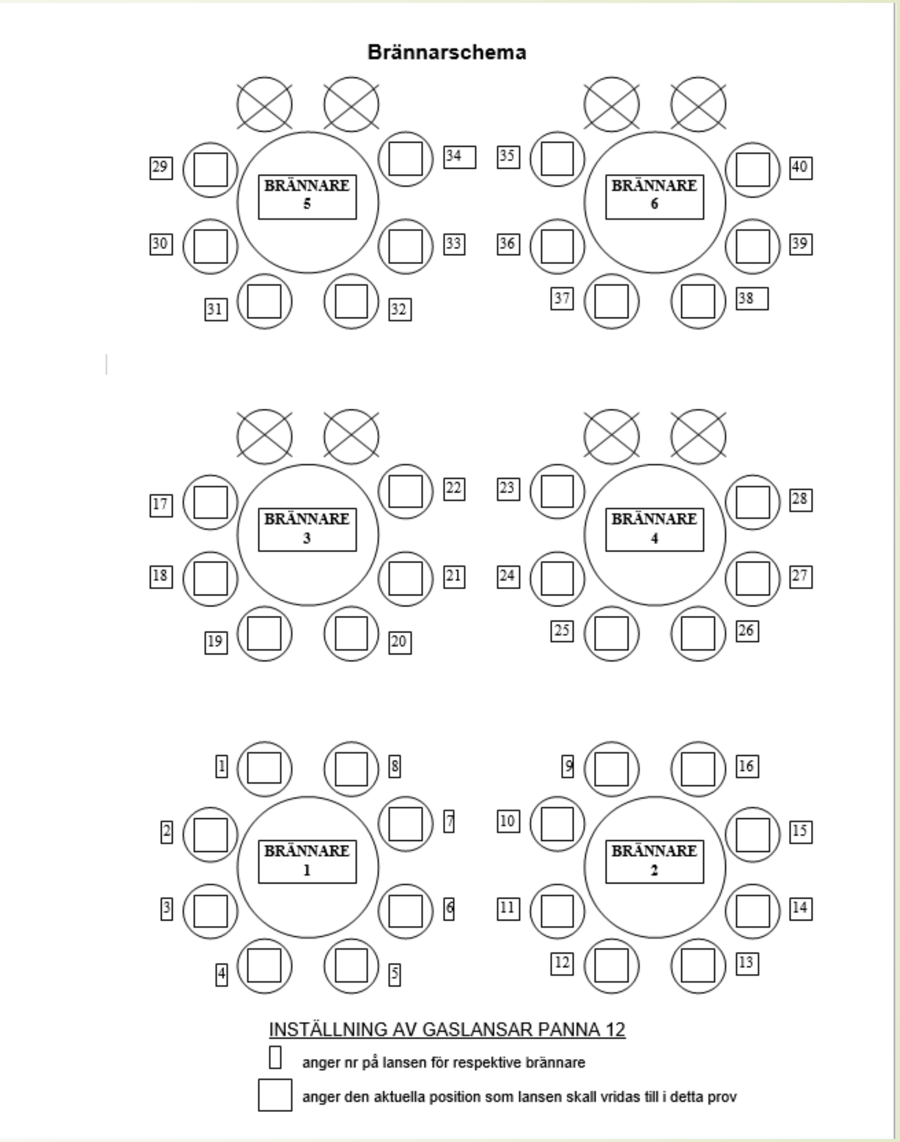
Burner wall layout

The burners are arranged in a burner wall

A total of forty burner lances are grouped in 6 burner groups.

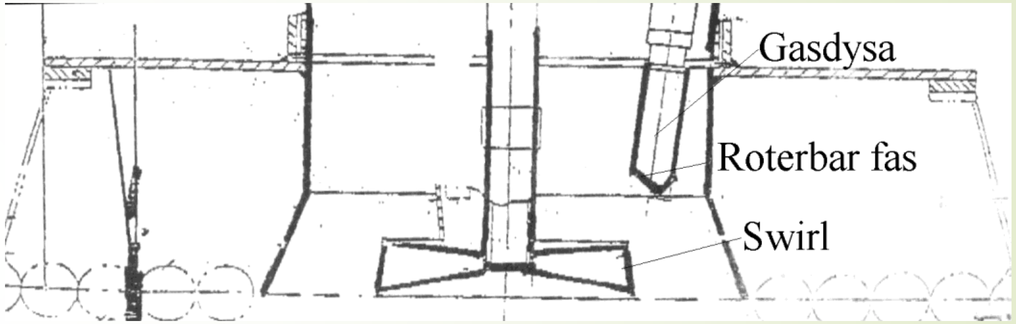
The low burner level is equipped with 8 burner lances.

The middle and the top level is equipped with 6 burner lances.



Lance burner design

The lance burner is a concentric two cone serial structure approximating a Venturi. A swirl is mounted concentrically in the Venturi. The swirl has a gas mixer function and is built as a “fixed turbine” wheel with evenly distributed angled blades mounted perpendicular to the air and gas flow. Upstream the swirl, an asymmetrically placed gas lance, is injecting natural gas into the air flow. The end of the lance is shaped to direct the fuel into or bypassing the swirl depending on the tubes rotational angular position. The gas lance nozzle can be rotated 360 degrees. The result is a vortex gas mixer with lance rotation angle as mixer parameter.



