



**33**<sup>rd</sup> Annual **INCOSE**  
international symposium

hybrid event

Honolulu, HI, USA  
July 15 - 20, 2023



MBSE Application to a Medication Auto-Injector Design

# Bridging Systems Engineering Models and Multi-Fidelity Analytical Models

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# Meeting Challenges by 2035



Multiple Delivery Challenges



Many Physics Involved



Strong Regulations



MBSE as a Solution?



## Applications

1. Systems engineering contributes innovative solutions to major societal challenges.

2. Systems engineering demonstrates value for projects and enterprises of all scales, and applies across an increasing number of domains.



## Practices

3. Systems engineering anticipates and effectively responds to an increasingly dynamic and uncertain environment.

4. Model-based systems engineering, integrated with simulation, multi-disciplinary analysis, and immersive visualization environments is standard practice.

5. Systems engineering provides the analytic framework to define, realize, and sustain increasingly complex systems.

6. Systems engineering has widely adopted reuse practices such as product-line engineering, patterns, and composable design practices.

”By 2035, systems engineering will leverage the digital transformation in its tools and methods, and will be largely model-based using integrated **descriptive and analytical** digital representations of the systems.

Systems design, **analysis, and simulation models**, immersive technologies, and an **analytic framework** will enable **broad trade-space exploration**, rapid design evolution, and provide a shared understanding of the system throughout its life cycle.”

# Agenda

- Challenges and System Context Definition
- Enabling Analytics in the System Model
- Need for Multi-Fidelity Analytical Models
- Integrating Analyses with the System Architecture Model
- Design Space Exploration, from Conceptual to Detailed Design
- Benefits & Challenges
- Conclusion



# Challenges and System Context Definition

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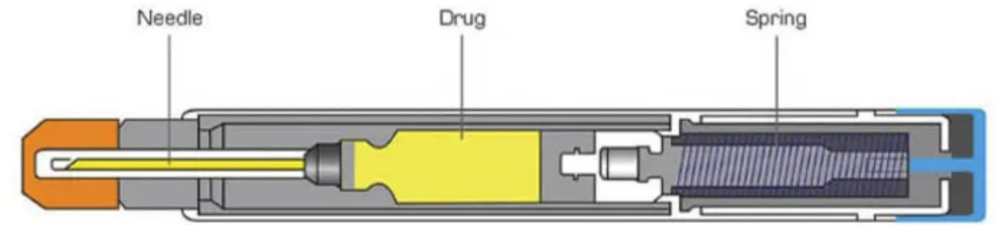


# Auto-Injectors - Background

Auto-injector devices are used to treat a variety of diseases

Highly convenient as they support patient independence

Increased drug effectiveness and reduced percentage of errors vs syringes



With pen injectors, the patient actuates the needle and subsequent flow of medication through the engagement of the push-button. This design is commonly used for patients with chronic diseases. (Credit: Instron)



# Auto-Injectors - Delivery Challenges



Figure 3: Complex molecules of biotherapeutics and biologics.

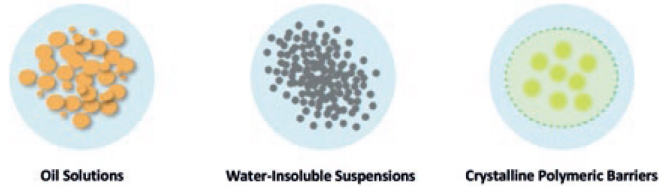


Figure 4: Formulation vehicles for LAIs.

\* Source: ONdrugDelivery Prefilled Syringes & Injection Device, Issue 125 (2021)

