Using Design of Experiments Analysis with Autodesk® Moldflow® Insight

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Please silence your Cell Phone
Class Summary

- In this class, you will learn how to set up, run, and interpret the results for a Design of Experiments (DOE) analysis. The class will also provide some tips and detailed information to help you get the most from the DOE analysis and show several case studies.
Learning Objectives

At the end of this class, you will be able to:

- Determine analysis objectives
- Pick the experiment type required
- Select analysis variables and quality criteria
- Run the analysis
- Interpret the analysis results
Introduction to Design of Experiments (DOE)
What is DOE

- Definition
- Terminology
  - Factors
  - Levels
  - Output
  - Noise
- Brief History

Factors (A) → Process → Output (B)
Noise (C)

Fisher
Rao
Taguchi
Use a DOE to understand

- The sensitivity of results (B) to variables (A)
- Interactions between variables
- The influence of a variable on a desired result
## DOE Versus Optimization

<table>
<thead>
<tr>
<th></th>
<th>Design of Experiment</th>
<th>Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary objective</td>
<td>Analyze the process</td>
<td>Find the optimum</td>
</tr>
<tr>
<td></td>
<td>environment</td>
<td></td>
</tr>
<tr>
<td>Analysis runs</td>
<td>Predefined before</td>
<td>Defined step by step</td>
</tr>
<tr>
<td></td>
<td>execution</td>
<td></td>
</tr>
<tr>
<td>Favored execution</td>
<td>Parallel</td>
<td>Sequential</td>
</tr>
<tr>
<td>End of execution</td>
<td>Completion of defined set of runs</td>
<td>Accuracy criteria or maximum number of runs</td>
</tr>
<tr>
<td>Process mapping</td>
<td>Homogeneous coverage</td>
<td>Defined by step path</td>
</tr>
<tr>
<td>Optimum</td>
<td>Estimate based on fitted equation</td>
<td>Accurate</td>
</tr>
</tbody>
</table>
DOE Inputs

- Processing parameters
- Boundary conditions
- Part Thickness

- Melt temperature $[+120, +160]$° C
- Mold temperature $[+60, +80]$° C
- Hydraulic pressure $[+20, +40]$ MPa
- Pack Time $[+5, +10]$ s
- Cooling inlet $\phi$ $[+5, +10]$ mm
- Flow rate $[+250, +300]$ mm$^3$/s
What DOE Does ...

**Input**
- Mold Temperature: [+60, +80] °C
- Melt Temperature: [+120, +160] °C
- Flow rate: [+25, +30] cm³/s

**Analysis**
- Moldflow® runs

<table>
<thead>
<tr>
<th>Mold Temperature</th>
<th>Melt Temperature</th>
<th>Flow Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>[+60, +120]</td>
<td>+25</td>
<td>1</td>
</tr>
<tr>
<td>[+60, +120]</td>
<td>+30</td>
<td>2</td>
</tr>
<tr>
<td>[+60, +160]</td>
<td>+25</td>
<td>3</td>
</tr>
<tr>
<td>[+60, +160]</td>
<td>+30</td>
<td>4</td>
</tr>
<tr>
<td>[+80, +120]</td>
<td>+25</td>
<td>5</td>
</tr>
<tr>
<td>[+80, +120]</td>
<td>+30</td>
<td>6</td>
</tr>
<tr>
<td>[+80, +160]</td>
<td>+25</td>
<td>7</td>
</tr>
<tr>
<td>[+80, +160]</td>
<td>+30</td>
<td>8</td>
</tr>
</tbody>
</table>

**Results**
- Solution space

**Influences on result**

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<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis Sequences</td>
<td>All available (Cool, Flow, Warp, Over-moulding, Mu-Cell, ...)</td>
</tr>
<tr>
<td>Model types</td>
<td>All available, (Midplane, Dual-domain, 3D)</td>
</tr>
<tr>
<td>Input variables</td>
<td>Common processing parameters (single values and profiles)</td>
</tr>
</tbody>
</table>
| Quality criteria     | Relevant analysis results
                       | Critical dimensions and localized deflection                               |
| Results generated    | Influence rankings
                       | 2D and 3D Quality response surfaces
                       | Contour plots                                                             |

- **Midplane**
- **Dual-domain**
- **3D**
Why Use DOE

- More information at the same or lower costs.
  - OFAT = \(2^7\) = 128 runs
  - DOE = 32 runs

- Higher precision estimates

- Systematic estimation of interaction

- Predict behavior within the design space

- Extrapolate behavior outside the design space
DOE Sequence

1. Run Initial Analysis
2. Design Experiment
3. Determine Objectives
4. Run DOE Analysis
5. Interpret results
DOE Limitations

