KeepLean

Plastic Injection Molding Process Simulator

Complete User Tutorial — DOE · PID Control · Cycle Animation · Defect Tracking

PA6-GF25 · Automotive
KEEPLEAN v4

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📋 Table of Contents

1. Introduction

What is the Injection Molding Simulator?

The **KEEPLEAN Injection Molding Simulator** is an interactive tool designed to teach **Design of Experiments (DOE)**, **PID Control** and **process variability** concepts through the real-world context of plastic injection molding of automotive parts.

By adjusting process parameters (temperature, pressure, injection speed, mold temperature) and PID controller tuning, users observe how different settings affect part quality — weight, flatness — and the appearance of manufacturing defects.

🎯 **Learning Objectives:**

- Understand how process parameters influence part quality (weight & flatness)
- Learn the role of PID controllers in process stability
- Discover the effect of injection speed profiles on defect generation
- Identify main effects and interactions between factors (DOE mindset)
- Connect process settings to real manufacturing defects
- Apply statistical thinking to experimental results

Simulator Capabilities

Feature	Description

4 Automotive Parts	NOx Sensor Housing, Intake Manifold Cover, EGR Valve Housing, Fuel Pump Flange
3 PID Controllers	Barrel Temperature · Injection Pressure · Mold Temperature — each fully tunable
3-Stage Speed Profile	S1 Fill · S2 Transition · S3 Pack/Hold — independent control
Cycle Animation	6-phase realistic injection cycle with SVG animation
Defect Tracking	9 defect types tracked cumulatively across runs
Run History	Full results table with all parameters and measured outputs
Export	Excel (.xlsx) data export for statistical analysis

The DOE Connection:
This simulator is ideal for teaching **full factorial and fractional factorial designs** where multiple factors (A=Temperature, B=Pressure, C=Speed, D=Mold Temp) are varied simultaneously to study their effects on quality outputs.

2. Quick Start (90 Seconds)

✨ Follow these steps to run your first experiment:

1 Select a Part

Click one of the 4 part cards at the top. Start with **NOx Sensor Housing** (default). The specs panel updates automatically.

2 Set the Barrel Temperature Setpoint

In the **Barrel Temperature** PID card, drag the Setpoint slider. Try **260°C**. Adjust Kp / Ki / Kd sliders — leave at default for now.

3 Set the Injection Pressure Setpoint

In the **Injection Pressure** PID card, set Setpoint to **1200 bar**.

4 Configure Injection Speed Stages

In the Speed section, try: S1 = **85 mm/s** · S2 = **50 mm/s** · S3 = **8 mm/s**

5 Set the Mold Temperature Setpoint

In the **Mold Temperature** PID card, set Setpoint to **65°C**.

6 Click ▶ LAUNCH RUN

The 6-phase animation starts. Watch the mold close, inject, hold, cool, open and eject the part.

7 Check Your Results

After the cycle: the PV (Process Values) update · Weight and Flatness appear in the table · Defect cards update.

Expected Results (optimal settings):
Weight: ~47–49 g | Flatness: < 0.20 mm | Status: ✅ CONFORM
Results vary slightly due to realistic process noise — this is intentional and reflects real manufacturing variability.