Delivery Challenges

Molecule size and fragility



High dose concentrations

Large delivery volumes

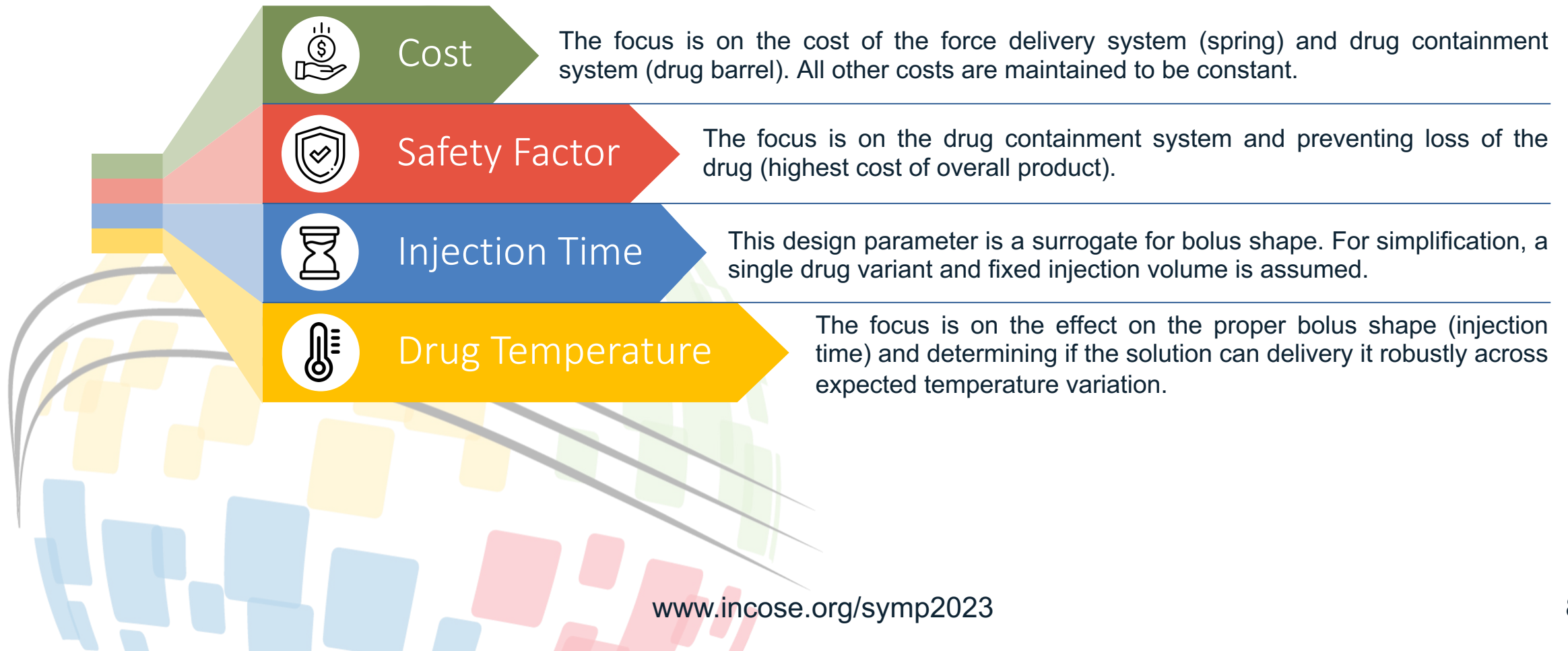
Temperature effects

Optimizing bolus shape

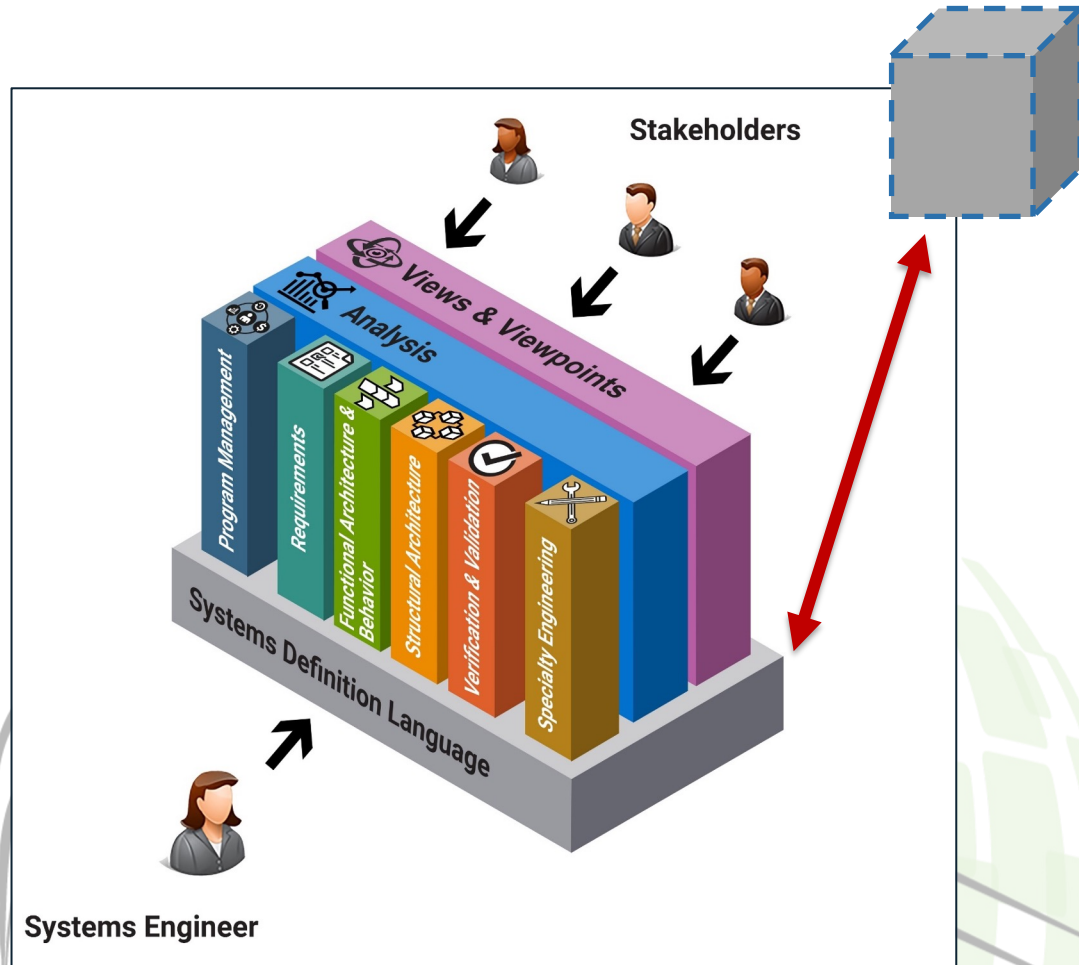
# Auto-Injectors - Analyses

-  Determine which solutions meet our cost, safety and bolus shape (delivery time) requirements.