- DOE’s don't directly compare results against a control or standard
- Must have a defined objective to be effective
Determining DOE Analysis Objectives
DOE Objectives

- Must have defined objectives to be effective

- Categories
  - Compare alternatives
  - Significant variables affecting a result
  - Targeting an output
  - Optimal process
  - Balancing tradeoffs
DOE Variables

- Identify Variables
- Brainstorm
- Fishbone Diagram
DOE Quality Criteria

- Identify Quality Criteria
  - Analysis results
  - Multiple criteria allowed
  - Weighting
<table>
<thead>
<tr>
<th>Example</th>
<th>Variables</th>
<th>Quality Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compare alternatives</td>
<td>Pack Time (Duration)</td>
<td>Deflection: Z component</td>
</tr>
<tr>
<td>Which pack time is better for warp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significant Variables</td>
<td>Mold Temperature</td>
<td>Injection Pressure</td>
</tr>
<tr>
<td>My tool is pressure limited, what variables</td>
<td>Melt Temperature</td>
<td></td>
</tr>
<tr>
<td>affect the pressure to fill the most?</td>
<td>Injection time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pack Pressure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pack Time (Duration)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Runner Diameter</td>
<td></td>
</tr>
<tr>
<td>Targeting an output</td>
<td>Melt temperature</td>
<td>Clamp force</td>
</tr>
<tr>
<td>Can I achieve uniform packing within the</td>
<td>Injection time</td>
<td>Injection pressure</td>
</tr>
<tr>
<td>available clamp force.</td>
<td>Pack profile</td>
<td>Volumetric shrinkage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## DOE Examples

<table>
<thead>
<tr>
<th>Example</th>
<th>Variables</th>
<th>Quality Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal process</td>
<td>V/P switchover %</td>
<td>Shear Rate</td>
</tr>
<tr>
<td></td>
<td>Pack Pressure</td>
<td>Volumetric Shrinkage</td>
</tr>
<tr>
<td></td>
<td>Mold Temperature</td>
<td>Temperature at Flow Front</td>
</tr>
<tr>
<td></td>
<td>Melt Temperature</td>
<td>Sink Mark Depth</td>
</tr>
<tr>
<td></td>
<td>Injection time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pack Pressure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pack Time (Duration)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balancing Tradeoffs</td>
<td>Mold temperature</td>
<td>Flatness of an edge</td>
</tr>
<tr>
<td></td>
<td>Melt temperature</td>
<td>2 critical dimensions</td>
</tr>
<tr>
<td></td>
<td>Injection time</td>
<td>Sink mark depth</td>
</tr>
<tr>
<td></td>
<td>Pack profile</td>
<td>Clamp force</td>
</tr>
<tr>
<td></td>
<td>3 circuit temperatures</td>
<td>Volumetric shrinkage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mold surface temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>What are the significant variables and what</td>
<td></td>
<td></td>
</tr>
<tr>
<td>are the levels to achieve the best quality?</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- V/P switchover %
- Pack Pressure
- Mold Temperature
- Melt Temperature
- Injection time
- Pack Pressure
- Pack Time (Duration)
- Shear Rate
- Volumetric Shrinkage
- Temperature at Flow Front
- Sink Mark Depth
- Mold temperature
- Melt temperature
- Injection time
- Pack profile
- 3 circuit temperatures
- Flatness of an edge
- 2 critical dimensions
- Sink mark depth
- Clamp force
- Volumetric shrinkage
- Mold surface temperature

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Design the experiment

The DOE Builder
Open the DOE Builder

- The Home tab
- The Study tasks list
DOE Builder

- Wizard helps you set up a DOE
  - Experiment
  - Variables
  - Quality Criteria
  - Options
- Based on existing analysis sequence
Experiment Tab

- Defines type of experiment
  - One variable
  - Variable Influences
  - Variable Responses
  - Variable Influences then Responses

![DOE Builder interface showing options for experiment types and variable influences.](image)
Experiment tab

- One Variable

- Variable Influences
  - Influence of each variable
  - Taguchi design based on orthogonal design
DOE Analysis Modes

- Variable Responses
  - Quality response surfaces
  - Optimum variable values

- Combined Influence then Response analysis
  - Filter ‘N’ most influential variables before determination of the quality responses.
  - Default to 3 are transferred
Variables Tab

- Pick the variables used by DOE
  - Based on analysis sequence
- Includes most
  - Numerical inputs from Process Settings Wizard
  - Boundary conditions
  - Thickness variation
- Min and Max values must be symmetric around middle value
Variables tab - Profiles

- Profiles used as inputs
  - Velocity
  - Packing
  - Gas injection
- Profile’s X & Y axis are different variables
- Profile simplified to a range of -1 to +1
Variables tab – Dimension Scale Factor

- Change the “thickness”