Factors, Levels and Experimental Design

- XRTECH and a competitor made bids for the work. The competing company did a bid on an optimization with a maximum of ten factors. This would mean a slower and possibly less precise process involving groups of burner lances i.e. not lance by lance. The customer decided to accept the XRTECH proposition of one factor for each gas lance. The design was built on a 40 factor, 81 run 3 level L81 matrix with 6 replicated runs. A total of total of 87 test runs was ordered.
- The experiment strategy was to make one large shot and treat it as a sample covering the largest possible design parameter hyper volume. The probability of one low NOx value would be high given at least one active factor. After the first gain a second degree large factor model would be estimated. This would imply an even lower NOx result. This on the assumption the interaction effects would be negligible. All given a 100 ppm operation restriction CO limit.
- The angles of the forty gas lances had been adjusted during normal operation prior to the experiment. Thus a zero-degree reference point was defined as the, at the time, best available factor settings corresponding to the 63 mg/MJ normal operation NOx level. As the L81 design is a three level design the center point where assigned the zero degree code. The plus and minus levels placed symmetrically at each side of the zero point where then to be specified. An initial guess was plus minus 120 degrees, with a backup plan of plus minus 60 degrees, in case of severe problems sustaining a stable combustion.

L81 matrix designed experiment : 81 test run settings + 6 replicates

STD	1	2	3	4	5	6	7	8
1	-1	-1	-1	-1	-1	-1	-1	-1
2	-1	-1	-1	-1	-1	-1	-1	-1
3	-1	-1	-1	-1	-1	-1	-1	-1
4	-1	-1	-1	-1	0	0	0	0
5	-1	-1	-1	-1	0	0	0	0
6	-1	-1	-1	-1	0	0	0	0
7	-1	-1	-1	-1	1	1	1	1
8	-1	-1	-1	-1	1	1	1	1
9	-1	-1	-1	-1	1	1	1	1
10	-1	0	0	0	-1	-1	-1	0
11	-1	0	0	0	-1	-1	-1	0
12	-1	0	0	0	-1	-1	-1	0

40 factors (columns) at 87 test runs (rows)

This matrix is a representation illustrating the first 8 columns and the first 12 rows. The matrix is sorted in standard order (STD). The matrix is executed in random order (RND).

(Randomization is a measure critical to avoid model bias from disturbance factors in the analysis phase.)

Test Run procedure

- The standard run order of the 87 row matrix (81 standard runs and 6 randomly picked standard runs replicated) was randomized.
- Rows with parameter settings with elevated risk for plant shutdown or other disturbances where placed first in run order (bypassing random order setting).
- Each of the 87 runs where performed in a three hour cyclic routine with the following main phases:
  - Adjustment phase. Adjustment of the 40 lance angles to run design target settings. A checklist for angle setting of each the 40 lances.
  - Process settling phase. Time for process to reach steady state. This is monitored in the control room during test;
  - Measuring phase. A measurement period; Notes of key values and process disturbances; Logging of process parameters with power plants stationary data logging system; Shift manager sign off when the test is terminated.
- Test runs were performed by the regular eight hour shifts according to established checklists given a stable base-load of 140 MW thermal. "In test"- operation guideline was to keep process variations as small as possible.

Process data logger – important process parameters

PROV 1	Remark:-								
yyyy-mm-dd		12NO	12NO2	12NOx	12O2f	12O2t	12CO2	12COf	12QBg
	09:30:04				2.098				
	09:30:25							45.340	
	09:30:52			71.245					
	09:31:50								12921.156
	09:32:09				2.133				
	09:32:29							48.206	
	09:32:53			71.245					
	09:33:50								12920.559

		12MWb	GOTng	12SO2	Air pressure	
	09:30:52	141.783				
	09:32:53	141.782				
	09:33:11				1014.748	
	09:34:52	141.770				
	09:36:54	141.780				
	09:37:18			1.024		
	09:38:12				1014.737	
	09:38:54	141.772				
	09:40:55	141.786				
	09:42:56	141.778				
	09:43:15				1014.789	
	09:44:53	141.776				
	09:45:48			0,561806		

Measurement plan – control room notes illustration Test run 87

	Measurement notes P12	Datum	yyyy-mm-dd	Test run 87
Position	Measurement	Unit	1:st reading	2:nd reading
			kl: 06:00	kl: 07:00
P	Gas flow	Nm3/h	12700	12700
P	Gas pressure burner inlet	kPa	80	80
P	Pressure Combustion Chamber	mm water column	-5	-5
P	Air flow, LF, left	%	60	57
P	Air flow, LF, right	%	70	69
P	Air/fuel ratio		1	1
T	Air temperature inlet	°C	179	180
O	Temperature turn shaft flue gas	°C	625	626
M	O2-level at luvo inlet, moist gas	vol- %	2,5	2,4
M	O2-level at luvo outlet (stack), dry gas	vol- %	5,7	5,1
M	CO- level at luvo outlet (stack), dry gas	ppm	182	256
M	NOx (stack)	mg/MJ	51	49
M	NOx (stack)	ppm	75	70
M	CO2 (stack)	vol- %	9,1	9,5