-  Trade-offs between multiple design configurations
-  Evaluate chosen solutions for robustness against temperature variation
-  Analytic framework that supports the integration of simulation models from conceptual to detailed design phases

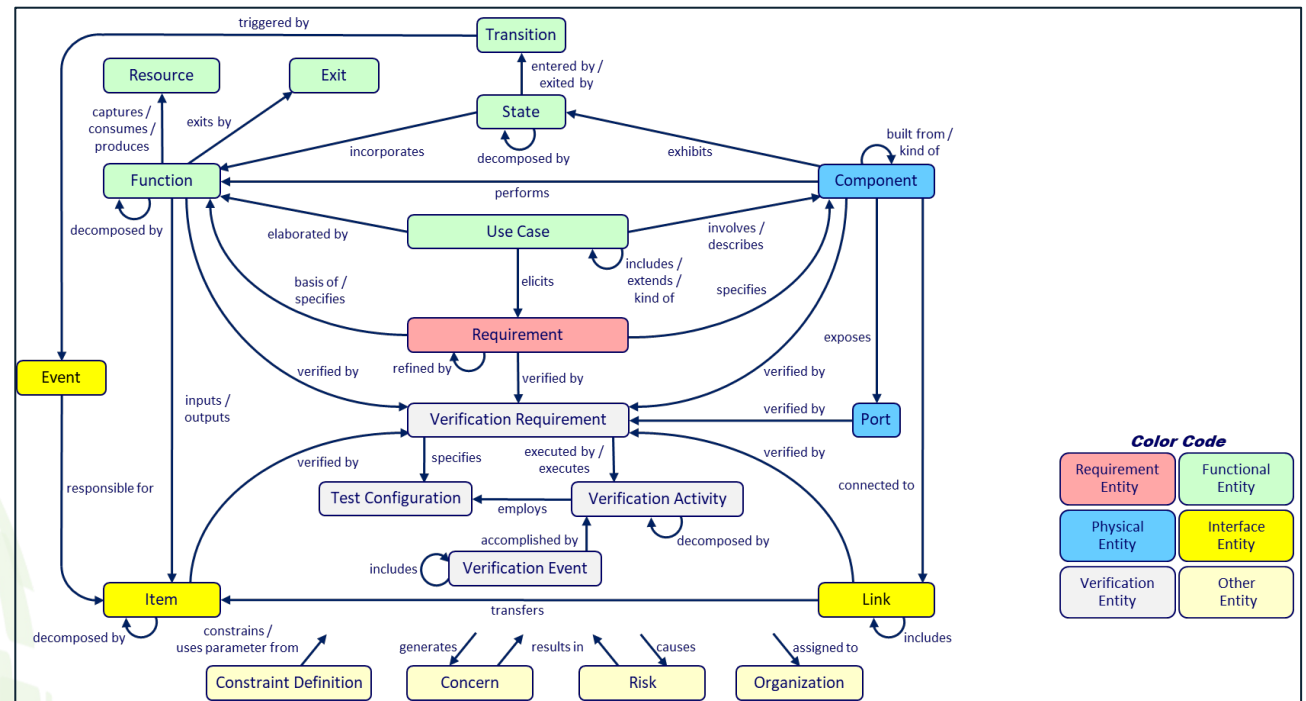
# Auto-Injectors - System Problem Focus and Assumptions



