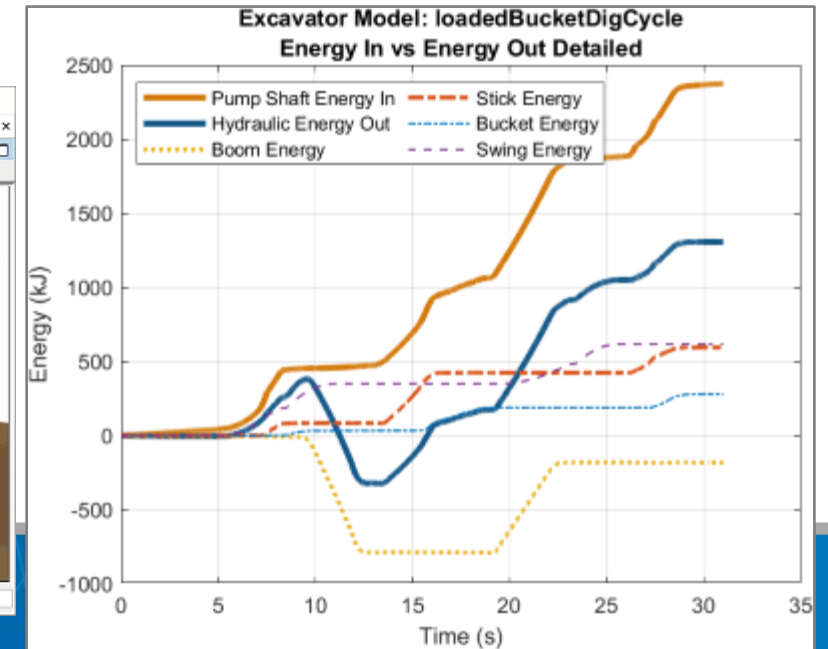
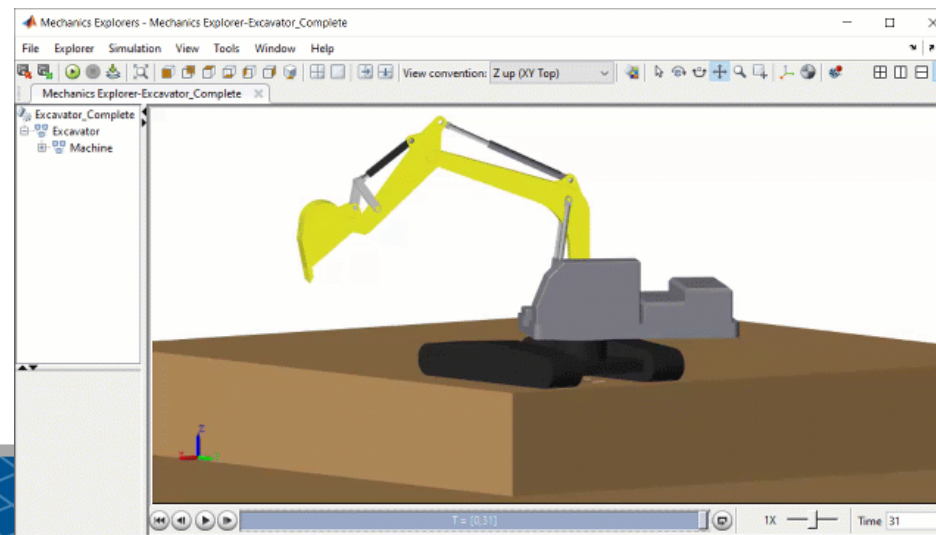
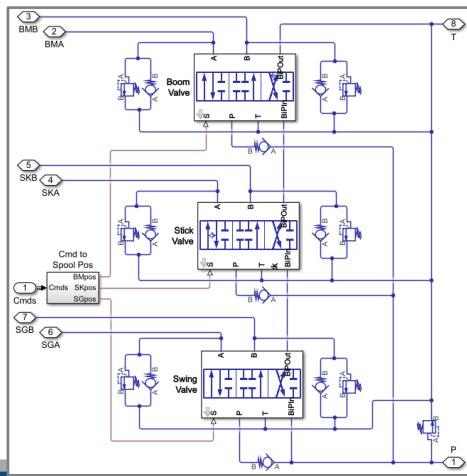


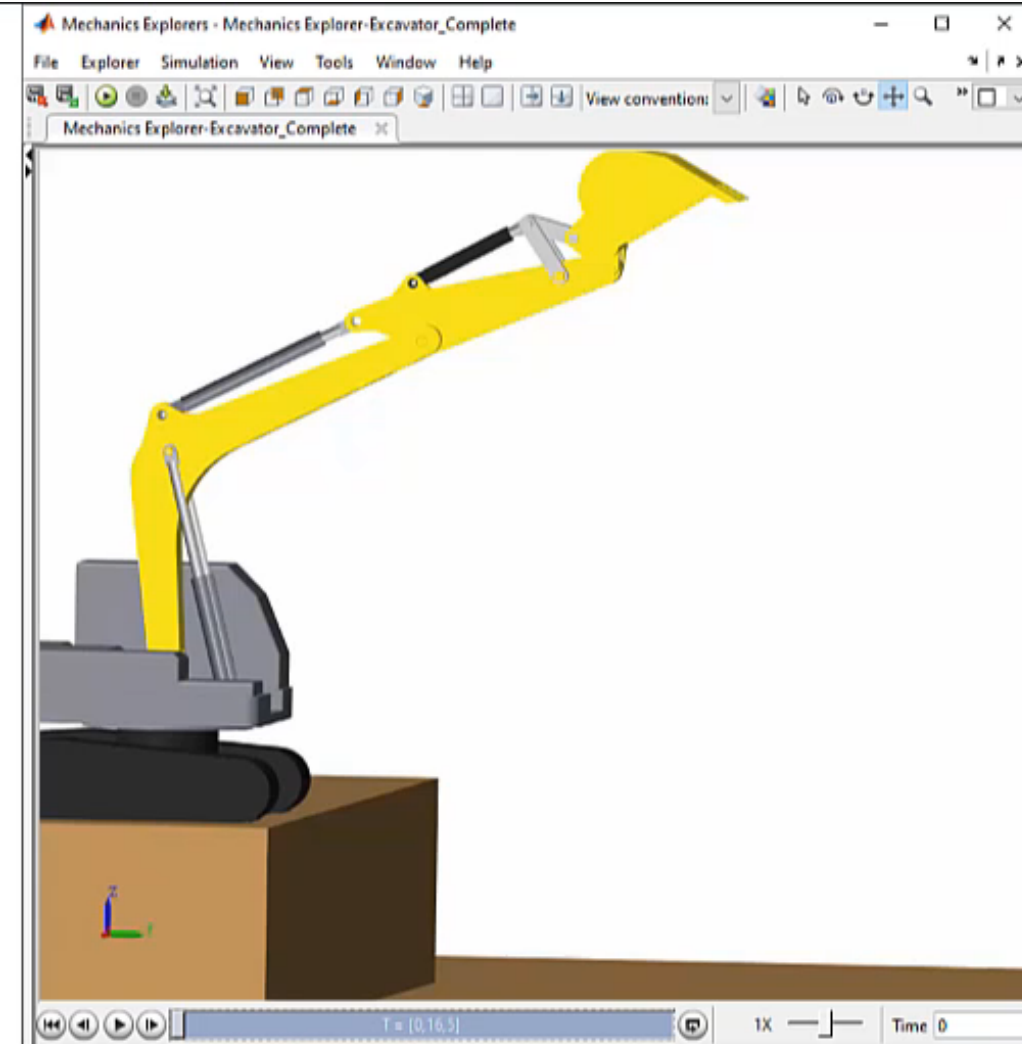
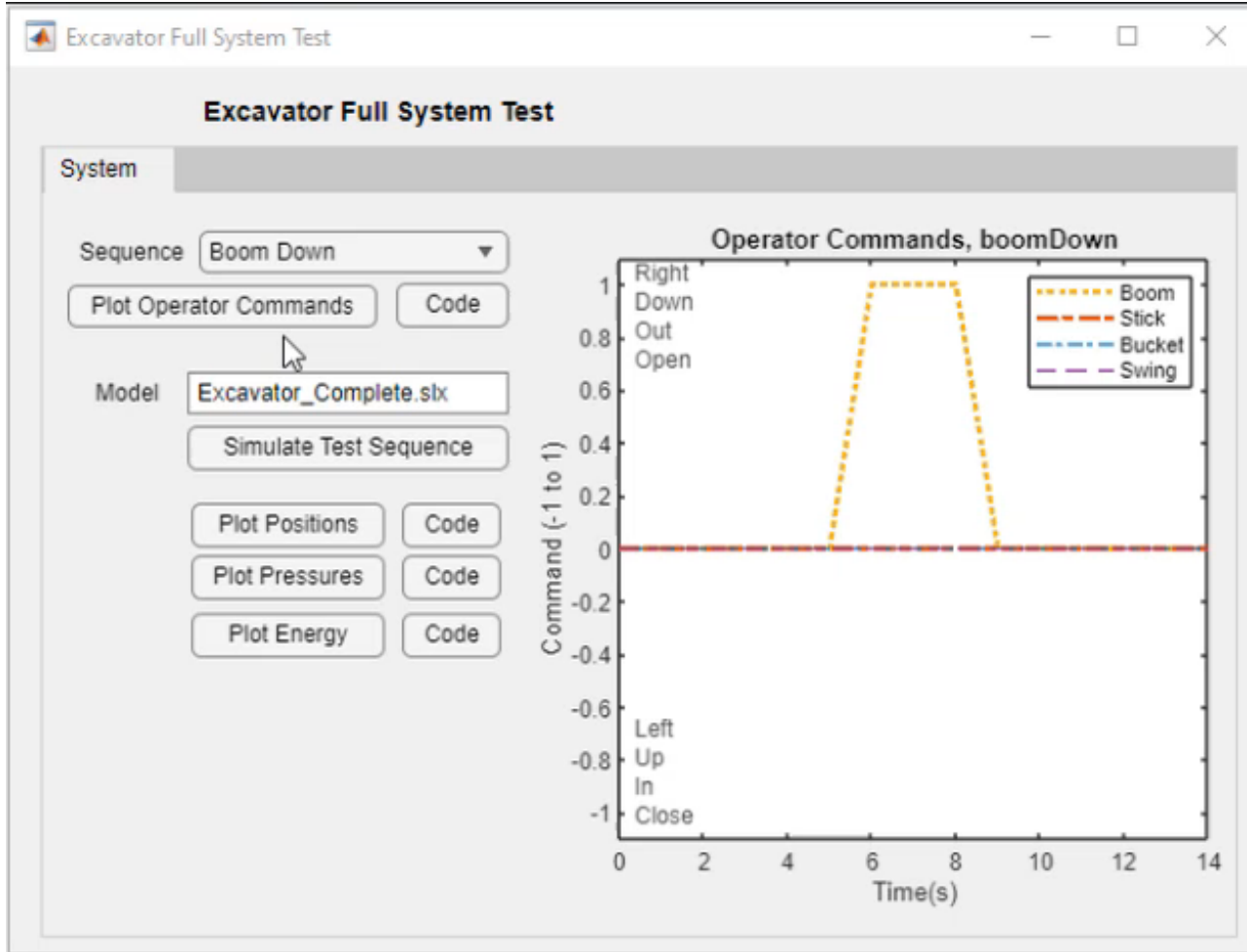
Virtuelle Maschinenentwicklung mit MATLAB und Simulink