- Workflow
  1. Highlight Dimension scale factor
  2. Select layer
  3. Set the percentage range
  4. Rename variable
Quality Criteria Tab

- Results determine part quality
  - Single point from log file
  - Nodal / Elemental data
  - Based on analysis sequence
- Pick as many as you want
- Each result has a description of how it is used
Quality Criteria - Definitions

- **Weight** - Relative importance to overall quality
- **Goal** - Typically minimize
- **Calculate**
  - Single point – Typically value from log file
  - Maximum – Maximum nodal / elemental value
  - Standard deviation – Minimize variation in the result
    - Most nodal / elemental results are standard deviation
- **Description**

The Volumetric shrinkage at ejection result is evaluated. The goal is to minimize the variation in the volumetric shrinkage. The lower the variation in shrinkage, the higher the quality.
Quality Criteria – Custom Warp Criterion

- Critical dimension
- Node list
Custom Warp Criterion – Critical Dimension

1. Pick Critical Dimensions for Design of Experiment
2. Select the nodes to define dimension
3. Assign a name to the dimension
4. Open the DOE Builder
5. Create a new Custom warp criterion
6. Select critical dimension
7. Select the result
8. Set the weight
9. Rename the warp criterion
Custom Warp Criterion – Critical Dimension Video
Quality Criteria – Custom Warp Criterion, Node List

1. Select the nodes to define list
2. Save the selection list
3. Open the DOE Builder
4. Create a new Custom warp criterion
5. Select nodes list
6. Select the result
7. Set the weight
8. Pick anchor plane
9. Rename the warp criterion
Quality Criteria – Node List Video
Options Tab

- Save CSV file
  - Checked by default
- Keep analysis results
  - Individual studies run for the DOE analysis
- Relaunch
  - If short shot occurs
Run the Analysis
Running the DOE Analysis

- Autodesk Moldflow Insight
  - Uses Distribution Queue
    - Runs as many analyses at a time as
      - Licenses allow (3 instances per licenses)
      - Processors available

Job Manager on Local machine running a DOE
Running the DOE Analysis

“Breaking the Sim Barrier”

- Moldflow Insight WS
  - Uses cloud computing
  - Studies processed in parallel

Log file showing the cloud running 16 analyses simultaneously
Interpret the Analysis Results

DOE Results

Interpret results
DOE Results

- Log file
- Response XY plots
- Response surface
- Contour plots
DOE Log Results

• Variable influences on quality criteria
  
<p>| Influences on quality #6, Edge Flatness |</p>
<table>
<thead>
<tr>
<th>Calculate</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.73%</td>
<td>Injection time</td>
</tr>
<tr>
<td>6.44%</td>
<td>Melt temperature</td>
</tr>
<tr>
<td>16.60%</td>
<td>Core Inlet 2:Coolant inlet temperature</td>
</tr>
<tr>
<td>11.49%</td>
<td>Core Inlet 3:Coolant inlet temperature</td>
</tr>
<tr>
<td>10.10%</td>
<td>Duration</td>
</tr>
<tr>
<td>5.54%</td>
<td>Injection + packing + cooling time</td>
</tr>
<tr>
<td>14.83%</td>
<td>Packing pressure</td>
</tr>
<tr>
<td>4.27%</td>
<td>Core Inlet 1:Coolant inlet temperature</td>
</tr>
</tbody>
</table>

• Quality range and estimate of optimum (using the response equation)

<p>| Optimum on quality #6, Edge Flatness |</p>
<table>
<thead>
<tr>
<th>Calculate</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>[0.151885 : 0.81515] mm</td>
</tr>
<tr>
<td>Minimum value</td>
<td>0.151885 mm</td>
</tr>
<tr>
<td>with 1 as Packing pressure</td>
<td></td>
</tr>
<tr>
<td>with 3.7 s as Injection time</td>
<td></td>
</tr>
<tr>
<td>with 9.99999 C as Core Inlet 3:Coolant inlet temperature</td>
<td></td>
</tr>
<tr>
<td>with -1 as Duration</td>
<td></td>
</tr>
</tbody>
</table>
DOE Results – 2D Response Graphs

- One variable plotted with quality criterion
- Other variables have sliders
- DOE control panel opens with Plot Properties
DOE Results – 2D Response Graphs Video

2D – One variable plotted with quality criterion
DOE Results – 3D Response Graphs

- Two variables plotted with quality criterion
- Other variables have sliders
DOE Results – 3D Response Graphs Video

3D – Two variables plotted with quality criterion
DOE Results – Contour

- Observe the impact of variables on results
- All variables have sliders
Observe the impact of variables on results
Case Study #1

Solving Flow Related Problems
**Glove Box Door - Flow**

- **Objective**
  - Minimize surface finish defects

- **Experiment**
  - Evaluate processing variables
  - Quality based on
    - Sink marks
    - Shear stress
    - Volumetric shrinkage variation