# A Systems Engineering Modeling Framework



## Digital Engineering Tools



## Natural Language Modeling – the Systems Definition Language





# Enabling Analytics in the System Model

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# Step 1: Enabling Analytics in the System Model

Conceptual Phase

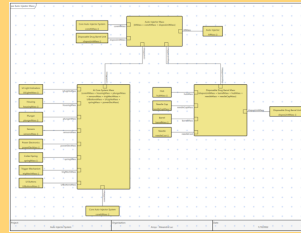
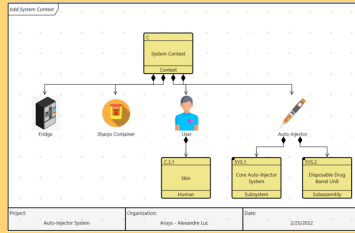
Preliminary Phase

Detailed Design Phase

Prototype & Test

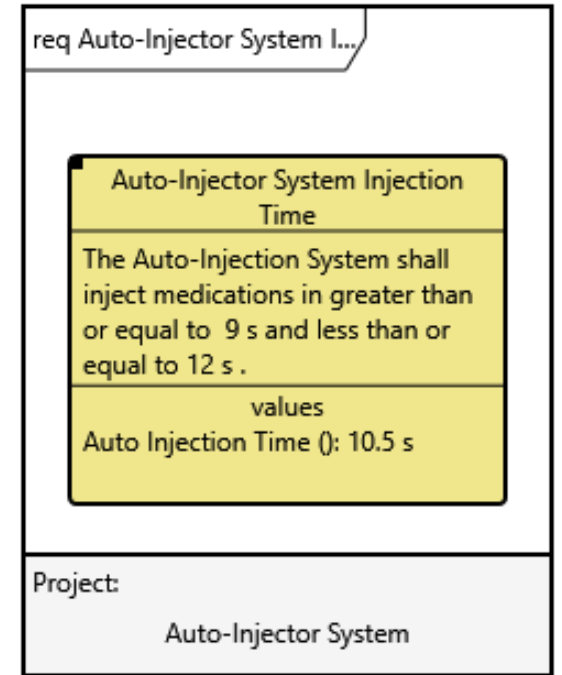
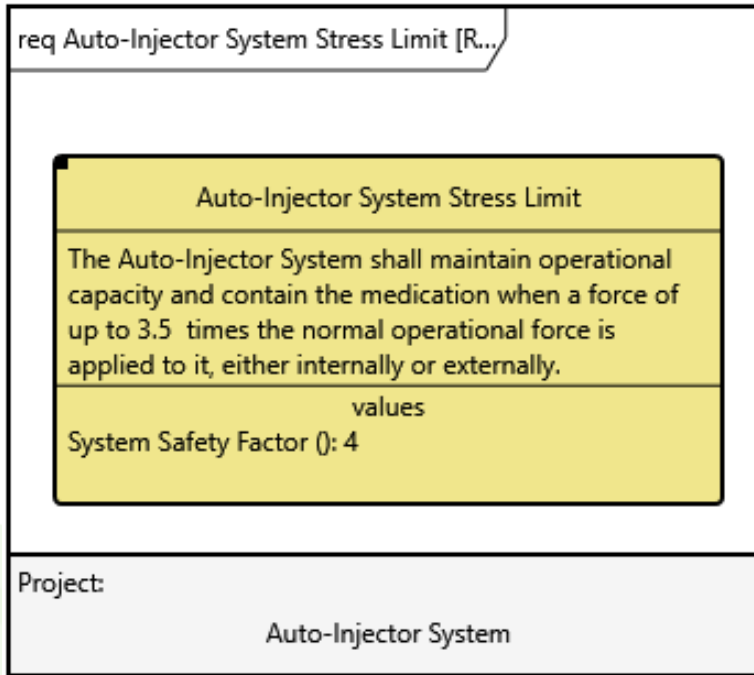
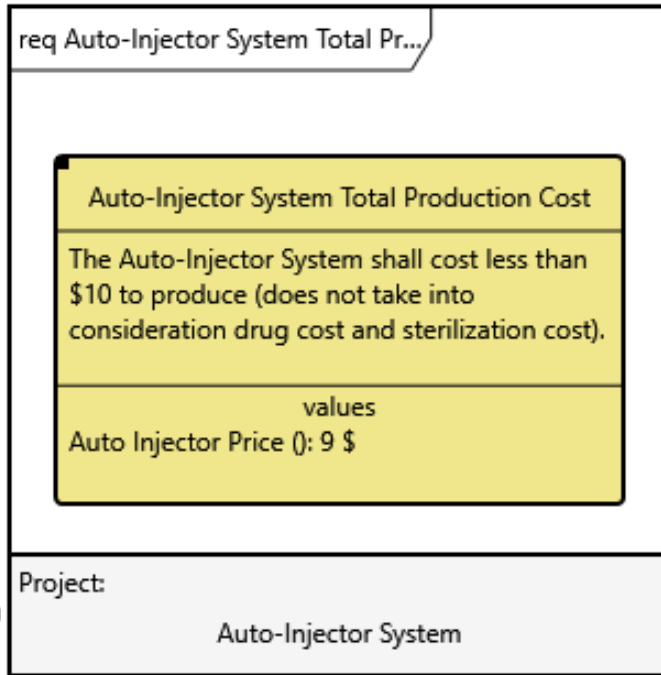
**SAM\* Tool**