Eva Pelster, Application Engineering (epelster@mathworks.com)
04.05.2023

Excavator Model

Test by function or full cycle and review results



Aalto University Works with Industry Partners to Develop Energy-Efficient Designs for Construction Equipment

Challenge

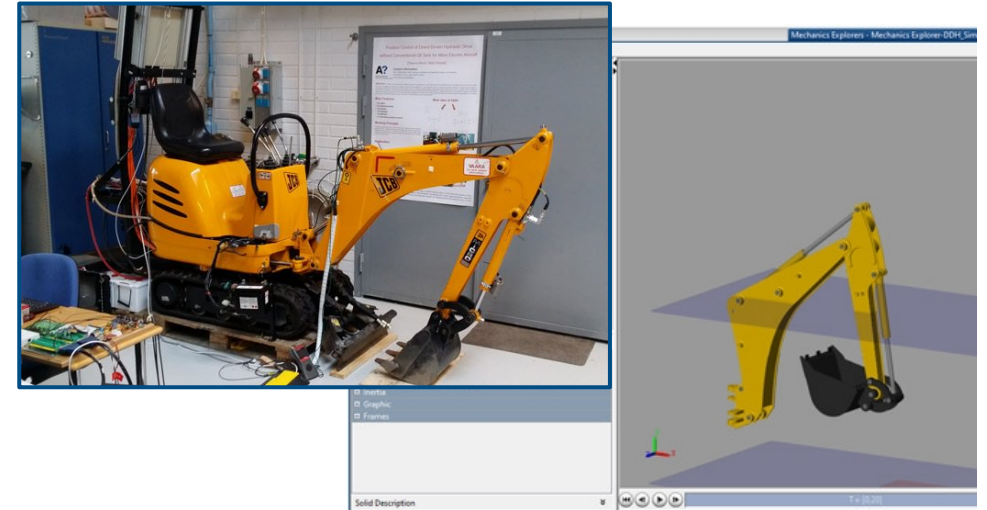
Work with manufacturers to develop more energy-efficient excavators, loaders, and other construction and off-road machinery

Solution

Use MATLAB, Simulink, and Simscape to model and simulate designs that incorporate hybrid technologies and decentralized hydraulic systems

Results

- Energy efficiency doubled
- Industry-academia collaboration established
- In-demand skills developed



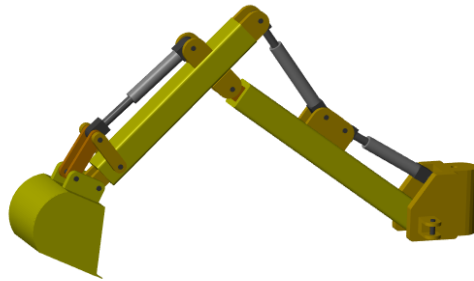
The one-tonne micro excavator modeled by Aalto University and Tampere University researchers in the EL-Zon and EZE projects.

“With MATLAB, Simulink, and Simscape we were able to create and validate designs spanning multiple domains—mechanical, electrical, and hydraulic—that are now being used by our commercial partners to improve energy efficiency on their machines.”

- Tatiana Minav, Aalto University and Tampere University

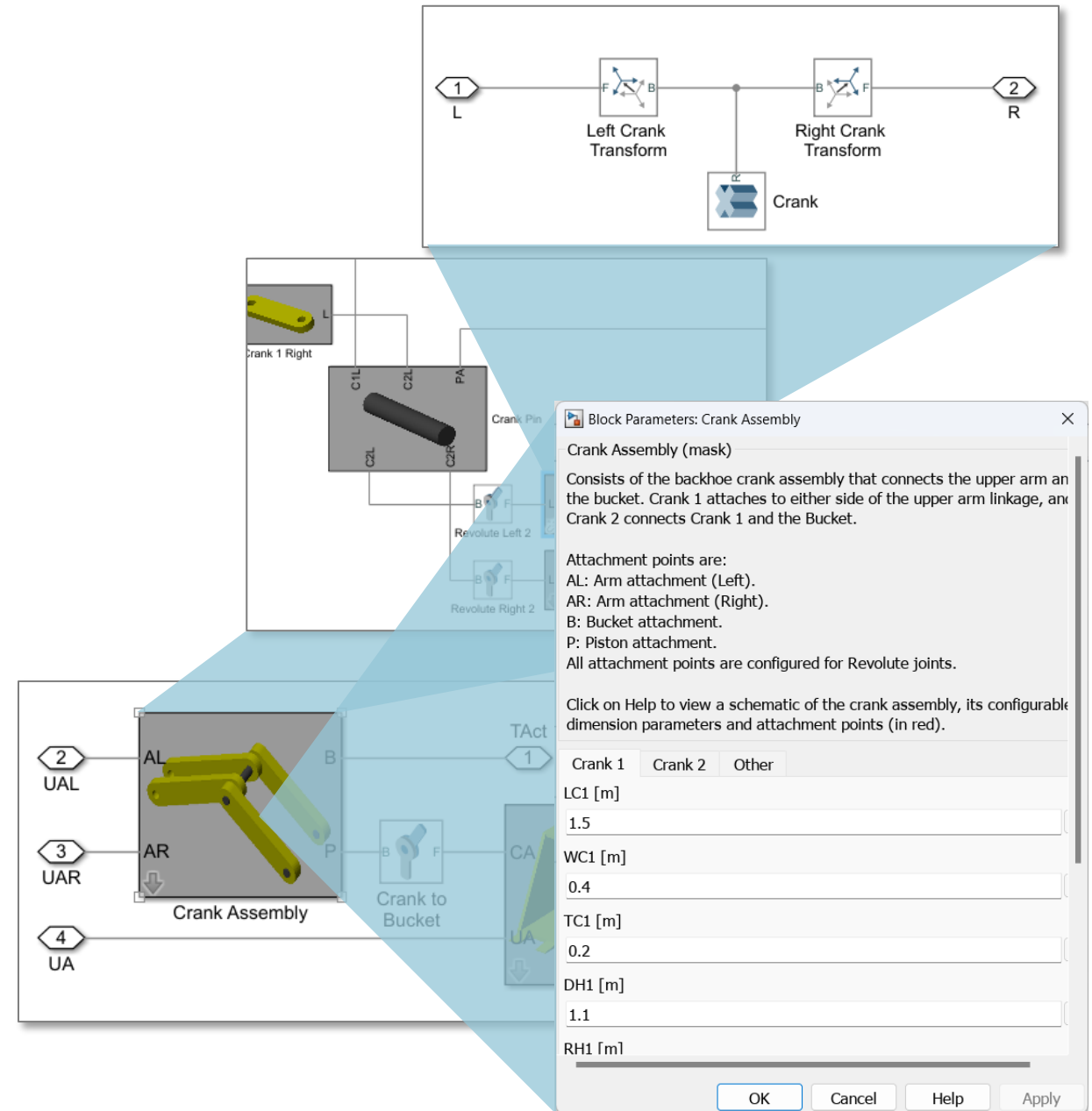
Modeling the Mechanical System

Model:



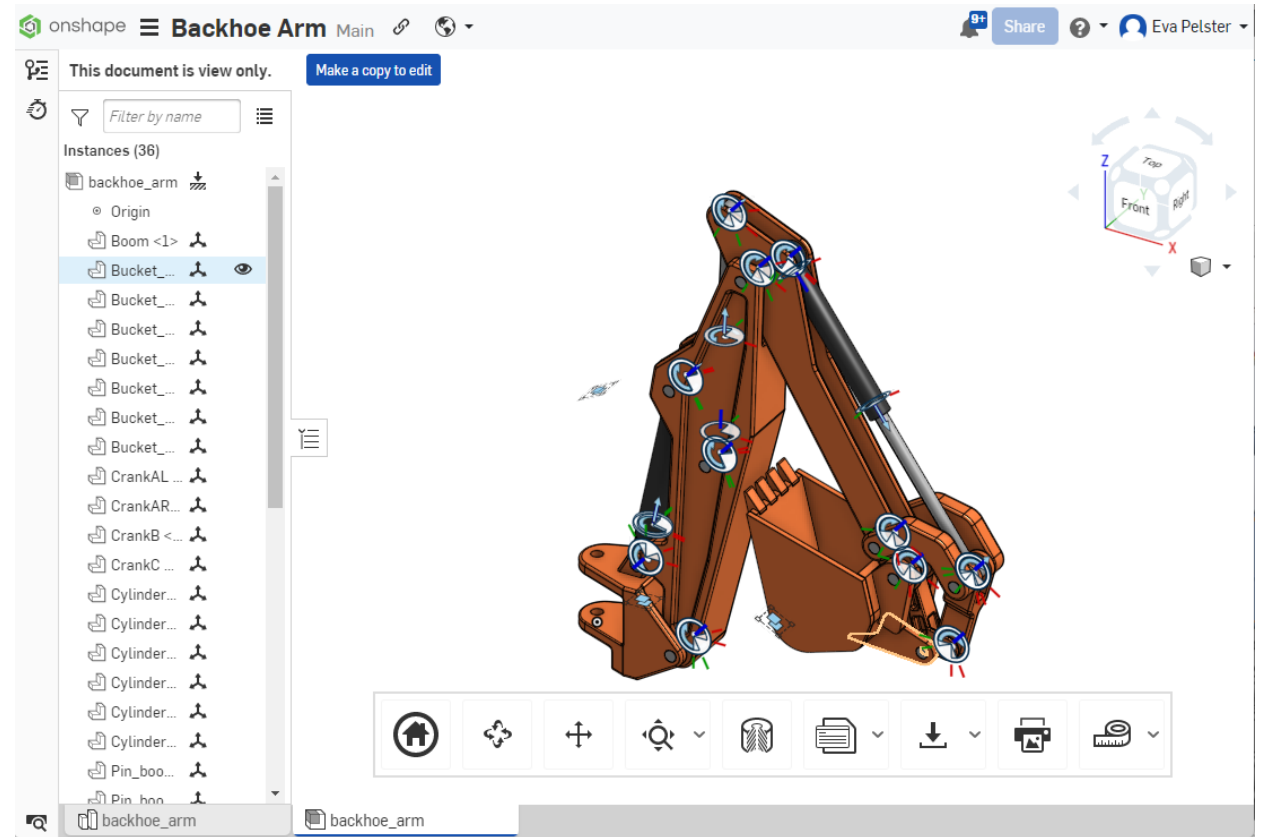
Challenge: Create a (parameterized) mechanical model of the backhoe

Solution: Use components created in [Simscape Multibody](#) to rapidly assemble the model in Simulink.



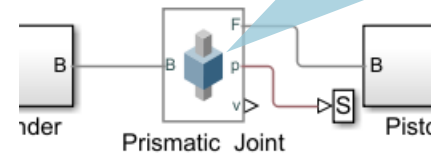
Reusing CAD Data

- Import CAD assemblies
 - Part definitions
 - Converts mate definitions to joints
 - SOLIDWORKS, Inventor, Onshape, and PTC Creo® (Pro/ENGINEER®)
- Import CAD Parts
 - CATIA, NX, SolidEdge, and others
 - STEP files

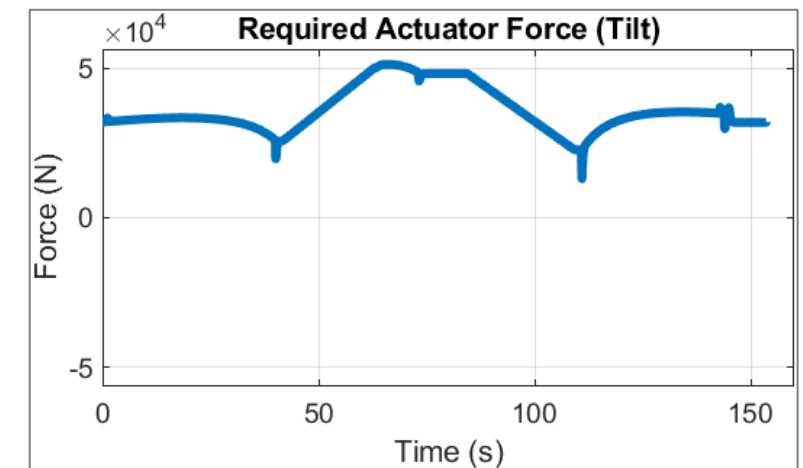
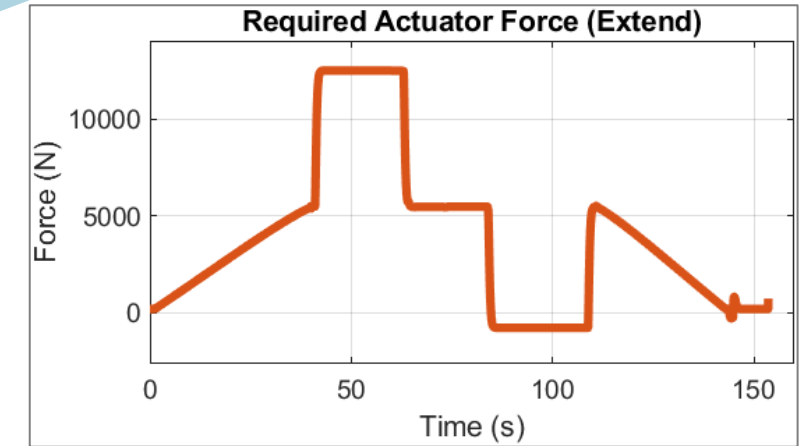


Determine Actuator Requirements

- Define and run a set of tests
 - Maximum payload, speed
 - Worst case friction levels
 - Full range of movement
- Use dynamic simulations to calculate required torque and bearing forces
- If design changes, automatically rerun tests and re-evaluate results



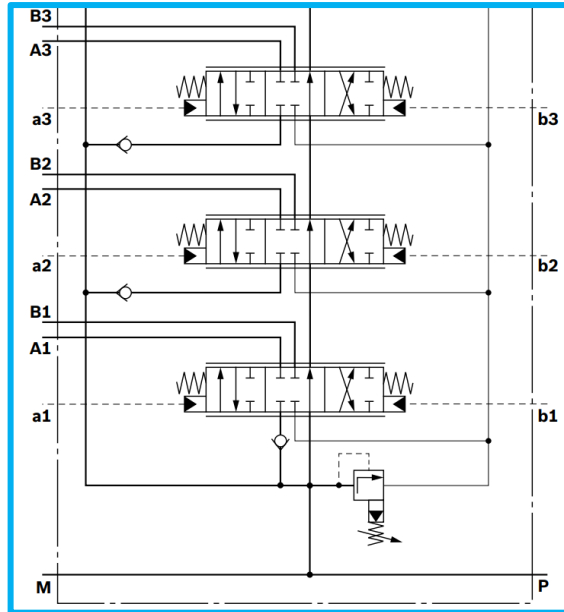
Properties	
Actuation	
Force	Automatically Computed
Motion	Provided by Input



Modeling the Hydraulic Actuation System

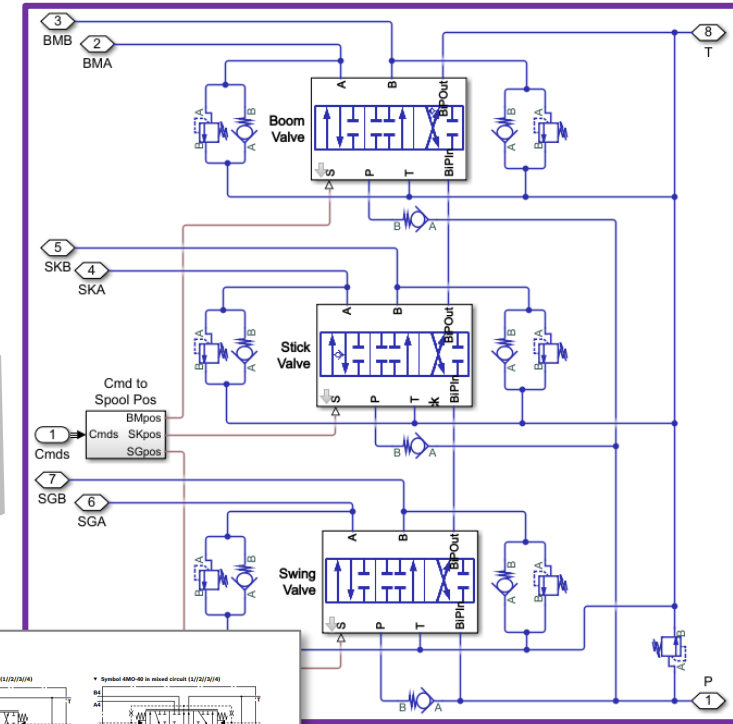
Model:

Schematic

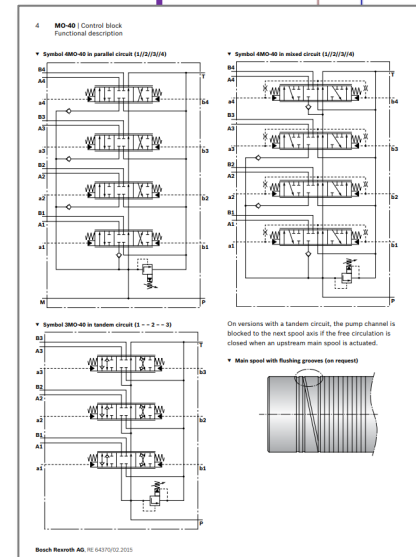


Problem: Translate the hydraulic schematic into a models

Solution: Use [Simscape Fluids](#) blocks and parameterize using data sheets



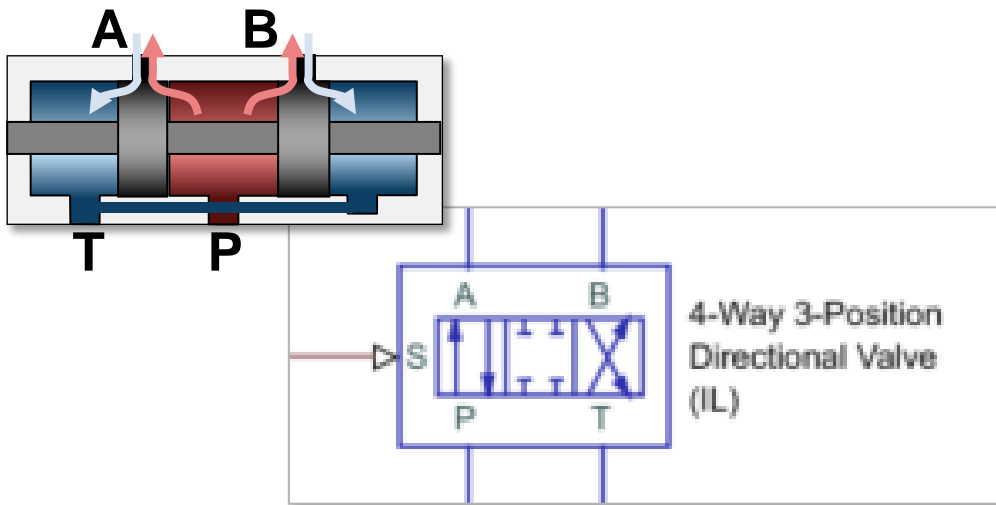
Simscape Model



Data Sheet

Enhancing the Model with Simscape Add-on Libraries

- Advanced components and effects
 - Comprehensive components
 - Parameterization options
 - Physical effects (losses, thermal dependency)