- **Interpret results**
  - Find processing conditions to minimize surface defects
Glove Box Door – Experiment Setup

- Experiment – Variable Influences then Responses
  - Pass to the responses analysis the 3 most influential variables

<table>
<thead>
<tr>
<th>Variables</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt temperature</td>
<td>225 – 265 [C]</td>
</tr>
<tr>
<td>Injection time</td>
<td>0.5 – 4.5 [s]</td>
</tr>
<tr>
<td>V/P switch-over</td>
<td>98 – 99%</td>
</tr>
<tr>
<td>Pack Time (duration)</td>
<td>4 – 14 [s]</td>
</tr>
<tr>
<td>Pack Pressure</td>
<td>60 – 110 [MPa]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quality Criteria</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Stress</td>
<td>Cooling time</td>
</tr>
<tr>
<td>Sink mark depth</td>
<td>Time at end of pack</td>
</tr>
<tr>
<td>Volumetric shrinkage at ejection</td>
<td>Part Weight</td>
</tr>
<tr>
<td>Temperature at flow front</td>
<td>Clamp Force</td>
</tr>
<tr>
<td>Bulk Temperature EOF</td>
<td>Injection Pressure</td>
</tr>
</tbody>
</table>
Glove Box Door – Running the Analysis

- Analysis run is 3 steps
  - Base analysis
    - This should be run first and the results checked
  - Variable influences (Taguchi) analysis
    - 8 analyses
  - Variable responses (Face Centered Cubic) analysis
    - 15 analyses
- Total runs 24
Breaking the Sim Barrier

- Autodesk Moldflow Insight Option
  - One license – Solves at one time
    - 1 DOE Analysis
    - 2 Flow Analyses
  - Total analysis time
    - 3 hours 22 min

- Autodesk Moldflow Insight WS Option (In the Cloud)
  - Solves analyses simultaneously for DOE
  - Total analysis time
    - 1 hour 16 minutes
  - Saving
    - 2 hours 6 minutes
Glove Box Door – DOE Log Results

- What did I get myself into?
- Information overload!
- I messed up by picking too many quality criteria!
Glove Box Door – DOE Log Results

- I should have only picked the quality criteria I really needed!
- Concentrate only on the ones needed
  - Shear stress
  - Sink marks
  - Volumetric shrinkage
- Compare to
  - Injection pressure
  - Clamp force

<p>| Influences on quality #4, Shear stress |</p>
<table>
<thead>
<tr>
<th>Calculate</th>
<th>Single value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.14%</td>
<td>Packing pressure</td>
</tr>
<tr>
<td>50.48%</td>
<td>Melt temperature</td>
</tr>
<tr>
<td>49.09%</td>
<td>Injection time</td>
</tr>
<tr>
<td>0.14%</td>
<td>U/P switch-over by % volume filled</td>
</tr>
<tr>
<td>0.14%</td>
<td>Duration</td>
</tr>
</tbody>
</table>

<p>| Influences on quality #5, Sink mark depth |</p>
<table>
<thead>
<tr>
<th>Calculate</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>48.50%</td>
<td>Packing pressure</td>
</tr>
<tr>
<td>5.86%</td>
<td>Melt temperature</td>
</tr>
<tr>
<td>23.51%</td>
<td>Injection time</td>
</tr>
<tr>
<td>2.28%</td>
<td>U/P switch-over by % volume filled</td>
</tr>
<tr>
<td>19.92%</td>
<td>Duration</td>
</tr>
</tbody>
</table>

<p>| Influences on quality #8, Volumetric shrinkage at ejection |</p>
<table>
<thead>
<tr>
<th>Calculate</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>75.62%</td>
<td>Packing pressure</td>
</tr>
<tr>
<td>6.28%</td>
<td>Melt temperature</td>
</tr>
<tr>
<td>11.21%</td>
<td>Injection time</td>
</tr>
<tr>
<td>4.58%</td>
<td>U/P switch-over by % volume filled</td>
</tr>
<tr>
<td>2.31%</td>
<td>Duration</td>
</tr>
</tbody>
</table>
Glove Box Door – DOE Log Results

- Top 3 most influential variables passed to the response analysis:
  - Injection time
  - Packing pressure
  - Melt temperature

- Compare the conditions that produce the highest quality:

  **Optimum on quality #4, Shear stress**
  - Calculate = Single value
  - Range = [ 0.29707 : 0.708956 ] MPa
  - Minimum value = 0.29707 MPa
  - with 3.41649 s as Injection time
  - with -1 as Packing pressure
  - with 265 C as Melt temperature