Deviations from initial plan

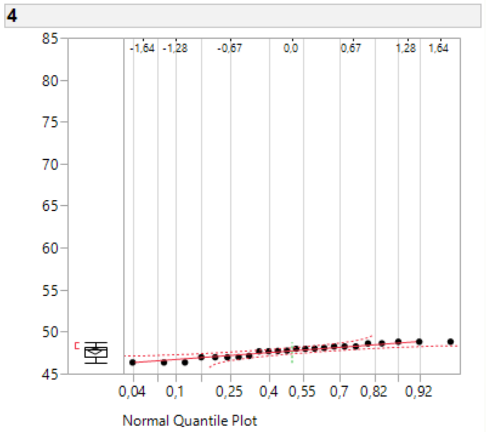
- As the experiment was started, it was obvious that large lance angles i.e. plus minus 120 degrees led to an unacceptable high rate of disrupted test runs. These interruptions were caused by high level CO trips, or flame monitor initiated trips, indicating unstable combustion conditions.
- Thus, the experiment was restarted with the revised 60 degrees level backup plan. 14 of the subsequent 87 60 degrees test runs where aborted due to flame monitor trips or high CO level.
- After adjustment of the trip points, a set of follow up test runs where made. All previous aborted tests where completed successfully. This with the exception of two test runs with burner trips and one with high CO trip.
- As one of the original test runs – RND 80, had a bad O2 setting this test run was repeated with correct settings in a final test. In addition, two previously omitted replicates did complete the experimental work.
- The operators were unable to reach stable combustion in *three* of the 87 lance angle combinations. Thus, we have *missing data* in three of the test matrix 87 rows.

Test run with lowest NOx value

- The experiment time to completion, from the initial test run to the final including reruns, was eight calendar days
- Two test runs generated low NOx values, one of these within the CO limit
- Test run RND 75 generated a 48 mg/MJ NOx value at a CO of 24 ppm i.e. considerably below the 100 ppm limit. (Note that this indicate room for further optimization.)
- The NOx reduction with reference to optimum parameter settings prior to the experiment is 63 – 48 = 15 mg/MJ. Thus, a nearly 25 percent's reduction in NOx emission levels.

Logged NOx data characteristics - distribution and process stability

- NOx test run RND 75 (STD 4)



Quantiles

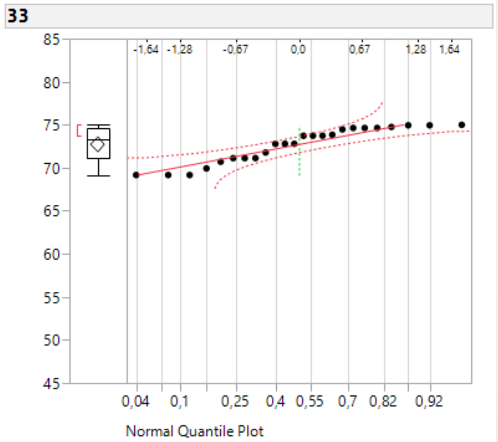
100.0%	maximum	48,807
99.5%		48,807
97.5%		48,807
90.0%		48,807
75.0%	quartile	48,24475
50.0%	median	47,8585
25.0%	quartile	46,96775
10.0%		46,344
2.5%		46,344
0.5%		46,344
0.0%	minimum	46,344

Summary Statistics

Mean	47,717208
Std Dev	0,7960813
Std Err Mean	0,1624994
Upper 95% Mean	48,053364
Lower 95% Mean	47,381053
N	24

A stable normal distribution (straight line in a normal plot). Most of the test runs showed a similar profile at different locations (mean values).

- NOx test run RND 4 (STD 33)



Quantiles

100.0%	maximum	74,992
99.5%		74,992
97.5%		74,992
90.0%		74,943
75.0%	quartile	74,633
50.0%	median	73,257
25.0%	quartile	71,128
10.0%		69,163
2.5%		69,162
0.5%		69,162
0.0%	minimum	69,162

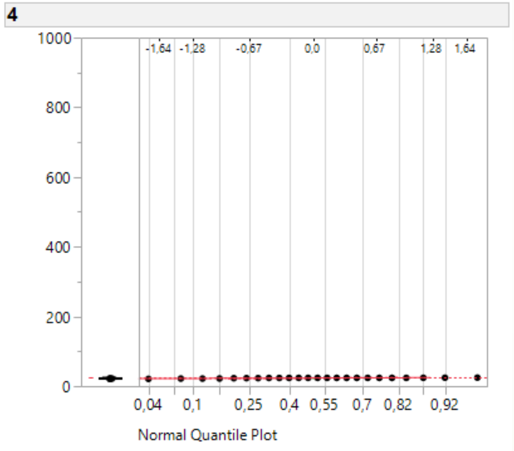
Summary Statistics

Mean	72,695083
Std Dev	2,0408229
Std Err Mean	0,4165812
Upper 95% Mean	73,556847
Lower 95% Mean	71,833319
N	24

Plot comparison gave RND 4 as the data set with largest deviation from the typical sample. It indicates a somewhat unstable process. It was a rerun of an initially tripped test run, with unstable combustion conditions. However, nothing from either process or statistics point of view, suggested further actions.