3. Interface Overview

Layout — Top to Bottom

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┌──────────────────────────────────────────────────────────────────────┐
│  🌐 KEEPLEAN HEADER                                                  │
├──────────────────────────────────────────────────────────────────────┤
│  🔲 PART SELECTOR (4 cards: NOx Housing · Intake · EGR · Flange)    │
├──────────────────────────────────────────────────────────────────────┤
│  📋 SPEC PANEL — Technical specs for selected part                   │
├──────────────────────────────────────────────────────────────────────┤
│  🎯 OBJECTIVE BANNER — Weight target · Flatness target (editable)    │
├──────────────────────────────────────────────────────────────────────┤
│  🎛 PID SECTION                                                     │
│  ┌──────────────┐  ┌──────────────┐  ┌──────────────┐               │
│  │ 🌡 Barrel    │  │ 💧 Pressure  │  │ ❄ Mold Temp  │              │
│  │  Temp (A)    │  │     (B)      │  │     (D)      │               │
│  │  SP slider   │  │  SP slider   │  │  SP slider   │               │
│  │  Kp Ki Kd    │  │  Kp Ki Kd    │  │  Kp Ki Kd    │               │
│  │  Oscillograph│  │  Oscillograph│  │  Oscillograph│               │
│  └──────────────┘  └──────────────┘  └──────────────┘               │
├──────────────────────────────────────────────────────────────────────┤
│  💨 SPEED SECTION — S1 Fill · S2 Transition · S3 Pack/Hold          │
├──────────────────────────────────────────────────────────────────────┤
│  🎬 ANIMATION SECTION                                                │
│  ▶ LAUNCH RUN  ↺ RESET                                              │
│  [Phase bar: 🔒→💉→⏸→❄→🔓→⬇]                                   │
│  [SVG Animation: Barrel · Mold · Screw · Melt · Cooling]            │
├──────────────────────────────────────────────────────────────────────┤
│  📊 RESULTS SECTION                                                  │
│  Defect Tracker (9 cards) + Run Results Table + Export               │
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```

Key Display Elements

Element	Location	Purpose
Part Selector	Top	Switch between 4 automotive parts — resets all results
Spec Panel	Below part cards	Shows dimensions, material, weight & flatness specs
Objective Banner	Below spec panel	Editable weight target and flatness max — customize your specs
PID Cards	Middle section	Set process setpoints and tune controller parameters
Oscillographs	Bottom of each PID card	Visual representation of process stability / noise level
Speed Stages	Below PID section	Set 3-phase injection speed profile
Phase Bar	Animation section	Shows current cycle phase highlighted in real time
SVG Animation	Animation section	Live visual of injection unit and mold during cycle
PV Displays	PID cards (after run)	Shows actual Process Value measured at end of cycle
Defect Grid	Results section	9 defect cards with risk level and cumulative count

Run Table	Results section	Full run history with all parameters and outputs

4. PID Controllers — The 3 Process Regulators

Each PID controller manages one critical process variable. The quality of your PID tuning directly affects the **process variability** — and therefore the scatter of your results.

🌡 Barrel Temp (A)

Range: 250–270°C
Affects: polymer melt viscosity, weight

💧 Pressure (B)

Range: 1000–1400 bar
Affects: cavity fill, flash, flatness

❄ Mold Temp (D)

Range: 50–80°C
Affects: cooling, warpage, surface

Setpoint Slider

Each PID card has a **Setpoint (SP) slider** at the top. This is the *target value* you want the process to reach and hold. The slider range corresponds to the experimental window for that variable.

> **SP vs PV — Key Concept:**
> **SP (Setpoint)** = the value you command (what you want).
> **PV (Process Value)** = what actually happens after the cycle.
> The gap between SP and PV — and the variability of PV across runs — depends on how well the PID is tuned.

Kp, Ki, Kd Parameters

Below the setpoint slider, three sliders control the PID tuning:

Parameter	Full Name	Role in the Controller
Kp	Proportional Gain	Reacts to current error. Too low = slow response. Too high = oscillation.
Ki	Integral Gain	Eliminates steady-state error over time. Too high = instability.
Kd	Derivative Gain	Anticipates future error. Reduces overshoot. Too high = noise amplification.

> ⚠ **Effect of Poor PID Tuning:**
> When Kp, Ki, Kd are far from optimal values, the simulator introduces **higher process noise**. This means your PV will deviate more from your SP run-to-run, increasing variability in Weight and Flatness results — just as in real manufacturing.

The Oscillograph

Each PID card displays a real-time **oscillograph** — a signal trace showing the simulated PV fluctuation. A **flat, stable line near center** = well-tuned controller. A **noisy, oscillating signal** = poor tuning and high process variability.

> 💡 **Exploration Idea:**
> Try setting Kp very high (e.g., 5.0) and Ki very high (e.g., 2.0) for the Pressure controller. Watch the oscillograph. Then run several cycles and observe the scatter in your results. Compare with well-tuned settings.