Rack & Pinion

Main Meshing Losses Viscous Losses

Friction model: No meshing losses - Suitable for HIL simulation
 Constant efficiency

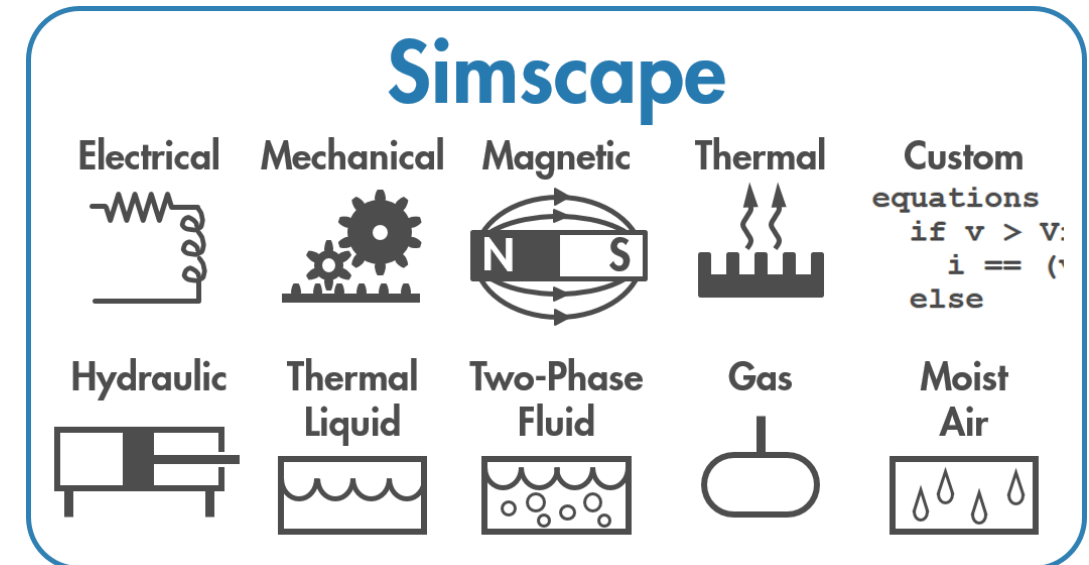
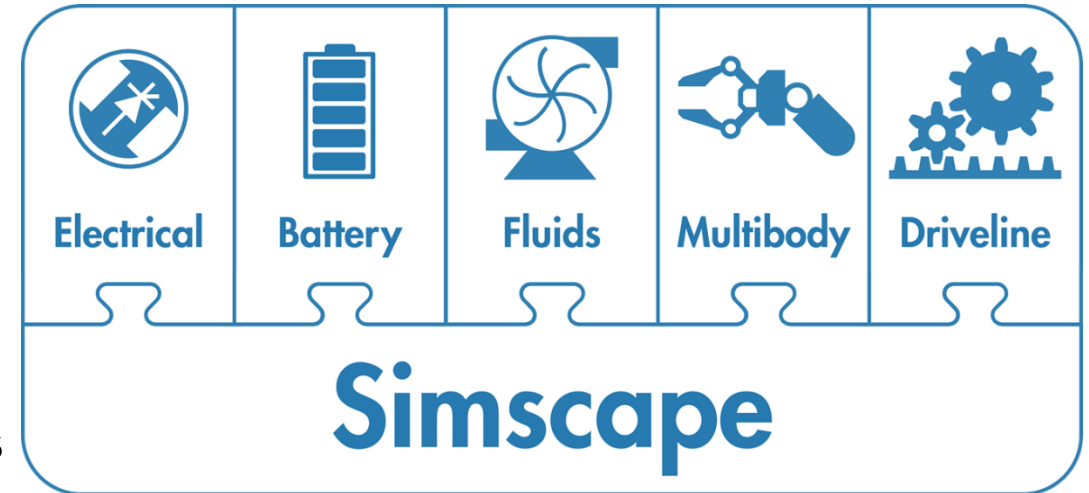
DC Motor

Electrical Torque Mechanical

Model parameterization: By equivalent circuit parameters
 By stall torque & no-load speed
 By rated power, rated speed & no-load speed

Simscape Add-on Libraries

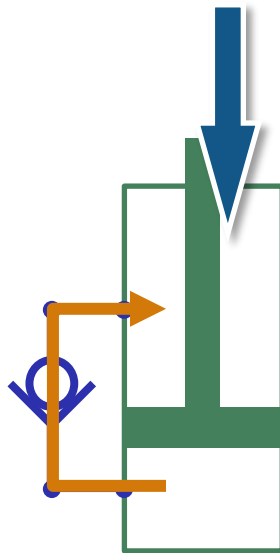
- **Simscape Battery**
 - Battery packs, cooling, charge management
- **Simscape Electrical**
 - Electronics, mechatronics, and power systems
- **Simscape Driveline**
 - Gears, leadscrew, clutches, tires, engines
- **Simscape Multibody**
 - Multibody systems: joints, bodies, frames
- **Simscape Fluids**
 - Pumps, actuators, pipelines, valves, tanks



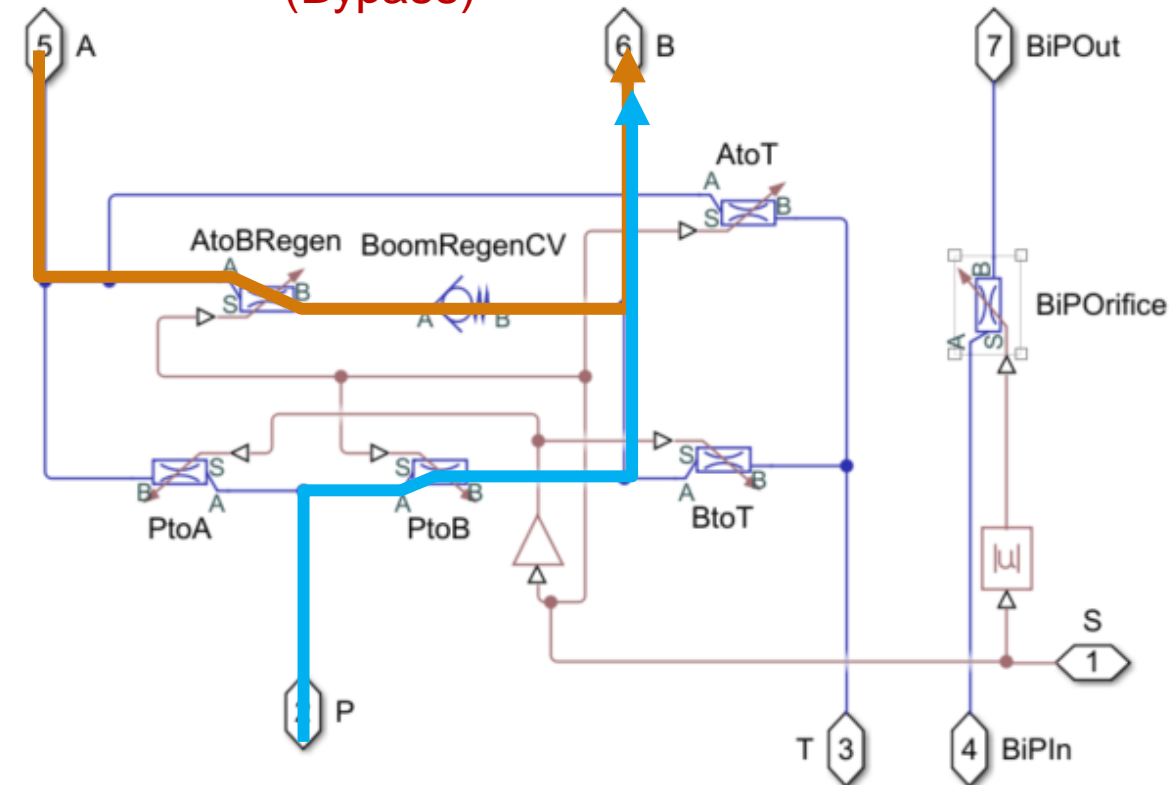
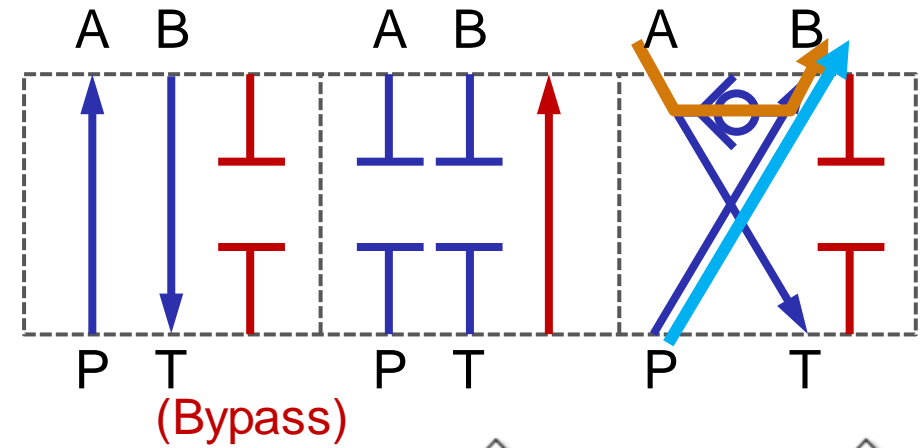
Add Regeneration Valves