Logged CO data characteristics - distribution and process stability

- CO test run RND 75 (STD 4)

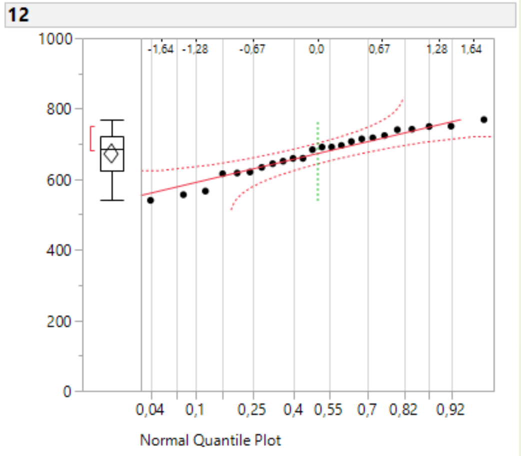


Quantiles		
100.0%	maximum	24,673
99.5%		24,673
97.5%		24,673
90.0%		24,3145
75.0%	quartile	23,9945
50.0%	median	23,9645
25.0%	quartile	23,3395
10.0%		21,9465
2.5%		21,062
0.5%		21,062
0.0%	minimum	21,062

Summary Statistics	
Mean	23,565042
Std Dev	0,8868459
Std Err Mean	0,1810267
Upper 95% Mean	23,939524
Lower 95% Mean	23,190559
N	24

This plot shows a stable normal distribution (straight line in a normal plot). A portion of the test runs showed a similar profile at very low CO values. Indicates combustion completion at stack measuring point.

- CO test run RND 14 (STD 12)



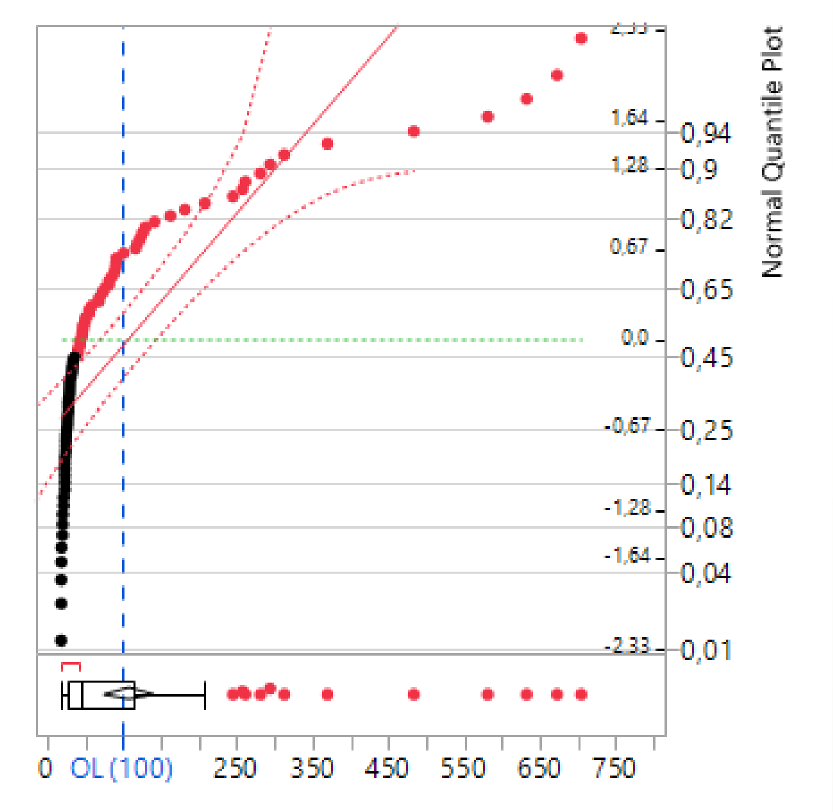
Quantiles		
100.0%	maximum	768,997
99.5%		768,997
97.5%		768,997
90.0%		750,155
75.0%	quartile	722,3655
50.0%	median	687,6555
25.0%	quartile	623,86725
10.0%		561,4125
2.5%		540,19
0.5%		540,19
0.0%	minimum	540,19

Summary Statistics	
Mean	672,58425
Std Dev	63,962928
Std Err Mean	13,056378
Upper 95% Mean	699,59343
Lower 95% Mean	645,57507
N	24

This plot shows less stable normal distribution at high CO values. Indicates insufficient combustion at stack measuring point.

Next two slides show test run mean value normal plots and validates that a set of the lower CO mean values are normally distributed.

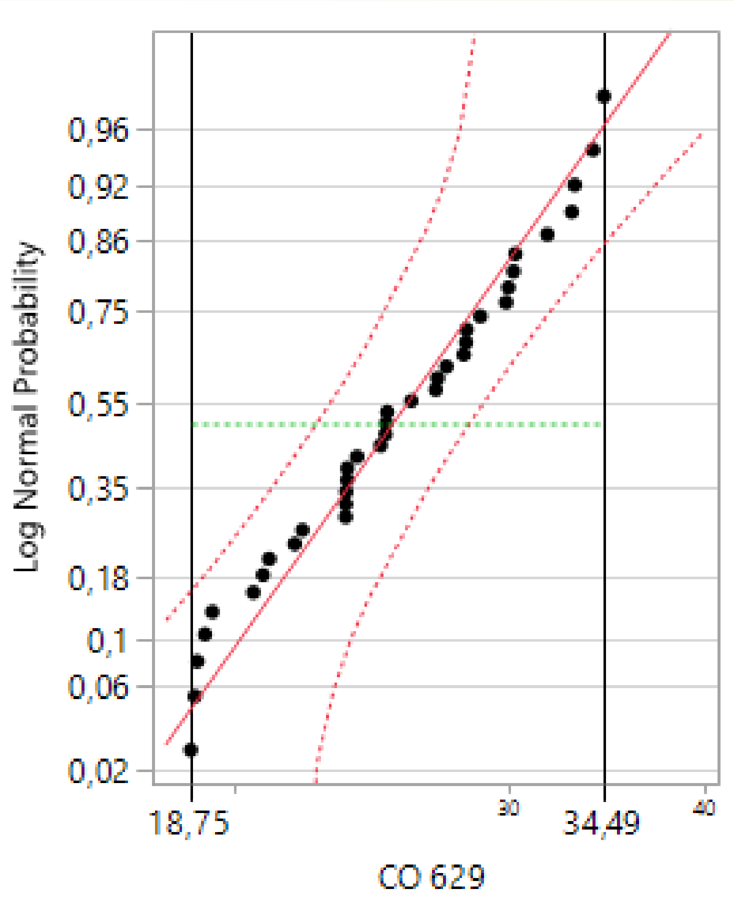
Analysis: The distribution of 84 CO test run means



