Exercise of AM Digital Shadow/Twin

A common characteristic of modern digital manufacturing is the over-abundance of not-directly-usable data. The exercise provides exposure to this work environment through a case where data of different modalities (measurement from microscopy images, sensor recording, Xray CT analysis data, etc) are combined together to identify operational process risk windows. To achieve this, the exercise attempts to link the process parameters (both controlled and typically uncontrolled parameters) and the consequent part properties (roughness, hardness, etc.). Overall, this exercise focuses on steps to create a digital shadow/twin of the powder bed fusion metal additive manufacturing process, based on combination of experimental data from different sources.

To solve this exercise, you will need the two files on 'DoE and results' (an xl spreadsheet) and '316L Hardness' (a zipped folder) – download them from DTULearn.

Start with the DoE given in the xl spreadsheet on gas flow variables. The two main process parameters for the DOE and Gas flow speed and Oxygen %.

STEP1: Filling in the table on the sheet "Result of DoE".

Filling the "Real GFS", "Real GFS STD", "Real O" and "Real O STD" columns

- For each of the 14 components, there are sheets (named as "Sample <num>")showing the recorded sensor data when making the component. Click on the sheet Sample1 to view it.
- The sheet contains multiple columns containing among others the layer number at which the data was collected (column D), the Oxygen value (column L) and the measured gas flow (column N).
- Select the gas flow column and plot a 2D line graph to observe the trend of the gas flow speed. You will observe that there is a sudden rise/drop in the sensor reading, corresponding to the process being interrupted (either because the process ends or because the production of support structures has started).
- Only use the data points before the sudden rise/drop at the end to calculate the mean and STD of the gas flow speed. Discuss in your group what is the appropriate way to calculate the mean and standard deviation for the observed data (e.g., when calculating mean value whether to use arithmetic mean, geometric mean or Root Mean Square) and **mention your approach in the report.**
- Use the same number of data points (as for gas flow speed) to calculate the mean and STD of the Oxygen % (column L).
- Transfer the mean and STD values of gas flow speed and oxygen % to the sheet "Result of DoE"
- Repeat all the above steps for each of the 14 Sample sheets.

Filling the Porosity column

- Open the sheet ”Porosity” and observe that the table shows the number of pores generated, the porosity % and the density % for each sample.
- Convert the porosity % and density % rows to have four significant digits after the decimal.
- Create a new row calculating the “Average pore size %” as “Porosity%” / “Number of pores”
- Discuss in your group which of the three porosity variables (Number of pores, Porosity %, Average pore size %) is more significant for the tensile strength and fatigue properties of the part. **Mention your arguments and conclusion in the report**
- Transfer the Porosity % value to the sheet “Result of DoE”

Filling the Hardness column

- The zipped folder contains 14 csv files corresponding to the hardness measurement for each sample. Open the file 316L_1 (it should open in Excel by default).
- The file shows the Vickers hardness value calculated in a grid of 18 points. The columns of Diag1 and Diag2 are evaluated from images of the indentation and the hardness is computed using the standardized equation (the equation can be found in the file on DTULearn named “Hardness calculation method”).
- Calculate the mean value of hardness (column D) as well as the standard deviation, and compare it to the hardness at the center grid point (at XDistanceToStartPoint value of 3 and YDistanceToStartPoint value of 1) . Once again discuss in your group what is the appropriate way to calculate the mean and standard deviation for the observed data (e.g., when calculating mean value whether to use arithmetic mean, geometric mean or Root Mean Square) and **mention your approach in the report.**
- Repeat the above procedure to calculate the Hardness from the 14 hardness measurement files, and transfer to the sheet “Result of DoE”

Filling the Converted GFS column

- The real GFS values should be scaled for a better DoE evaluation – discuss in your group why scaling is necessary for the nominal and real GFS variables, and **mention it in the report**.
- To scale the real GFS, identify the maximum real mean GFS observed across the 14 samples as well as the minimum real mean GFS observed. The scaled GFS is given by either

$$NominalScaled\_GFS = \frac{Real\_GFS - Min\_nominal\_GFS}{Max\_nominal\_GFS - Min\_nominal\_GFS}$$

or

$$RealScaled\_GFS = \frac{Real\_GFS - Min\_real\_GFS}{Max\_real\_GFS - Min\_real\_GFS}$$

Discuss in your group which of the scaling approach is more suitable and and **mention it in the report.**

- Calculate the scaled GFS values for column H.

STEP 2: Creating a JMP DoE

- Transfer the table from Excel to JMP. Ensure that the data transfer is correct and you have used the desired number of significant digits after the decimal.

STEP 3: Analyze with JMP

- Setup a Fit Model analysis using JMP. Discuss in your group which interaction terms to include in the evaluation.
    - Ensure that the Personality is set as Standard Least Squares and the Emphasis is Effect Screening.
- Discuss in your group whether to use the STD of Oxygen % and the STD of GFS in your analysis. **Mention the conclusion and your reasoning in the report.**
    - If you decide to use the STD values as well, you will need to add a new column to your JMP table for Scaled_STD_GFS. Since there are no nominal STD values at the start of the DoE, you will have to use the real maximum and minimum values for scaling.
- From the list on the left of the Fit Model window, select one output column (e.g. Pa, Avg D, Eq through D, Porosity % or Hardness) , and then under Pick Role Variables, click on Y.
- From the list on the left of the Fit Model window, select the parameter columns that will be used to create the model, and then under Construct Model Effects, click on Macros and Response Surface. This will allow extraction of a prediction model.
    - If you are using scaled GFS values and using STD values as well in your model, then also use scaled STD_GFS. If you are using real GFS and using STD values, use real STD of GFS.
- Click on Run to perform the computation.
- Look at the Effect Summary and Effects Test charts/tables to ensure that your model is not overfitted.
- Analyze the results and **document (as a minimum)** the Effect Summary, Actual by Predicted Plot, the Residuals by Predicted Plot and the Interaction Profiles.
- Repeat the procedure for the remaining output variables. Save the models as JMP reports (.jrp)

STEP 4: Extracting the reduced order models

- Start with any of the five response models you have created.
- Find the small red arrow next to "Response" at the start of the analysis results window, and click to display multiple options.
- Move down to Save Columns, and from the available options click on "Publish Prediction Formula". This opens up a new window with the title "Formula Depot".
- Find the small red arrow next to "Formula Depot"at the start of the newly opened window, and click to display multiple options.
- Select "Show Scripts". This will open the "Formula Window" where you can see the formula governing the response surface you have generated. Copy and **document** the prediction/response formula. Discuss within your group about the applicability of the prediction/response formula and **mention it in the report**.
- Repeat the steps for all five response models.
- Save your JMP files.