  **Optimum on quality #5, Sink mark depth**
  - Calculate = Maximum
  - Range = [ 0.0149519 : 0.0485081 ] mm
  - Minimum value = 0.0149519 mm
  - with 3.7 s as Injection time
  - with 1 as Packing pressure
  - with 265 C as Melt temperature

  **Optimum on quality #8, Volumetric shrinkage at ejection**
  - Calculate = Standard deviation
  - Range = [ 0.724451 : 1.28123 ] %
  - Minimum value = 0.724451 %
  - with 4.5 s as Injection time
  - with 1 as Packing pressure
  - with 265 C as Melt temperature
Glove Box Door – Response Surfaces – Sink Mark Depth

- Best parameters
  - Long injection time
  - High pack pressure
  - High melt temperature
Glove Box Door – Sink Mark Depth

Original mid-range conditions

Best conditions from DOE
Glove Box Door – Response Surfaces – Volumetric Shrinkage

- Best parameters
  - Long injection time
  - High pack pressure
  - High melt temperature
Glove Box Door – Volumetric Shrinkage

Original mid-range conditions

Best conditions from DOE

Volumetric shrinkage at ejection

= 4.200[\%]

[\%]
Glove Box Door – Response Surfaces – Shear Stress

- Best parameters
  - Long injection time
  - Any pack pressure
  - High melt temperature
### Glove Box – Door Shear Stress

From the log file –

<table>
<thead>
<tr>
<th><strong>Original mid-range conditions</strong></th>
<th><strong>Best conditions from DOE</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum Shear stress at times:</strong></td>
<td><strong>Maximum Shear stress at times:</strong></td>
</tr>
<tr>
<td>Filling Phase $= 2.866$ MPa at time $2.74$s</td>
<td>Filling Phase $= 3.609$ MPa at time $3.84$s</td>
</tr>
<tr>
<td>Packing Phase $= 2.868$ MPa at time $2.74$s</td>
<td>Packing Phase $= 6.343$ MPa at time $4.25$s</td>
</tr>
<tr>
<td><strong>Shear stress at 95th %ile at times:</strong></td>
<td><strong>Shear stress at 95th %ile at times:</strong></td>
</tr>
<tr>
<td><strong>Filling Phase</strong> $= 0.399$ MPa at time $0.13$s</td>
<td><strong>Filling Phase</strong> $= 0.345$ MPa at time $0.18$s</td>
</tr>
<tr>
<td>Packing Phase $= 0.468$ MPa at time $11.90$s</td>
<td>Packing Phase $= 0.437$ MPa at time $12.75$s</td>
</tr>
<tr>
<td><strong>Shear stress at End of Fill</strong></td>
<td><strong>Shear stress at End of Fill</strong></td>
</tr>
<tr>
<td>Maximum $= 2.866$ MPa</td>
<td>Maximum $= 3.609$ MPa</td>
</tr>
<tr>
<td>95th%ile $= 0.280$ MPa</td>
<td>95th%ile $= 0.285$ MPa</td>
</tr>
<tr>
<td>Average $= 0.200$ MPa</td>
<td>Average $= 0.199$ MPa</td>
</tr>
</tbody>
</table>

Values in red used for DOE analysis
Glove Box Door – Response Surfaces – Clamp Force

- Over 1200 tonnes of clamp force
  - At good conditions for
    - Shear stress
    - Volumetric shrinkage
    - Sink mark values
Glove Box Door – Response Surfaces

- Lowest Injection pressure still over 100 MPa
Conclusions – Glove Box Door – Flow Issues

- Sink marks
  - Improved significantly about 40% shallower

- Volumetric shrinkage
  - Lower maximum values
  - Smaller variation

- Shear Stress
  - Only minor improvement

Things to consider
- Higher packing pressures required
- Clamp tonnage goes up significantly

- Overall the results are great
- The cloud reduced the solve time by a factor of 2.7!
Case Study #2

Solving Cooling Related Problems
Glove Box Door – Mold Surface Temperature

- **Objective**
  - Minimize mold surface temperature variation

- **Experiment**
  - Evaluate coolant temperature modification
  - 3 cavity circuits
  - 3 core circuits

- **Quality based on**
  - Mold surface temperature

- **Interpret results**
  - Determine if needed or practical to change water temperatures
Glove Box Door – Experiment Setup

- Experiment – Variable Influences then Responses
  - Pass to the responses analysis the 3 most influential variables

- Variables
  - Coolant inlet temperature
  - All 6 circuits – 10C to 40C
Glove Box Door – Running the Analysis

- 3 steps
  - Base analysis
    - Run first and check results
  - Variable influences
    - 8 analyses
  - Variable responses
    - 15 analyses
- Total runs 24

First analysis ...

Analysis type = INFLUENCES
Number of variables = 6
Number of qualities = 3

Variable information ...