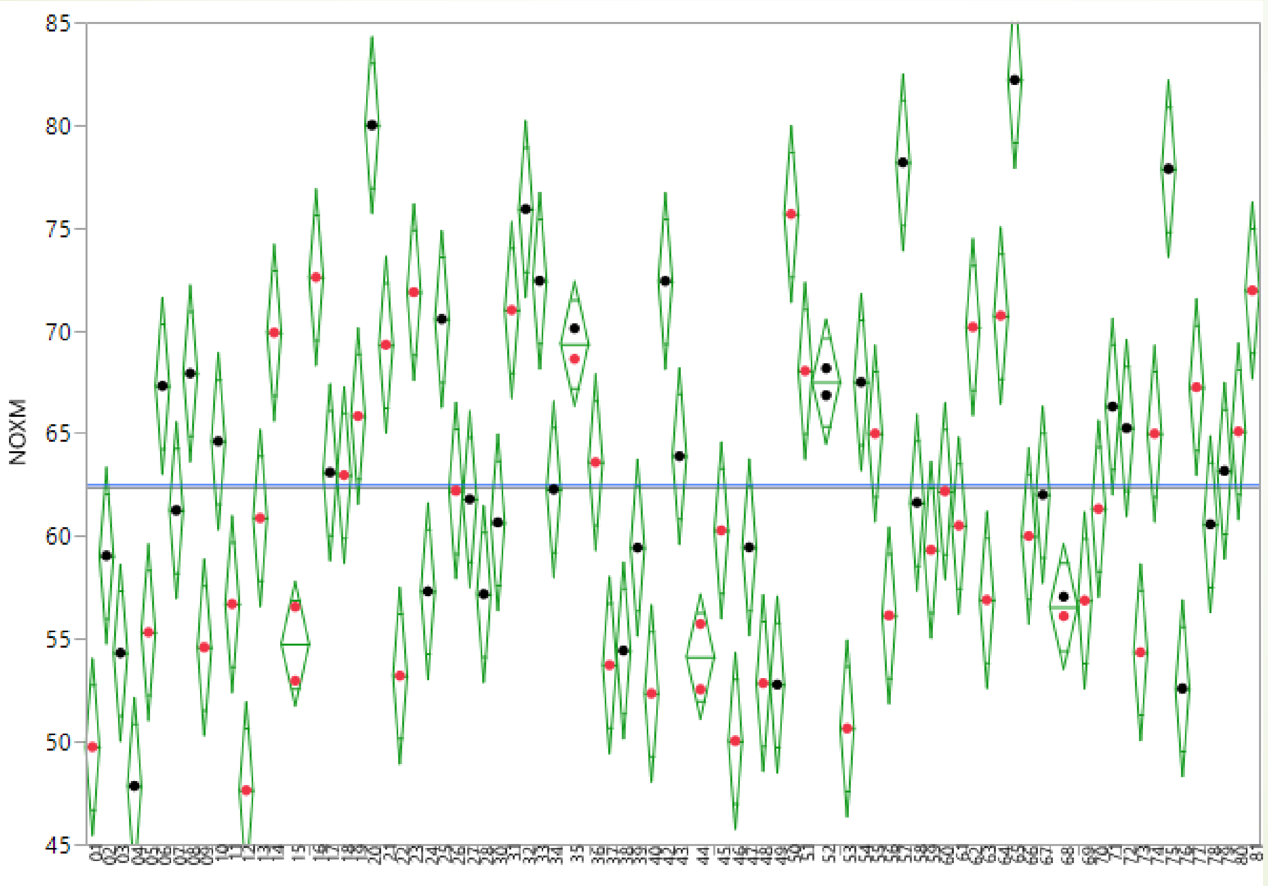
- CO can hypothetically be divided in a "stable" group (black dots) and a instable group (red dots)
- Limit for "normal combustion" could hypothetically be set where the black straight line portion transitions to a curved line. The black group maximum is 36 ppm.
- The 100 ppm operational limit is marked with a blue line
- Note that the 24 ppm CO level at optimal settings (RND 75) is within the stable interval.

CO black dot group stable process

- CO values in the interval 18 to 35 ppm
- CO is log normal distributed
- The combustion is stable in this interval (it is “in control”)



NOx analysis: ANOVA on 84 (87-3) factor levels (matrix response means)