**Step 1**  
System Model  
Creation



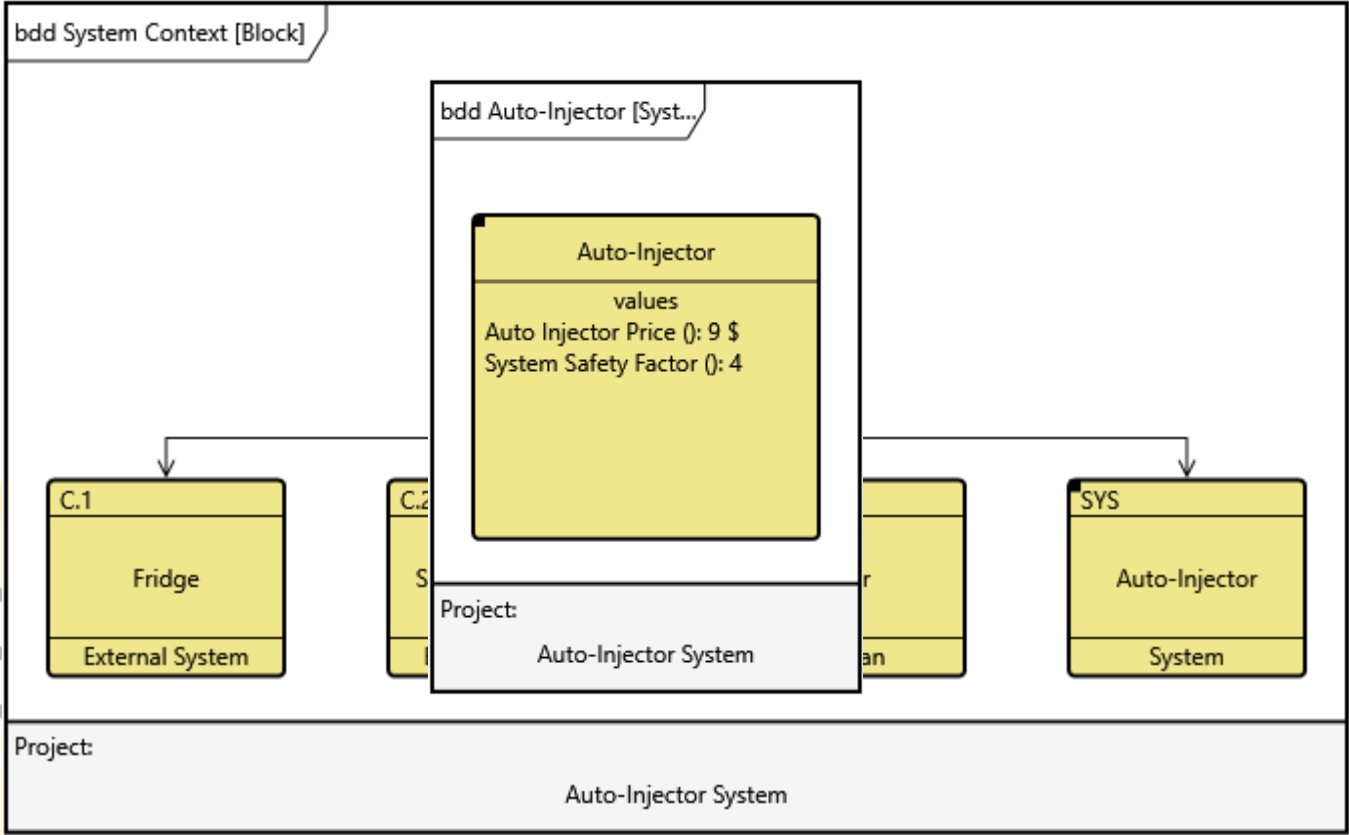
↑  
↓  
SAM\* = System  
Architecture Model