Cavity Inlet 2: Coolant inlet temperature
Range = [ 283.15 : 313.15 ]

Cavity Inlet 3: Coolant inlet temperature
Range = [ 283.15 : 313.15 ]

Cavity Inlet 1: Coolant inlet temperature
Range = [ 283.15 : 313.15 ]

Core Inlet 2: Coolant inlet temperature
Range = [ 283.15 : 313.15 ]

Core Inlet 3: Coolant inlet temperature
Range = [ 283.15 : 313.15 ]

Core Inlet 1: Coolant inlet temperature
Range = [ 283.15 : 313.15 ]
Breaking the Sim Barrier

- **Autodesk Moldflow Insight Option**
  - One license – Solves at one time
  - 1 DOE Analysis
  - 2 Cool Analyses
  - Total analysis time
    - 1 hours 37 min

- **Autodesk Moldflow Insight WS Option (In the Cloud)**
  - Solves analyses simultaneously for DOE
  - Total analysis time
    - 34 minutes
  - Saving
    - 1 hours 7 minutes
Glove Box Door – DOE Log Results

- The most critical
  - Core Inlet 2
  - Cavity Inlet 1
  - Core Inlet 3

- These are the variables passed to the response analysis

<table>
<thead>
<tr>
<th>Influences on quality #1, Mold surface temperature</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculate</td>
<td></td>
</tr>
<tr>
<td>12.64% Cavity Inlet 2: Coolant inlet temperature</td>
<td></td>
</tr>
<tr>
<td>7.06% Cavity Inlet 3: Coolant inlet temperature</td>
<td></td>
</tr>
<tr>
<td>18.11% Cavity Inlet 1: Coolant inlet temperature</td>
<td></td>
</tr>
<tr>
<td>34.41% Core Inlet 2: Coolant inlet temperature</td>
<td></td>
</tr>
<tr>
<td>16.13% Core Inlet 3: Coolant inlet temperature</td>
<td></td>
</tr>
<tr>
<td>11.64% Core Inlet 1: Coolant inlet temperature</td>
<td></td>
</tr>
</tbody>
</table>
Glove Box Door – DOE Log Results

- Coolant temperature of other lines at 25°C

Optimization of variables for each quality ...

Optimum on quality #1, Mold surface temperature
Calculate = Standard deviation
Range = [ 4.58746 : 9.19673 ] C
Minimum value = 4.58746 C
  with 18.6284 C as Core Inlet 2: Coolant inlet temperature
  with 29.3862 C as Cavity Inlet 1: Coolant inlet temperature
  with 19.2835 C as Core Inlet 3: Coolant inlet temperature

- Not practical to have 4 different coolant temperatures
Glove Box Door – Mold Surface Temperature

- The variation in mold temperature rather sensitive to all coolant temperature changes
Glove Box Door – Mold Surface Temperature - Comparison

- Compared mold surface temperatures with coolant temperature
  - Cavity 1 at 29C
  - Core 2 and 3 at 19C
  - All others at 25C
Glove Box Door – Mold Surface Temperature - Comparison

- Modest but noticeable change in the mold surface temperature
- Probably not worth having 3 coolant temperature controllers at the machine
Conclusions – Glove Box Door – Cooling

- The DOE results are better than the original
- The results are not practical
- DOE suggests a starting point requiring only two temperature controllers
- The cloud reduced the solve time by a factor of 3.0!
Case Study #3

Solving Shrink and Warp Related Problems
Glove Box Door – Shrinkage and Warpage

- Objective
  - Achieve critical dimensions
  - Minimize the warpage

- Experiment
  - Modify processing variables
  - Quality based on
    - Injection pressure
    - Sink mark depth
    - 2 critical dimensions
    - 6 warpage measures

- Interpret results
  - To minimize warpage
  - Achieve acceptable warpage
**Glove Box Door – Experiment Setup**

- **Experiment – Variable Influences then Responses**
  - Pass to the responses analysis the 3 most influential variables

<table>
<thead>
<tr>
<th>Variables</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt temperature</td>
<td>225 – 265 [C]</td>
</tr>
<tr>
<td>Inject-Pack-Cool time</td>
<td>25 – 55 [s]</td>
</tr>
<tr>
<td>Injection time</td>
<td>0.5 – 4.5 [s]</td>
</tr>
<tr>
<td>Pack Time (duration)</td>
<td>3 – 15 [s]</td>
</tr>
<tr>
<td>Pack Pressure</td>
<td>45 – 125 [MPa]</td>
</tr>
<tr>
<td>3 – Core circuits</td>
<td>10 – 40 [C]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quality Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection pressure</td>
</tr>
<tr>
<td>X-direction +Y side</td>
</tr>
<tr>
<td>Edge flatness</td>
</tr>
<tr>
<td>Bottom flatness</td>
</tr>
<tr>
<td>Bottom flatness DS</td>
</tr>
</tbody>
</table>
Glove Box Door – Running the Analysis

- 3 steps
  - Base analysis
    - Run first and check results
    - Create 3 node lists and 2 critical dimensions
  - Variable influences
    - 16 analyses
  - Variable responses
    - 25 analyses
  - Total runs 42

First analysis ...