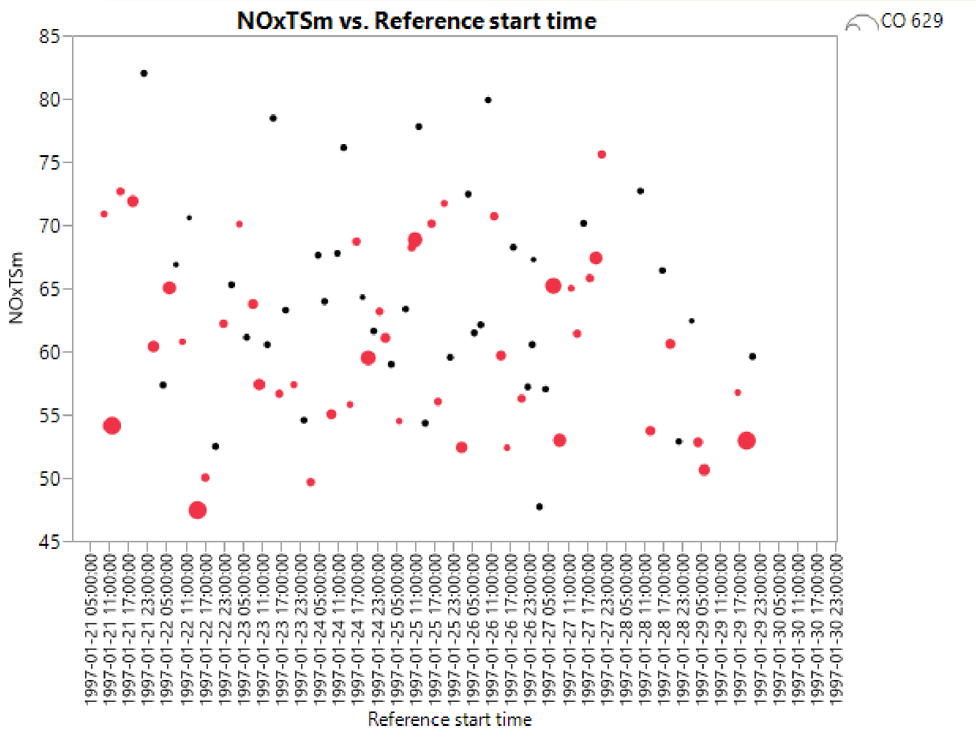


This plot shows effects of the 84 level treatment factor. The green diamonds are error estimates based on the replicates. The black dots are stable CO process and the red unstable process. Numbers are row in the L81 standard matrix before randomization (RND).

Note that stable low CO (black) and unstable high CO (red) processes are distributed over the whole NOx range.

NOx versus time, stable or unstable process, and CO as dot size

- Low O2 result in high CO and low NOx and vice verse given all other factors constant
- In this experiment we vary a large number of factors influencing CO and NOx given O2 constant.
- The graph shows distribution of NOx over time with black and red dots tagging stable and unstable CO processes. Small dot size is low and large is high CO level.
- This sample shows low NOx at stable CO is possible and that lower levels are waiting to be discovered!



Least square model 1997

- A set of linear ordinary least square NOx and CO models where estimated with the limits of the project budget, software and best practices at the time
- Based on NOx and CO models an optimal parameter setting experimental area (hyperspace) was determined.
- Based on this a set of “validating runs” where planned
- We will illustrate this procedure more in detail in the next slide and illustrate the result in a NOx, CO, O2 plot.