- Regeneration valves
 - As cylinders move with gravity, oil from high pressure side is fed to low pressure side
 - Reduces load on pump and increases efficiency

Boom cylinder: regeneration when pump supplies rod end

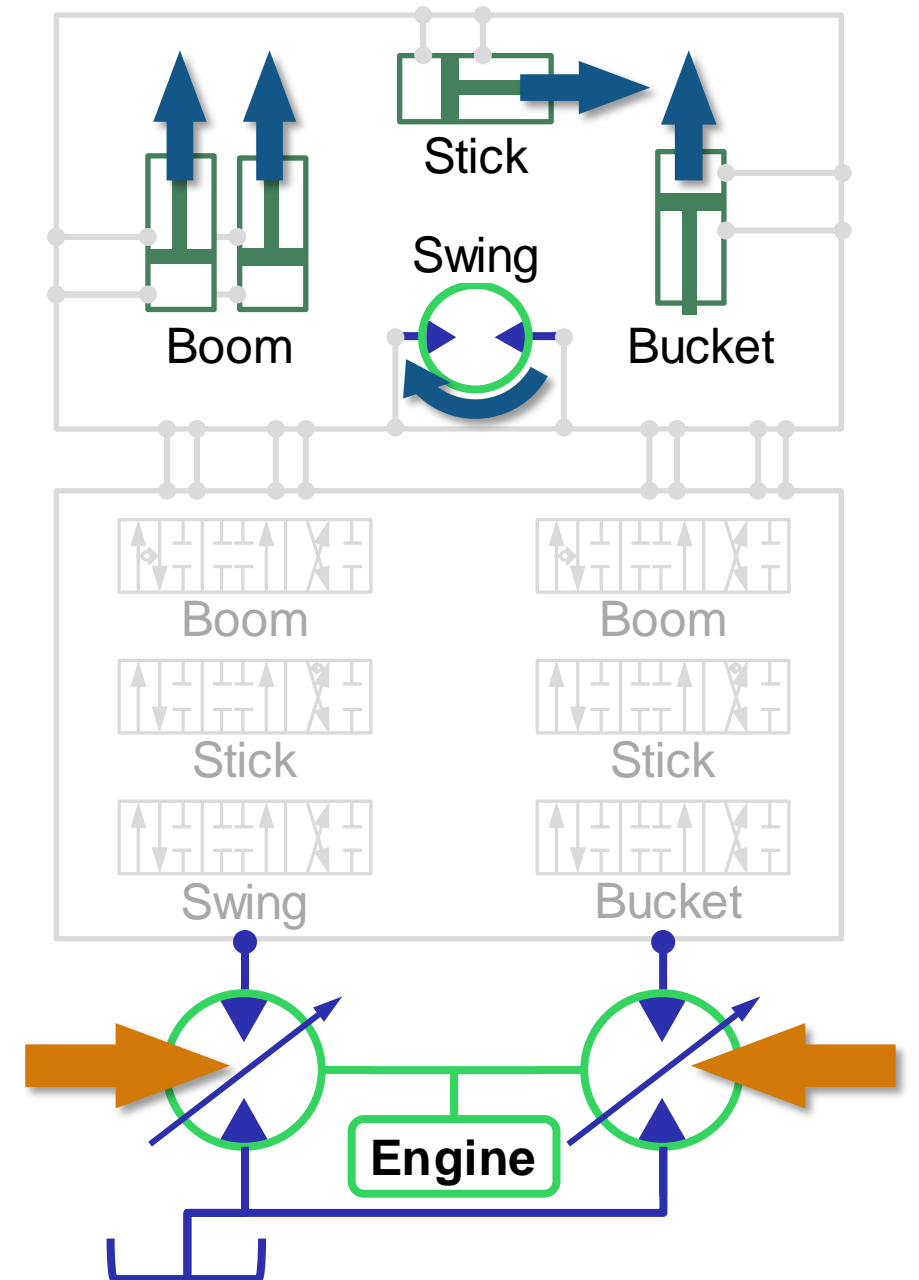
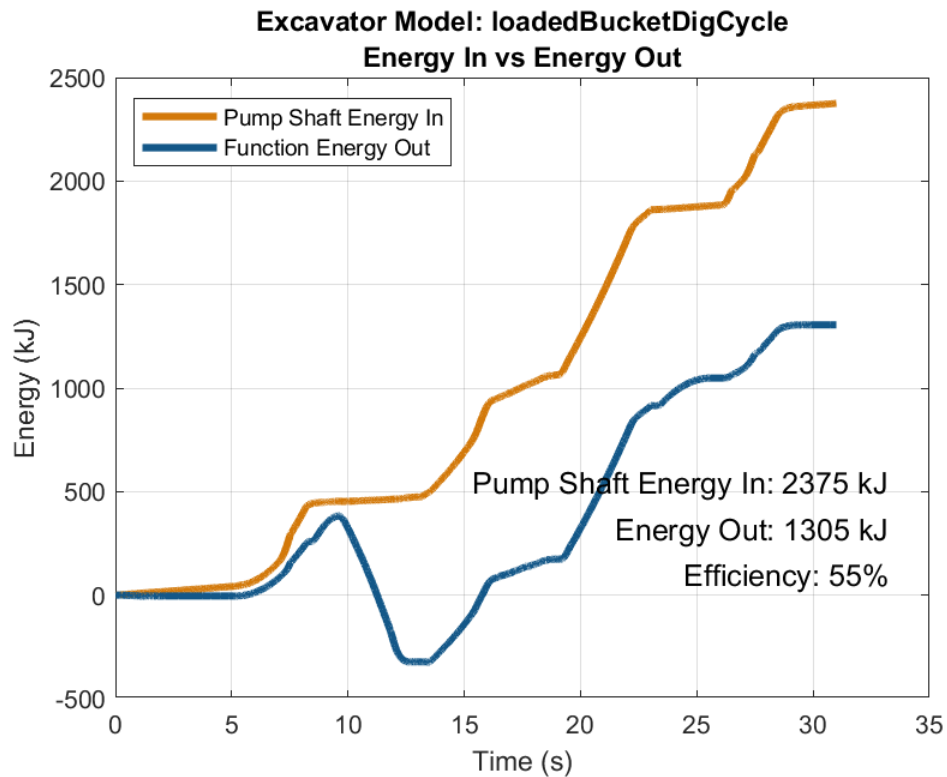


Boom Valve



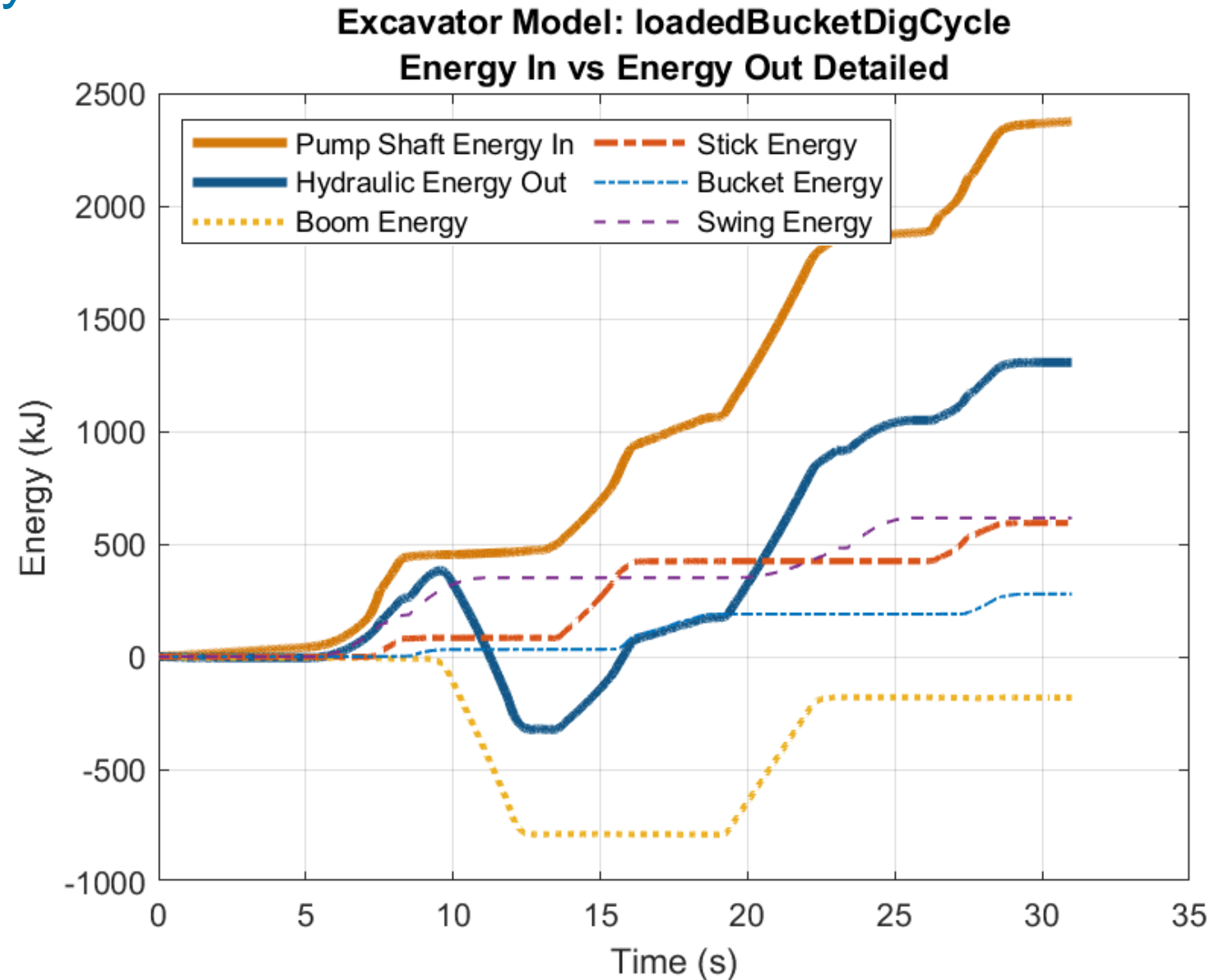
Assessing Overall Efficiency

- Simulation results used to calculate
 - Energy input to excavator
 - Energy output by excavator



Assessing Overall Efficiency

- Periods of “negative” energy show where gravity helped lower the arm
 - Potential energy converted to energy we measured
- Efficiency would be lower if we did not use regenerative flow



Explore Design Space: Load Chart

- Datasheets provide load charts to show lift capacity throughout excavator reach zone

While general information, pictures, and descriptions are provided, some illustrations and text may include product options and accessories NOT included in the region, and to ensure compliance with the local regulations of those countries.