<table>
<thead>
<tr>
<th>Analysis type</th>
<th>INFLUENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of variables</td>
<td>8</td>
</tr>
<tr>
<td>Number of qualities</td>
<td>11</td>
</tr>
</tbody>
</table>

Variable information ...

<table>
<thead>
<tr>
<th>Injection time</th>
<th>[0.5 : 4.5]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt temperature Range</td>
<td>[498.15 : 538.15]</td>
</tr>
<tr>
<td>Core Inlet 2: Coolant inlet temperature Range</td>
<td>[283.15 : 313.15]</td>
</tr>
<tr>
<td>Core Inlet 3: Coolant inlet temperature Range</td>
<td>[283.15 : 313.15]</td>
</tr>
<tr>
<td>Duration Range</td>
<td>based on multiple values, simplified to [-1, +1]</td>
</tr>
<tr>
<td>Injection + packing + cooling time Range</td>
<td>[25 : 55]</td>
</tr>
<tr>
<td>Packing pressure Range</td>
<td>based on multiple values, simplified to [-1, +1]</td>
</tr>
<tr>
<td>Core Inlet 1: Coolant inlet temperature Range</td>
<td>[283.15 : 313.15]</td>
</tr>
</tbody>
</table>
Breaking the Sim Barrier

- Autodesk Moldflow Insight Option
  - One license – Solves at one time
  - 1 DOE Analysis
  - 2 Analysis of any type
  - Total analysis time
    - 7 hours 40 min

- Autodesk Moldflow Insight WS Option (In the Cloud)
  - Solves analyses simultaneously for DOE
  - Total analysis time
    - 2 hours 26 minutes
  - Saving
    - 5 hours 14 minutes
Glove Box Door – DOE Log Results

- Wow!
- Can you say information overload?
- There are 11 quality criteria
- How do I look at all this information?
Glove Box Door – DOE Log Results

- Only 3 quality criteria are critical
  - Edge flatness
  - Bottom edge flatness
  - Bottom flatness all effects

- The rest are there so we can look at other parameters once we see what is best for warpage
Glove Box Door – DOE Log Results

- Top 4 most influential variables passed to the variable response analysis
- Compare the conditions that produce the highest quality
- In order of influence
  - Packing pressure
  - Injection time
  - Core inlet 3 temperature
  - Pack time (duration)

Second analysis ...
Analysis type = RESPONSES
Number of variables = 4
Number of qualities = 11

Variable information ...
  - Packing pressure
    Range = based on multiple values, simplified to [-1, +1]
  - Injection time
    Range = [ 0.5 : 4.5 ]
  - Core Inlet 3: Coolant inlet temperature
    Range = [ 283.15 : 313.15 ]
  - Duration
    Range = based on multiple values, simplified to [-1, +1]

Create Design of Experiments ...
Design of Experiments = FACE CENTERED CUBIC
Number of experiments = 25
Glove Box Door – Response Surfaces – Edge Flatness

- Lowest Standard Deviation
  - 125 MPa pack pressure
  - 4.5 s injection time
  - 10 C Core inlet 3 temperature
  - 4.0 s packing time
Glove Box Door – Response Surfaces – Bottom Edge Flatness

- Lowest Standard Deviation
  - 125 MPa pack pressure
  - 2.1s injection time
  - 10C Core inlet 3 temperature
  - 12.6 s packing time
Glove Box Door – Response Surfaces – Bottom Flatness

- Lowest Standard Deviation
  - 125 MPa pack pressure
  - 3.7 s injection time
  - 16 C Core inlet 3 temperature
  - 12.6 s packing time
Each shown at its optimum conditions
Glove Box Door – Response Surfaces – Compare

- Each shown at the same conditions
Glove Box Door – Deflection – Edge

- Lowest edge deflection 1.25 mm
  - 125 MPa pack pressure
  - 4.5 s injection time
  - 10°C Core inlet 3 temperature
  - 11.2 s packing time

- The lowest deflection is not necessarily at the same conditions as the lowest standard deviation
Glove Box Door – Deflection – Bottom

- Lowest edge deflection 1.91 mm
  - 125 MPa pack pressure
  - 2.7 s injection time
  - 34 C Core inlet 3 temperature
  - 13.6 s packing time
Glove Box Door – Deflection – Edge