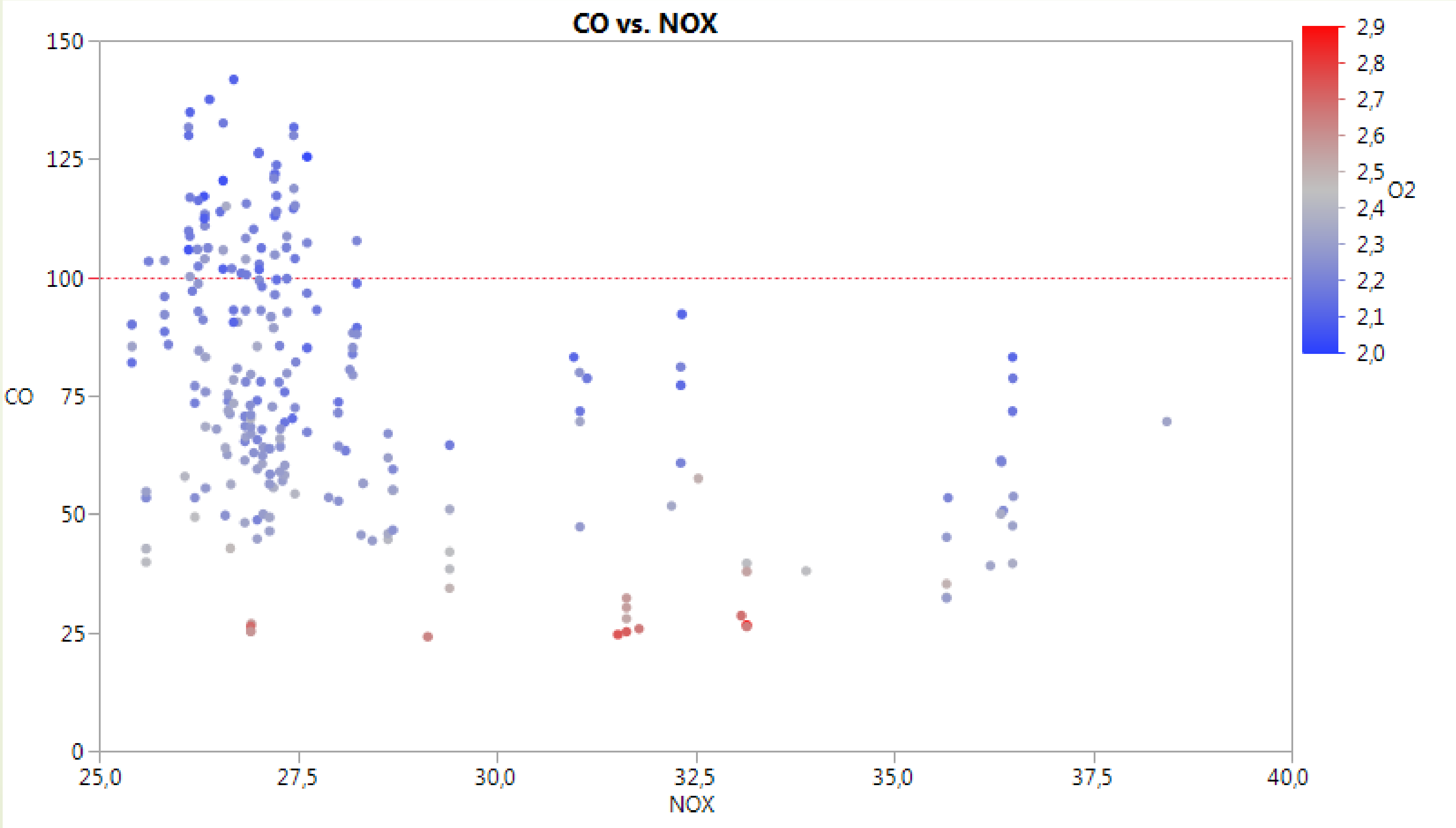
Lance Angle Adjustment Procedure

Factor	Best NOx model	Run 75(RND)	CO lock	Angle from ref 75 (degrees)	p value
C1	-1	-1		-43	0,0116
C2	0	1		16	0,0716
C3	1	1	1	60	0,0061
C4	-1	-1	1	60	0,0003
C5	-1	0		-48	0,0421
C6	0	0		24	0,0001
C7	-1	0		-60	0,0015
C8	1	0		60	0,2788
C9	0	0		12	0,0096
C10	0	0		-17	0,0053
C11	-1	0		-60	0,0423
C12	-1	0		-60	0,0509
C13	-1	0		-60	0,0288
C14	-1	-1		-60	0,0012
C15	1	-1		60	0,0118
C16	1	-1		60	0,0117
C17	-1	1		-60	0,0192
C18	-1	-1	-1	-60	0,0849
C19	0	1		28	0,0837
C20	0	-1		-9	0,0052

Factor	Best NOx model	Run 75(RND)	CO lock	Angle from ref 75 (degrees)	p value
C21	1	1	0	0	0,0005
C22	1	-1		60	0,5409
C23	0	0		-20	0,0048
C24	0	0	-1	-60	0,2073
C25	-1	0		-60	0,5938
C26	-1	0		-60	0,0525
C27	-1	0		-60	0,2129
C28	0	0		17	0,0075
C29	0	0	-1	-60	0,0005
C30	-1	0		-47	0,0840
C31	-1	0		-60	0,0072
C32	-1	-1	0	0	0,0065
C33	-1	1		-60	0,0041
C34	-1	-1	1	60	0,0084
C35	-1	1		13	0,0035
C36	-1	-1		-60	0,0036
C37	-1	1		-60	0,0845
C38	-1	1	1	60	0,0033
C39	-1	1	1	60	0,0499
C40	1	-1		60	0,1693

- Run 75 RND position is best known optimal setting and start point ref setting.
- To minimize CO lance C3, C4, C18, C21, C24, C29, C32, C34, C38 and C39 are set in low CO value locked position as shown in column *CO lock*.
- To minimize NOx the remaining gas lances is adjusted to optimal angle as shown in column *Angle from ref*.

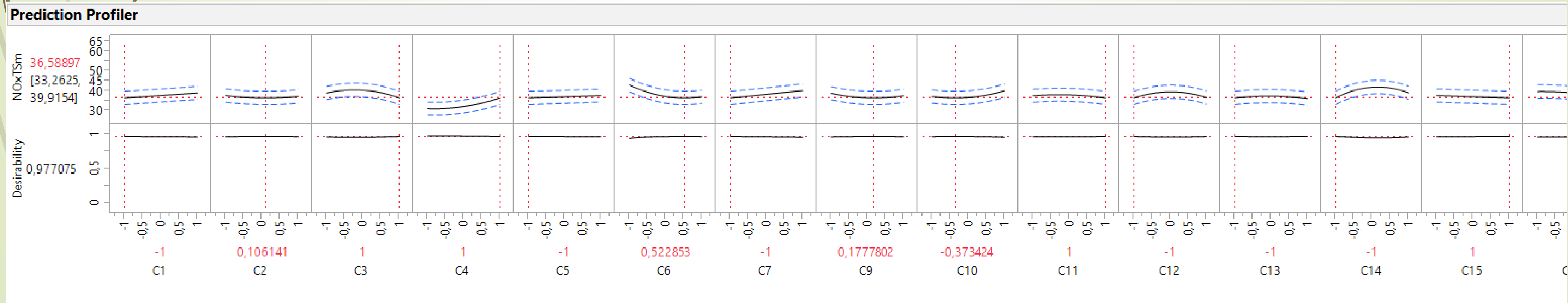
Validating tests at best lance angle combination



Test runs 1 to 87: O2 stack measurement in the 5 to 6 percent dry interval.