310L EP / 310L

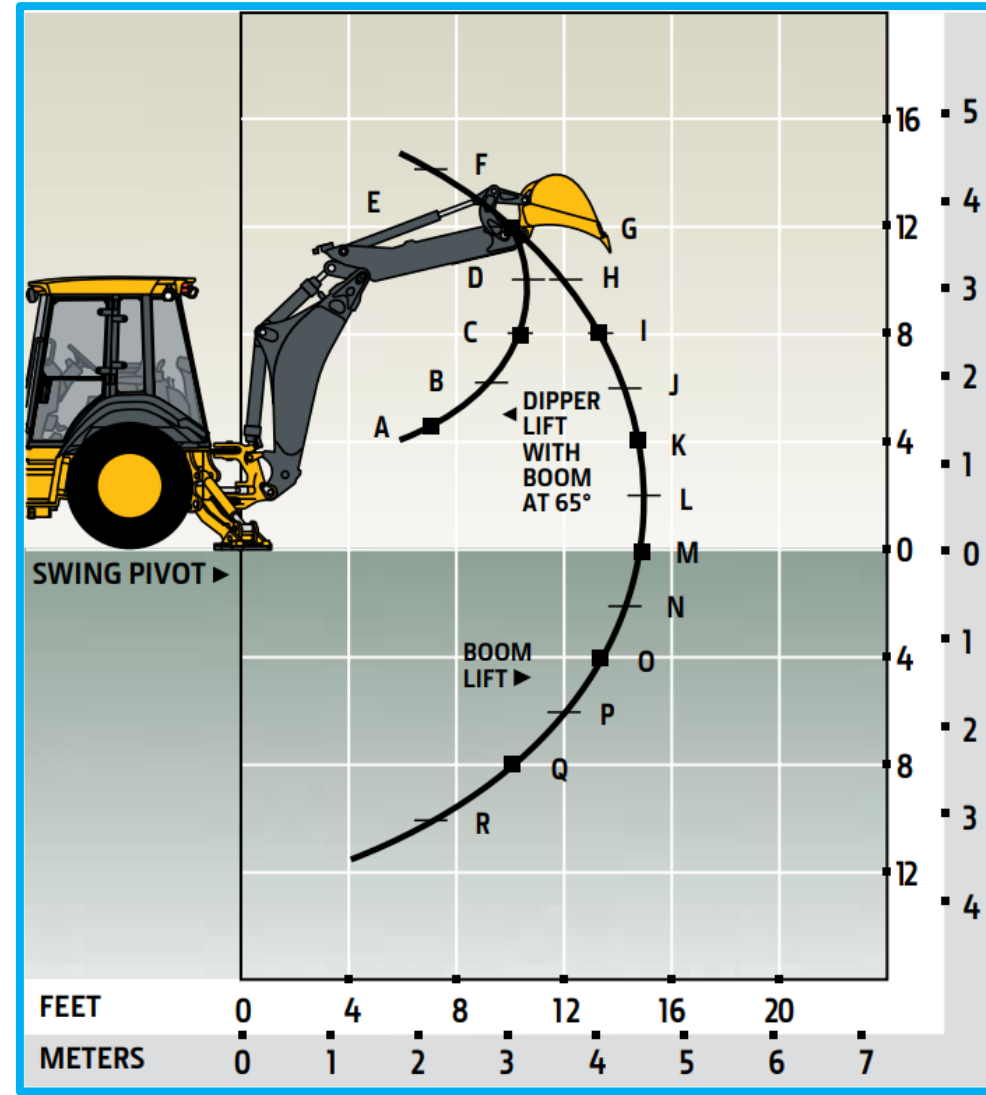
Loader Dimensions and Performance (continued)	310L EP		310L	
	Heavy-duty Long S	Heavy-duty Long S	Heavy-duty Long S	Heavy-duty Long S
Bucket Capacity	2270 cu yd 880 cu yd	2270 cu yd 880 cu yd	2270 cu yd 880 cu yd	2270 cu yd 880 cu yd
Reach	216 mm (85 in.)	216 mm (85 in.)	216 mm (85 in.)	216 mm (85 in.)
Height	363 kg (800 lb.)	363 kg (800 lb.)	363 kg (800 lb.)	363 kg (800 lb.)
Breakout Force	42 540 (94 262 lb.)	42 540 (94 262 lb.)	42 540 (94 262 lb.)	42 540 (94 262 lb.)
Lift Capacity Full Height	3721 kg (8 204 lb.)	2713 kg (5 980 lb.)	2370 kg (5 226 lb.)	2317 kg (5 109 lb.)
Reach at Full Height, Bucket at 45 deg.	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)
Reach at Full Height, Bucket at 65 deg.	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)
Reach at Full Height, Bucket at 90 deg.	110 mm (43 in.)	110 mm (43 in.) <td 110 mm (43 in.)	110 mm (43 in.)	
Reach at Full Height, Bucket at 120 deg.	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)
Reach at Full Height, Bucket at 150 deg.	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)
Reach at Full Height, Bucket at 180 deg.	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)
Reach at Full Height, Bucket at 210 deg.	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)
Reach at Full Height, Bucket at 240 deg.	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)
Reach at Full Height, Bucket at 270 deg.	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)
Reach at Full Height, Bucket at 300 deg.	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)
Reach at Full Height, Bucket at 330 deg.	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)
Reach at Full Height, Bucket at 360 deg.	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)	110 mm (43 in.)

Lift Capacities

Lift capacities are over-end values in kg (lb.). Figures listed are 100% of the maximum lift force available.

With Standard Dipperstick	310L EP	310L	310L EP	310L
A 3721 kg (8,204 lb.)	2713 kg (5,980 lb.)	2370 kg (5,226 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
B 2713 kg (5,980 lb.)	2370 kg (5,226 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
C 2370 kg (5,226 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
D 2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
E 2150 kg (4,739 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
F 1682 kg (3,708 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
G 1655 kg (3,648 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
H 1590 kg (3,506 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
I 1523 kg (3,358 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
J 1459 kg (3,217 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
K 1400 kg (3,086 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
L 1345 kg (2,965 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
M 1295 kg (2,855 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
N 1249 kg (2,754 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
O 1207 kg (2,662 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
P 1171 kg (2,581 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
Q 1140 kg (2,514 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)
R 1131 kg (2,494 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)	2317 kg (5,109 lb.)