- Edge deflection 1.91 mm at conditions that have lowest bottom warpage
Glove Box Door – Shrinkage

- Response curve at conditions with best warpage
- NOT within tolerance
  - Conditions that produce lower warpage
Glove Box Door – Shrinkage

- Response curve at the conditions that have the best warpage
- Within tolerance
  - Conditions that produce lower warpage
Conclusions – Glove Box Door – Shrink and Warp Issues

- **Edge warpage**
  - Minimum 1.25 mm
  - 1.91 mm at conditions that were best for the bottom

- **Bottom warpage**
  - Minimum 1.91 mm

- **Shrinkage**
  - Only one dimension within tolerance
    - With conditions of best warp

- The cloud reduced the solve time by a factor of **3.2**
Case Study #4

Studying an assembly problem
Automotive Console Side Panel

- **Objective**
  - Minimize Installation problems
    - Caused by part distortion
- **Experiment**
  - Modify processing variables
  - Quality based on
    - 2 primary warpage measures
    - 2 secondary warpage measures
    - 3 filling parameters
      - Low weighting
- **Interpret results**
  - See if a change in processing will reduce the warpage
Side Panel – Experiment Setup

- Experiment – Variable Influences then Responses
  - Pass to the responses analysis the 4 most influential variables

<table>
<thead>
<tr>
<th>Variables</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt temperature</td>
<td>400 – 480 [F]</td>
</tr>
<tr>
<td>Injection time</td>
<td>1.0 – 3.0 [s]</td>
</tr>
<tr>
<td>V/P switchover</td>
<td>96 – 100 [%]</td>
</tr>
<tr>
<td>Pack Time (duration)</td>
<td>3 – 33 [s]</td>
</tr>
<tr>
<td>Pack Pressure</td>
<td>3000 – 10000 [psi]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quality Criteria</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Finger Nodes (10)</td>
<td>Edge Nodes (10)</td>
</tr>
<tr>
<td>Deflection all Z-Component (5)</td>
<td>Deflection all effects (2)</td>
</tr>
<tr>
<td>Volumetric shrinkage at ejection (1)</td>
<td>Injection pressure (1)</td>
</tr>
<tr>
<td>Clamp force (1)</td>
<td></td>
</tr>
</tbody>
</table>
Side Panel – Running the Analysis

- 3 steps
  - Base analysis
    - Current conditions run in production
  - Variable influences
    - 8 analyses
  - Variable responses
    - 25 analyses
- Total runs 34

First analysis ...
Analysis type = INFLUENCES
Number of variables = 5
Number of qualities = 7

Variable information ...

- Injection time
  - Range = [ 1 : 3 ]

- Melt temperature
  - Range = [ 477.601 : 522.039 ]

- U/P switch-over by % volume filled
  - Range = [ 96 : 100 ]

- Duration
  - Range = based on multiple values, simplified to [-1, +1]

- Packing pressure
  - Range = based on multiple values, simplified to [-1, +1]
Breaking the Sim Barrier

- Autodesk Moldflow Insight  Option
  - One license – Solves at one time
    - 1 DOE Analysis
    - 2 Analysis of any type
  - Total analysis time
    - 8 hours 2 min

- Autodesk Moldflow Insight  WS Option (In the Cloud)
  - Solves analyses simultaneously for DOE
  - Total analysis time
    - 6 hours 0 minutes
  - Saving
    - 2 hours 2 minutes
The most critical
- Pack time (Duration)
- Pack pressure
- Injection time
- Melt temperature

Analysis type = RESPONSES
Number of variables = 4
Number of qualities = 7

Variable information ...

Duration
Range = based on multiple values, simplified to [-1, +1]

Packing pressure
Range = based on multiple values, simplified to [-1, +1]

Injection time
Range = [1 : 3]

Melt temperature
Range = [477.601 : 522.039]
Side Panel – Critical Warpage Locations

- Fingers
- Leading edge
Side Panel– Finger Nodes

- Most critical for assembly
- Highly non-linear regarding pack time
- Some influence with pack pressure
Side Panel– Edge Nodes

- Most critical assembled appearance
- Comparable results to Finger nodes
- Fix one you fix both
Side Panel – Deflection
Conclusions – Automotive Console Side Panel

- Assembly problem can be fixed by processing
- Most influential variable
  - Pack time
- Other variables make a noticeable difference
  - Pack pressure
  - Injection time
  - Melt temperature
- The cloud reduced the solve time by a factor of 1.4
Conclusions:

- 5 step sequence

  - Run Initial Analysis
  - Design Experiment
  - Determine Objectives
  - Run DOE Analysis
  - Interpret results

- DOE allows you to
  - Gather more information at the same or lower costs
  - Understand the sensitivity of results to variables
  - Identify the influence of a variable on a desired result
  - Identify optimum variable values
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