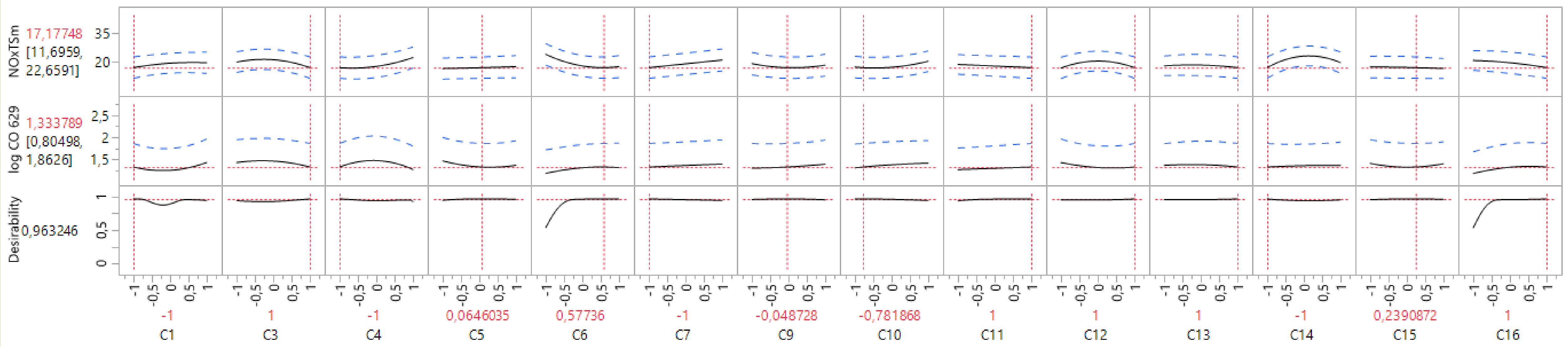
NOx regression analysis/optimization based on the 1997 procedure

- We did a JMP 12 pro software (2015 edition) regression analysis following the procedure used 1997, locking the CO factors at the same levels as 1997 and then searched parameter space with an algorithm. The result was a 37 mg/MJ prediction (5,5 percent O2 dry in stack). This is illustrated in the figure below. The gas lance angle can be calculated as proportions of the 60 degree angle.
- Note that the prediction profiler indicates even lower values. E.g. C1 settings exceeding minus 60 degrees will lower the NOx further.



Simultaneous optimization of NOx and CO

- With contemporary statistical modelling packages, simultaneous optimization of two responses, can be “a straight forward process”.
- JMP 12 Pro is well prepared for this task. Selection of a joint set of model parameters is possible, including regression analysis of NOx, CO with ANOVA, *t* tests of quadratic model parameter estimates, joint diagnostic plots etc. are all integrated in the package.
- Profiler of such an optimized model indicate 17 mg/MJ at 20 ppm as viable.
- Note that the prediction profiler indicates even lower values outside the investigated space also in this new model.



L81 Confounding of Interactions

The L81 second degree confounding pattern has been constructed as part of the original analysis. From a response surface view we have to consider that as there are number of significant second degree parameters, we have no reason to reject the hypothesis that we have a number of significant cross product parameters. E.g. ,the following factor C1 two factor interaction confounding pattern is :

C_1- 0,5*C_2C_3- 0,5*C_2C_4- 0,5*C_3C_4 - 0,5*C_5C_6- 0,5*C_5C_7- 0,5*C_6C_7 - 0,5*C_8C_9- 0,5*C_8C10- 0,5*C_9C10 - 0,5*C11C12- 0,5*C11C13- 0,5*C12C13 - 0,5*C14C15- 0,5*C14C16- 0,5*C15C16 - 0,5*C17C18- 0,5*C17C19- 0,5*C18C19 - 0,5*C20C21- 0,5*C20C22- 0,5*C21C22 - 0,5*C23C24- 0,5*C23C25- 0,5*C24C25- 0,5*C26C27- 0,5*C26C28- 0,5*C27C28 - 0,5*C29C30- 0,5*C29C31- 0,5*C30C31- 0,5*C32C33- 0,5*C32C34- 0,5*C33C34- 0,5*C35C36- 0,5*C35C37 - 0,5*C36C37- 0,5*C38C39- 0,5*C38C40- 0,5*C39C40

This confounding pattern is repeated with other factor pairing in contrast C2, C3, …, C40.
This is a weighted confounding pattern i.e. all interactions are multiplied with the factor – 0,5. This is similar to partially confounding patterns in Placket Burman designs. In practical application analysis one does from time to time disregard these and look at the result in terms of economical gains. This is common practice in L81 analysis (ref Taguchi). The alternative is to do a Bayes analysis as suggested by Box et al. You will then get information regarding active factors in the string. This work has been done on PB designs but remains in the L81 case.

Definitive screening design with 40 two level factors and a center point

A definitive screening design applicable for the NOx CO described is easily constructed with available software including JMP 12. The first rows and column of a 40 factor design looks like this:

Run	X1	X2	X3	X4	X5	X6	X7	X8
1	0	1	1	1	1	1	1	1
2	0	-1	-1	-1	-1	-1	-1	-1
3	1	0	-1	-1	1	-1	-1	1
4	-1	0	1	1	-1	1	1	-1
5	1	-1	0	-1	-1	1	-1	-1
6	-1	1	0	1	1	-1	1	1
7	1	-1	-1	0	-1	-1	1	-1
8	-1	1	1	0	1	1	-1	1
9	1	1	-1	-1	0	-1	-1	1
10	-1	-1	1	1	0	1	1	-1
11	1	-1	1	-1	-1	0	-1	-1
12	-1	1	-1	1	1	0	1	1

The analysis is easier as a full second degree model is possible. This with restriction in the number available of model parameters.
For future experiments: The definitive screening design should be an alternative to the L81 design.