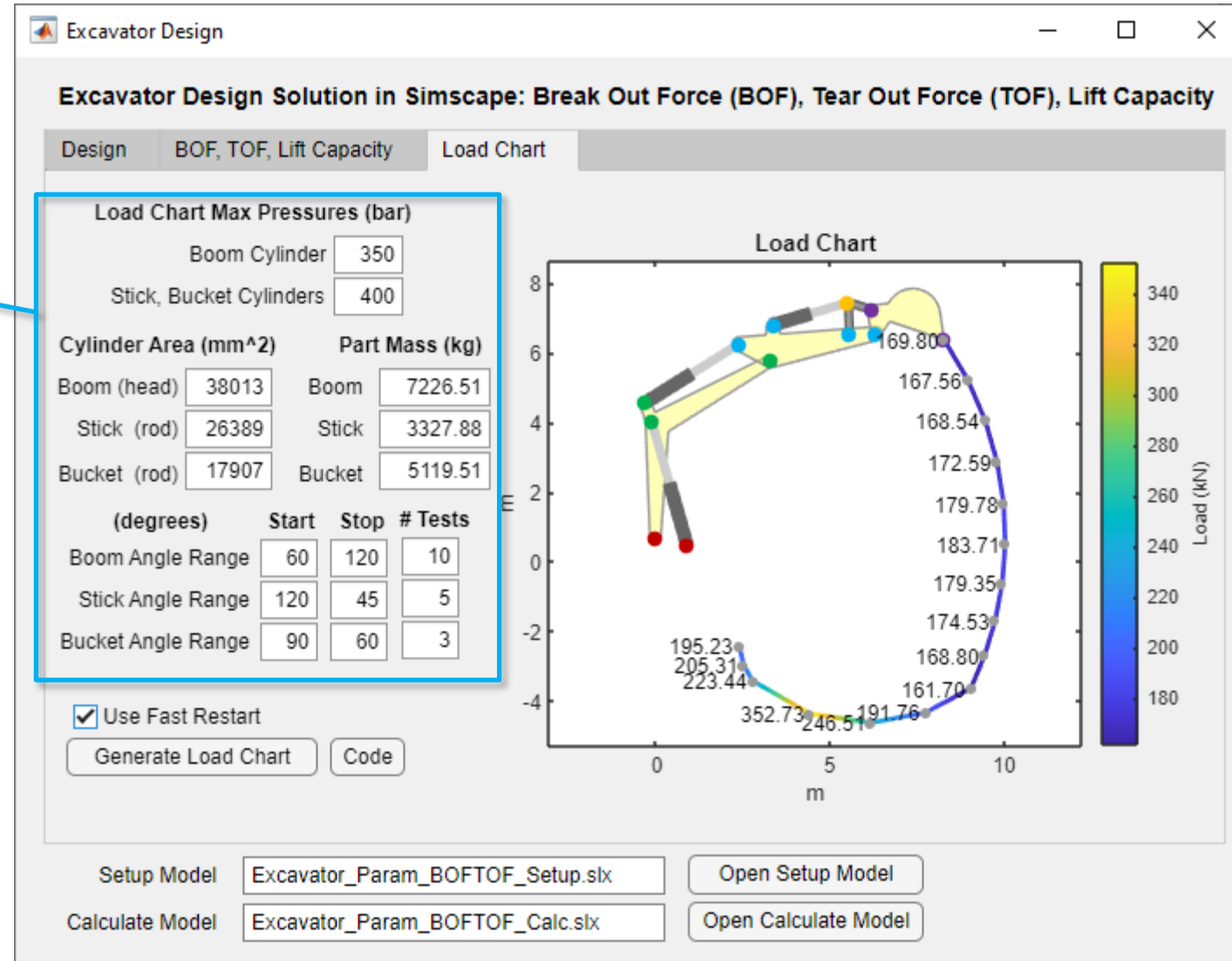
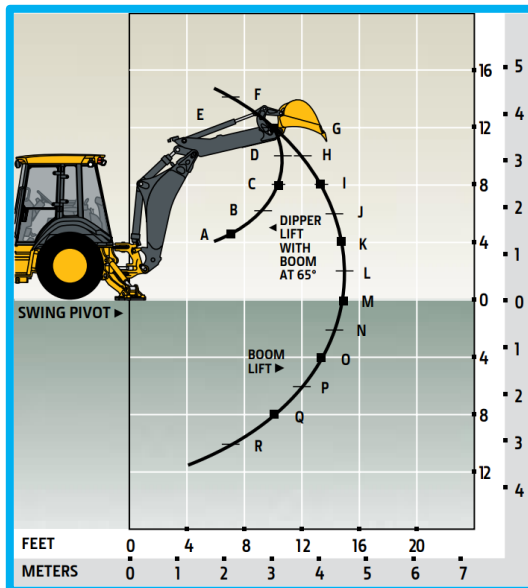
*Indicate capacity is stability limited. Lift capacities are over-end values and will diminish down and fore/aft to ground.
Reach of 305 mm (12 in.) for the 310L EP and 152 mm (6 in.) for the 310L.



A	3721 kg (8,204 lb.)
B	2713 kg (5,980 lb.)
C	2370 kg (5,226 lb.)
D	2317 kg (5,109 lb.)
E	2150 kg (4,739 lb.)
F	1682 kg (3,708 lb.)
G	1655 kg (3,648 lb.)
H	1590 kg (3,506 lb.)
I	1523 kg (3,358 lb.)
J	1459 kg (3,217 lb.)
K	1400 kg (3,086 lb.)
L	1345 kg (2,965 lb.)
M	1295 kg (2,855 lb.)
N	1249 kg (2,754 lb.)
O	1207 kg (2,662 lb.)
P	1171 kg (2,581 lb.)
Q	1140 kg (2,514 lb.)
R	1131 kg (2,494 lb.)

Explore Design Space: Load Chart

- MATLAB App lets you specify design space for load chart
 - Test positions
 - Pressure limits, actuator sizes
 - Part masses
- Results displayed in a plot



Explore Design Space: Load Chart

- Parameter sweep
 - Can run on multiple cores

Excavator Design

Excavator Design Solution in Simscape: Break Out Force

Load Chart App

Design BOF, TOF, Lift Capacity Load Chart

Load Chart Max Pressures (bar)

Boom Cylinder 350

Stick, Bucket Cylinders 400

Cylinder Area (mm ²)	Part Mass (kg)
Boom (head) 38013	Boom 7226.51
Stick (rod) 26389	Stick 3327.88
Bucket (rod) 17907	Bucket 5119.51

(degrees)	Start	Stop	# Tests
Boom Angle Range	60	120	10
Stick Angle Range	120	45	5
Bucket Angle Range	90	60	3

Use Fast Restart

Generate Load Chart Code

Setup Model Excavator_Param_BOFTOF_Setup.slx Open Setup Model

Calculate Model Excavator_Param_BOFTOF_Calc.slx Open Calculate Model

Simscape Model

File Explorer Simulation View Tools Window Help

+1 Mechanics Explorer-Excavator_Param_BOFTOF_Setup_pct_temp

T = [0,0,2] 1X Time 0,2

Roles of Design Solution and Full Actuation Model

Excavator Design Solution in Simscape: Break Out Force (BOF), Tear Out Force (TOF), Lift Capacity

Design | BOF, TOF, Lift Capacity | Load Chart

Label	Part	Location	X(m)	Y(m)
A1	Chassis	Boom	0	0.7000
A2	Chassis	Boom Cylinder	0.9000	0.4750
B1	Boom	Boom Cylinder	1.6825	3.6050
B2	Boom	Stick Cylinder	1.8050	4.1269
B3	Boom	Stick	5.7012	3.2253
C1	Stick	Stick Cylinder	5.6642	4.2641
C2	Stick	Bucket Cylinder	6.4528	3.6418
C3	Stick	Linkage	7.2375	1.5979
C4	Stick	Bucket	7.5958	0.9339
E1	Linkage	Bucket Cylinder	8.0225	2.0441
D1	Bucket	Linkage	8.1467	1.3393
D2	Bucket	Cutting Edge	8.3501	-0.8885
D3	Bucket	CG	8.3501	-0.8885

Plot Design Position | Model Design Position

Load Design and Modify Points | Design A | Load | View in Excel

Setup Model | Excavator_Param_BOFTOF_Setup.slx | Open Setup Model

Calculate Model | Excavator_Param_BOFTOF_Calc.slx | Open Calculate Model

Mechanics Explorers - Mechanics Explorer-Excavator_start

File | Explorer | Simulation | View | Tools | Window | Help

View convention: [dropdown]

Mechanics Explorer-Excavator_start

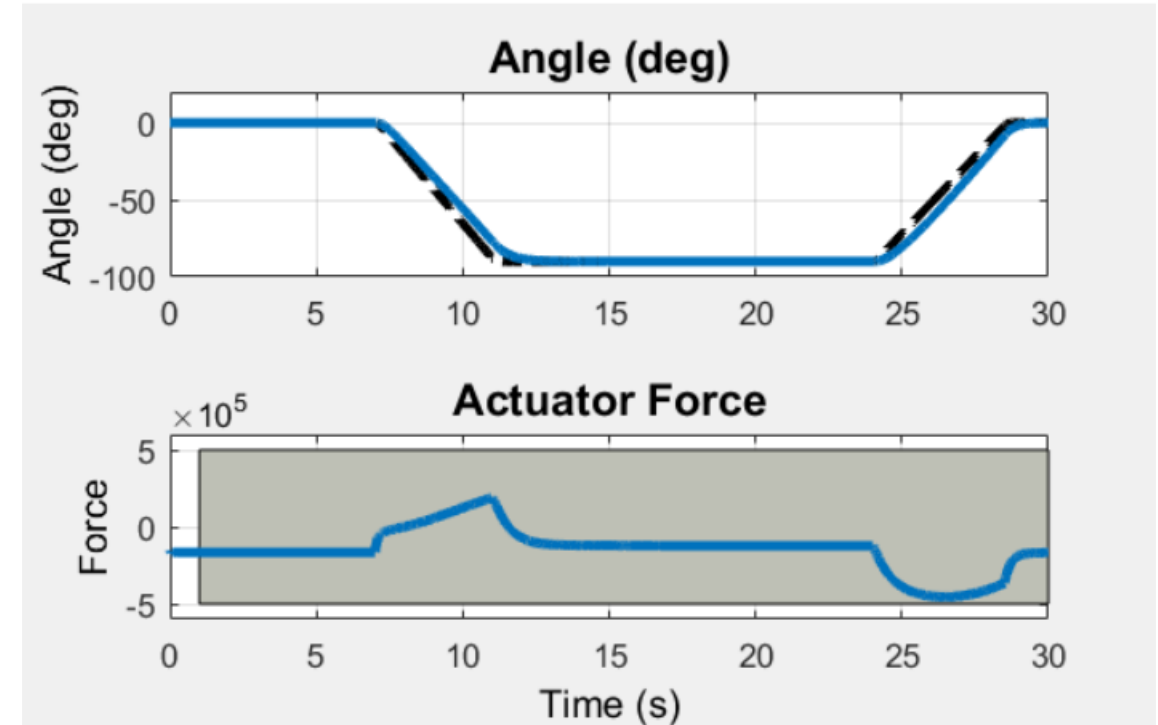
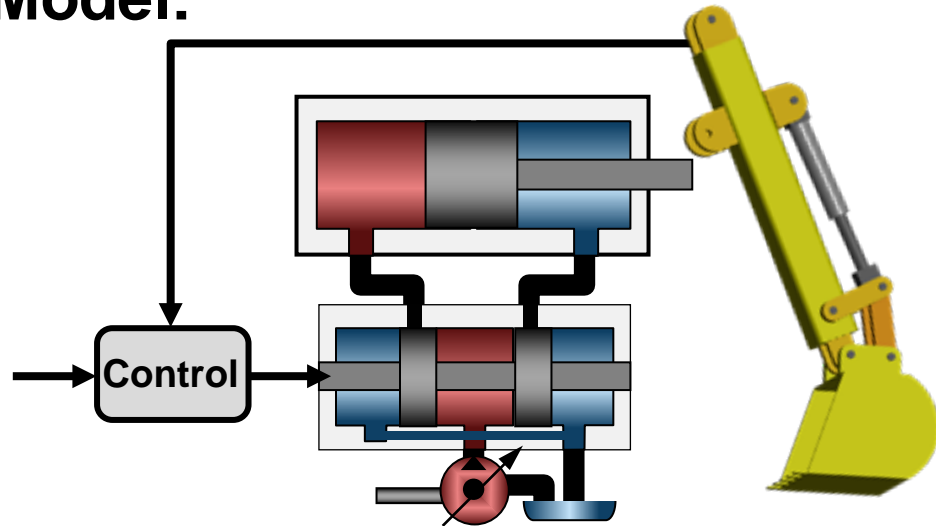
CAD