5. Injection Speed — 3-Stage Profile

Unlike a simple single speed, real injection machines use a **multi-stage speed profile** to optimize part quality at each phase of cavity filling. The simulator implements 3 stages:

S1 — Initial Fill 0 → 80% volume
Range: 80–100 mm/s
High speed to fill main cavity quickly

S2 — Transition 80 → 95% volume
Range: 40–60 mm/s
Speed reduction near end of fill to avoid defects

S3 — Pack / Hold 95–100% + pack
Range: 5–30 mm/s
Very slow speed to pack material and compensate shrinkage

Effective Speed (Weighted Average)

The simulator calculates an **Effective Speed (C)** as a weighted average of the 3 stages, reflecting the dominant influence of each phase on the overall process. This is the value used in the DOE model.

Stage	Volume Range	Slider Range	Typical Effect
S1 — Fill	0 → 80%	80–100 mm/s	Too fast → Jetting, Silver Streak. Too slow → Short Shot.
S2 — Transition	80 → 95%	40–60 mm/s	Too fast → Flash, Weld Lines. Controls V/P switchover quality.
S3 — Pack	95–100%	5–30 mm/s	Too fast → Sink Marks, Sticking. Too slow → incomplete pack.

Fill Bars: Each stage has a small fill bar showing its relative position within range. The overall **Effective Speed** summary box (right side) gives the weighted average at a glance.

💡 **Key principle to explore:**
Each stage interacts with pressure and temperature. Changing S1 alone while keeping S2 and S3 fixed will produce a different defect signature than changing S3 alone. This is the essence of **interaction effects** in DOE.

6. Injection Cycle Animation — 6 Phases

When you click ▶ **LAUNCH RUN**, the simulator runs a complete injection cycle, animated in 6 sequential phases. Each phase is highlighted in the phase bar and shown in the SVG animation.

🔒 Mold Close	💉 Injection	⏸ Hold Press.	❄ Cooling	🔓 Mold Open	⬇ Ejection
1.5s	1.0s	1.5s	2.5s	1.0s	0.8s

Phase	What Happens	What to Watch
🔒 **Mold Close**	Mobile platen moves to close mold. Clamping force applied.	Mold halves come together in animation
💉 **Injection**	Screw advances, pushing molten plastic through nozzle into mold cavity at set speed & pressure.	Screw moves forward · Melt flow visible · Cavity starts filling
⏸ **Hold Pressure**	Screw maintains pressure to compensate for shrinkage as material begins to cool. Critical for part weight.	Pulsing indicator at nozzle · Partial fill visible
❄ **Cooling**	Mold cooling channels remove heat. Part solidifies. Screw retracts to prepare next shot.	Animated cooling lines · Screw retracts · Part color changes
🔓 **Mold Open**	Clamping force released, mobile platen retracts. Part remains on core side.	Mold halves separate
⬇ **Ejection**	Ejector pins push part out of mold. Part drops. Weight and conformity displayed.	Part appears below mold · Weight shown with ✓ or ✗

Control Buttons

Button	Function	Notes
▶ **LAUNCH RUN**	Starts one complete injection cycle	Disabled during animation. Results added to table after cycle.
↺ **RESET**	Clears all run results and resets the animation	Does NOT change your parameter settings

⚠ **During Animation:**
Buttons are disabled and the page scroll is locked while the cycle runs. This is intentional — do not try to scroll or click buttons during the animation. Everything resumes automatically after ejection.

7. Understanding Results

Quality Outputs — What is Measured?

After each cycle, two quality measurements are calculated:

Output	Unit	What it Represents	Conformity
Weight	grams (g)	Mass of the ejected part. Reflects how completely the cavity was filled and packed. Influenced by pressure, temperature, speed.	Must be within Target ± Tolerance (e.g., 48 ± 1 g)
Flatness	mm	Geometric deviation of the part's reference surface. Reflects warpage and residual stress from cooling and pressure gradients.	Must be below maximum (e.g., < 0.20 mm)

PV vs SP — After the Run

At the end of each cycle, the PID cards update their **PV (Process Value)** display, showing the actual value achieved during the run. Compare PV to SP to understand control performance:

- **PV ≈ SP** → Good control, low noise
- **PV far from SP** → Poor control, high variability
- **PV varies a lot run-to-run** → PID needs better tuning

The Run Results Table

Every run is logged in the results table with all parameters and outputs:

Column	Content
Run #	Sequential run number
Barrel °C (PV)	Actual barrel temperature achieved · SP shown in parentheses
Press. bar (PV)	Actual injection pressure achieved · SP in parentheses
S1 / S2 / S3 mm/s	Injection speed at each stage (as set)
Mold °C (PV)	Actual mold temperature achieved · SP in parentheses
Weight (g)	Measured part weight — green if within spec, red if out
Flatness (mm)	Measured flatness — green if within spec, red if out

Conformity Rate

The header area shows a running **Conformity Rate (%)** — the percentage of runs producing parts that meet both weight AND flatness specifications. This is your key process performance indicator.

Interpretation Guide:

90–100% → Excellent process — well-tuned settings
60–89% → Moderate — some parameters need adjustment
Below 60% → Poor — significant parameter or PID issues
0% → All parts non-conform — check extreme settings

8. Defect Tracker — 9 Defect Types

The simulator tracks 9 classic injection molding defects, each linked to specific process conditions. Cards show **cumulative count** and **percentage across runs**, with colour-coded risk levels:

Risk Level	Threshold	Card Colour
✅ Low	< 20% of runs	Green border
⚠ Medium	20–50% of runs	Orange border
❌ High	> 50% of runs	Red border + glow

Defect Reference Guide

Stage	Defect	What it Looks Like	Parameter Direction to Watch
S1 Fill	**Short Shot ■**	Incomplete cavity fill — part is missing material	Pressure too low · Speed S1 too slow · Temp too low
	Silver Streak ∿	Silvery streaks on surface — moisture or gas trapped during filling	S1 speed too high · Temperature too high
	Jetting ↝	Worm-like marks from melt jetting across open cavity before wall contact	S1 speed very high · Pressure high · Mold temp low
S2 Trans.	**Weld Line 〰**	Visible line where two melt fronts meet — potential weakness	S2 speed too high · Temperature too low
	Flash ⚡	Thin film of plastic at parting line — overflow outside cavity	Pressure too high · S2 speed too high
	Bubble / Void ○	Internal air pocket or surface blister — gas entrapment	S2 speed too high · Mold temp too low · S3 too slow
S3 Pack	**Sink Mark ⌣**	Surface depression on thick sections — insufficient pack	S3 too fast · Pressure insufficient during hold
	Warpage ⌇	Part bends or twists after ejection — uneven residual stress	Flatness out of spec · Cooling imbalance · Pressure issues
	Sticking ⊡	Part difficult to eject — adheres to mold surface	S3 too fast · Mold temp too low · Pressure too high

⚠ **Important:**
Defects are triggered by **combinations** of parameters — not just one factor. A high S1 speed alone may not cause Jetting, but high S1 + high pressure + low mold temperature together create the right conditions. This is the essence of **interaction effects**.

9. Exporting Data

Export to Excel (.xlsx)

Click the 📥 **Export Excel** button in the results section to download all run data as an Excel file. The file is named automatically with the part name and date:

`KEEPLEAN_NOx-Sensor-Housing_2025-02-28.xlsx`

Column in Export	Content
Run #	Sequential run number
Barrel SP / PV	Setpoint and actual barrel temperature
Press. SP / PV	Setpoint and actual injection pressure
S1 / S2 / S3 mm/s	Injection speed at each stage
Mold SP / PV	Setpoint and actual mold temperature
Weight (g)	Measured part weight
Flatness (mm)	Measured part flatness
OK?	OK or NOK conformity verdict

> 💡 **Use the exported data in:**
> **Minitab:** Factorial plots, Main Effects, Interaction Plots, ANOVA
> **Excel:** Quick charts, pivot tables, basic statistics
> **JMP / R / Python:** Full regression and response surface analysis

10. DOE Applications

Factors and Their Levels

The simulator has **4 main factors** that can be treated as DOE factors:

Factor	Symbol	Low Level (−)	High Level (+)	Units
Barrel Temperature	**A**	250	270	°C
Injection Pressure	**B**	1000	1400	bar
Injection Speed (eff.)	**C**	Low	High	mm/s
Mold Temperature	**D**	50	80	°C

Suggested Experiment Designs

	Runs	

Design	Required	What You Learn
One-Factor-at-a-Time (OFAT)	8–12	Individual effects only — misses interactions
Full Factorial 2^2 (A, B only)	4	Effects of Temp + Pressure + their interaction
Full Factorial 2^3 (A, B, C)	8	3 main effects + 3 two-factor interactions
Full Factorial 2^4 (A, B, C, D)	16	All 4 factors, all interactions
Fractional Factorial 2^{4-1}	8	Efficient screening — half the runs of full 2^4

Response Variables

Run your DOE using **Weight (g)** and **Flatness (mm)** as responses. You can run separate analyses for each or use a multi-response optimization approach.

> **Replication Tip:**
> Run the same factor combination 2–3 times to estimate **pure error** (process noise). The simulator introduces realistic variability that changes run-to-run — just like a real machine. Replicated runs reveal this natural scatter.

> ⚠ **PID Consistency in DOE:**
> When running a designed experiment, keep the **same PID settings** for all runs — or make PID tuning itself a factor to study. Changing Kp, Ki, Kd between runs will introduce uncontrolled variability that confounds your results.

11. Practical Tips & Exploration

Suggested Exploration Exercises

A PID Tuning Impact

Run 6 cycles with Kp=0.5, Ki=0.1 (Pressure). Then reset and run 6 cycles with Kp=1.8, Ki=0.5. Compare the scatter in Weight results. What does this tell you about process capability and Gage R&R?

B Speed Profile Effects

Keep Temperature and Pressure constant. Vary only S1 from 80 to 100 mm/s across 4 runs. Observe which defects appear and how Weight changes.

C Part Comparison

Switch between the 4 parts. Notice how the spec targets change. The same parameter settings that give good results on the NOx Housing may produce different conformity on the Intake Manifold Cover (much larger part).

D Generate NOK Parts Intentionally

Set S3 = 25 mm/s (maximum), Pressure = 1400 bar, Mold Temp = 50°C. Run 4 cycles. Observe which defects consistently appear. This is a "worst case" scenario useful for teaching defect recognition.

E Full Factorial 2^2 Mini-DOE

Using Barrel Temp (A) and Pressure (B) as factors, run the 4 combinations: (Low,Low) · (High,Low) · (Low,High) · (High,High). Export to Excel and calculate main effects manually. Compare what you find.

Common Mistakes to Avoid

Mistake	Consequence	Solution
Changing PID settings between DOE runs	Uncontrolled variability confounds results	Fix PID at start and keep constant
Only running 1 replicate per condition	Cannot estimate process noise	Run 2–3 replicates per factor combination
Changing part mid-experiment	Different model — incompatible data	Select part first, keep constant throughout
Ignoring defect tracker	Miss root causes of non-conformities	Check defect cards after every few runs
Forgetting to export before Reset	All data lost	Export Excel before clicking Reset

Quick Reference Card

Objective	Key Parameters to Adjust
Increase part Weight	↑ Pressure · ↑ Hold time (S3 slower) · ↑ Temperature
Improve Flatness	Balanced cooling · Moderate pressure · Reduce S3 speed
Eliminate Short Shot	↑ Pressure · ↑ S1 speed · ↑ Temperature
Eliminate Flash	↓ Pressure · ↓ S2 speed
Eliminate Jetting	↓ S1 speed · ↑ Mold Temperature
Reduce variability	Improve PID tuning (Kp, Ki, Kd near optimal)
Maximize conformity	Run a DOE — find the sweet spot for all 4 factors

🎓 **The Challenge:**
Finding settings that simultaneously satisfy **both Weight AND Flatness** specs, with **all 3 PID controllers well-tuned**, and **no defects**, is not trivial. This is exactly the multi-response optimization challenge that DOE methodology is designed to solve.