FEA

0% | 1X | Time 0

Optimizing System Performance

Model:



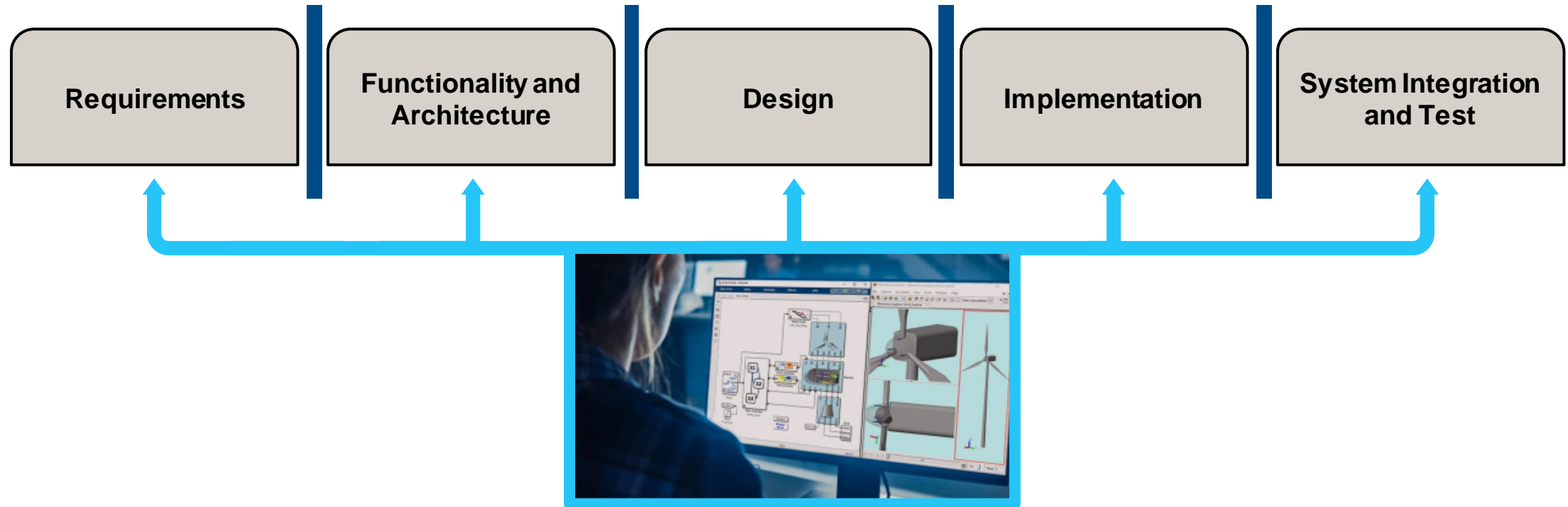
Problem: Optimize the position controller to meet system requirements

Solution: Tune controller parameters with [Simulink Design Optimization](#)

PI Position Control	K_p	K_i
	23.4	3.67

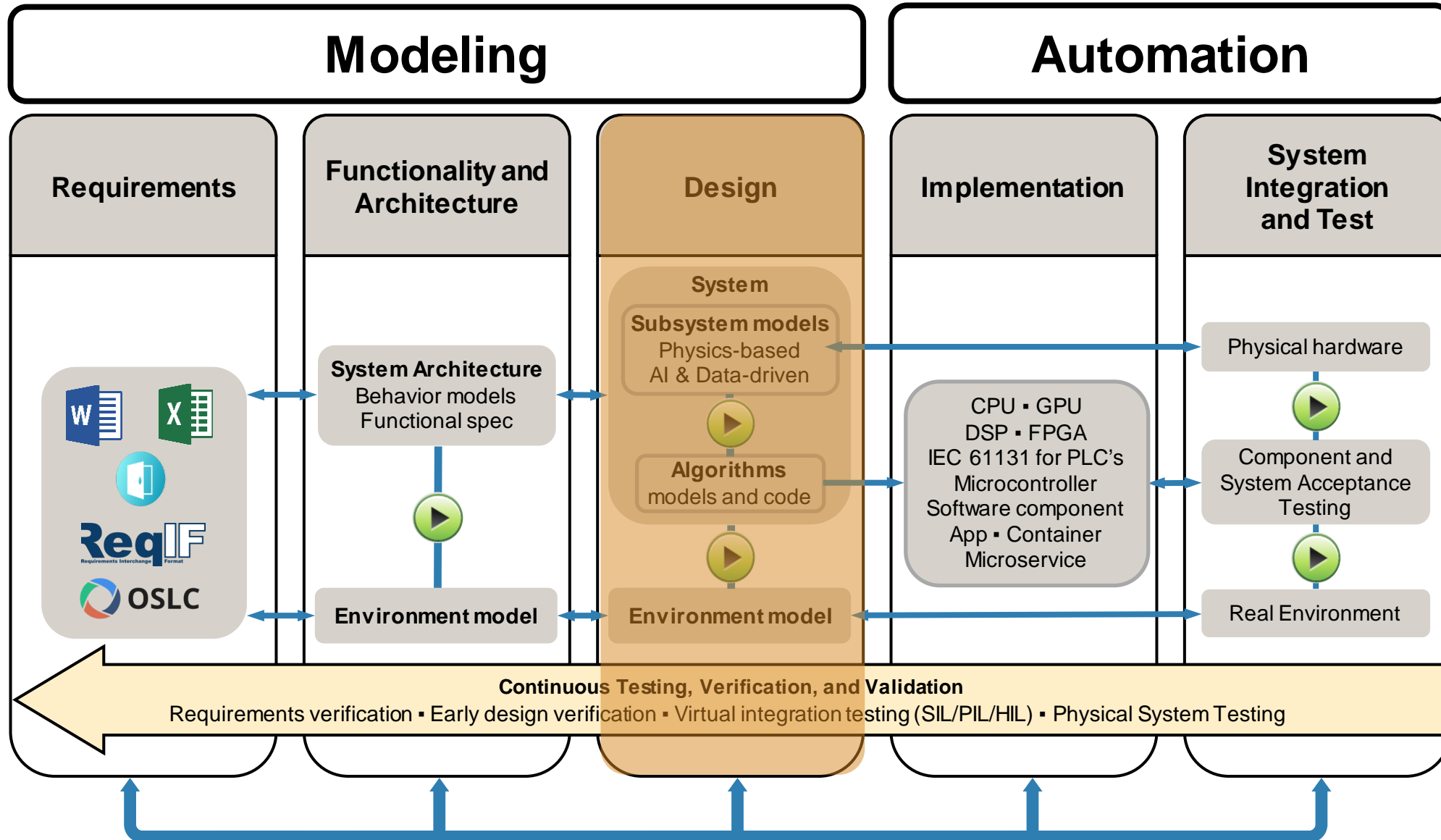
Use Physical Model in Model-Based Design Workflow

Model-Based Design



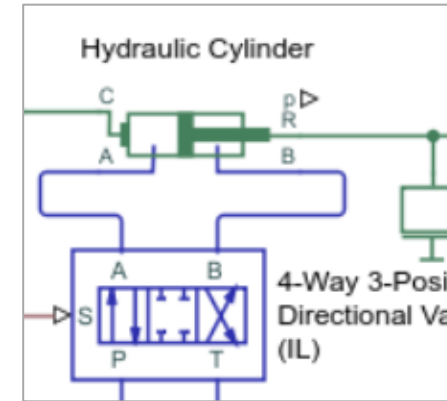
Models are at the **center** of your development process
Create a **digital thread**

Model-Based Design = Modeling + Automation



Key Points

- Simscape provides powerful libraries of component models for multi-domain systems
- Models can be adapted to your needs
 - Create reusable assemblies
 - Adjust parameterization
 - Define custom components
- Leverage MATLAB and Simulink
 - Use powerful analysis tools
 - Perform parameter sweeps and optimization



Block Parameters: Crank Assembly

Crank Assembly (mask)

Consists of the backhoe crank assembly that connects the upper arm and the bucket. Crank 1 attaches to either side of the upper arm linkage, and Crank 2 connects Crank 1 and the Bucket.

Attachment points are:
 AL: Arm attachment (Left).
 AR: Arm attachment (Right).
 B: Bucket attachment.
 P: Piston attachment.
 All attachment points are configured for Revolute joints.

Click on Help to view a schematic of the crank assembly, its configuration dimension parameters and attachment points (in red).

Crank 1	Crank 2	Other
LC1 [m]		
1.5		
WC1 [m]		
0.4		
TC1 [m]		
0.2		
DH1 [m]		
1.1		
RH1 [m]		

OK Cancel Help Apply

```

equations
Re == q/(area*viscosity_kin)*I
if(abs(Re)>=Recr) % Turbulent
q == Cd*area*sqrt(2/density)
    
```

Electrical

Battery

Fluids

Multibody

Driveline

Simscape

MATLAB & Simulink

Start with free Onramp Training

- Free hands-on tutorials
- Short videos and hands-on exercises with feedback
- Get up and running with MATLAB, Simulink and Simscape in hours



MATLAB Onramp

Get started quickly with the basics of MATLAB.



Simulink Onramp

Get started quickly with the basics of Simulink.



Stateflow Onramp

Learn the basics of creating, editing, and simulating state machines in Stateflow.



Simscape Onramp

Erlernen Sie die Grundlagen der Simulation physikalischer Systeme in Simscape.

...and more at matlabacademy.mathworks.com