# Requirements and Parameterization

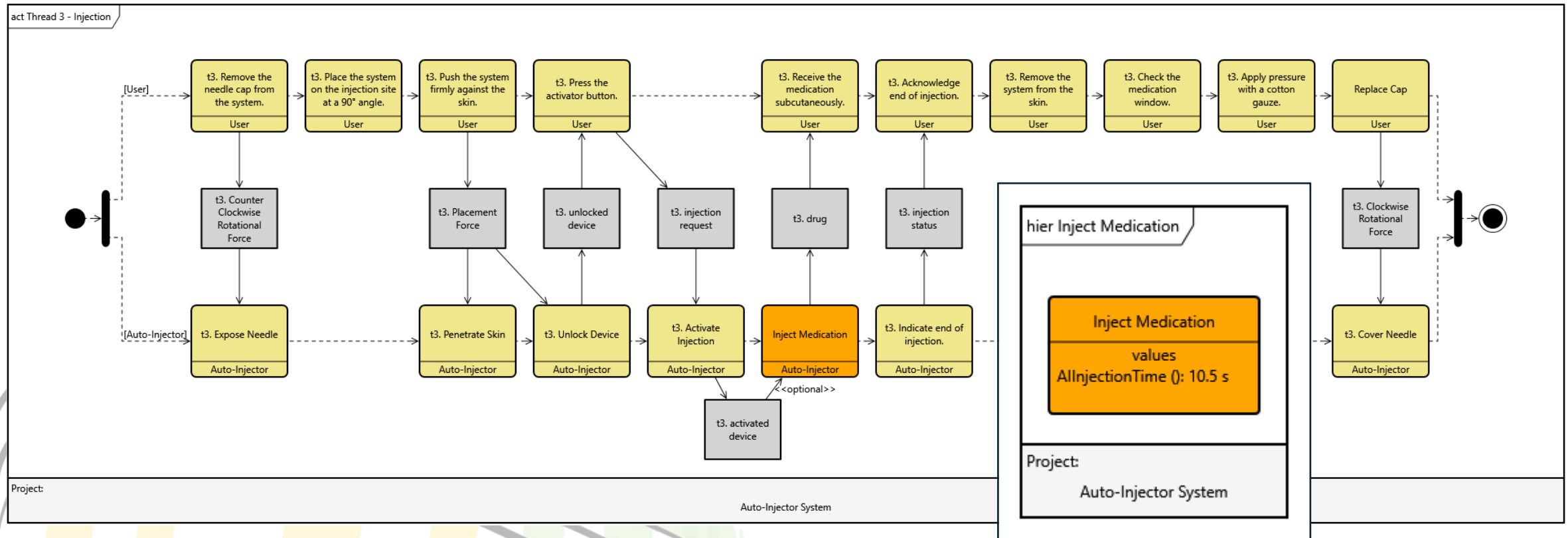


Requirements can be more than a statement. They can have values (parameters) behind them.

# Structural Architecture – System Parameterization

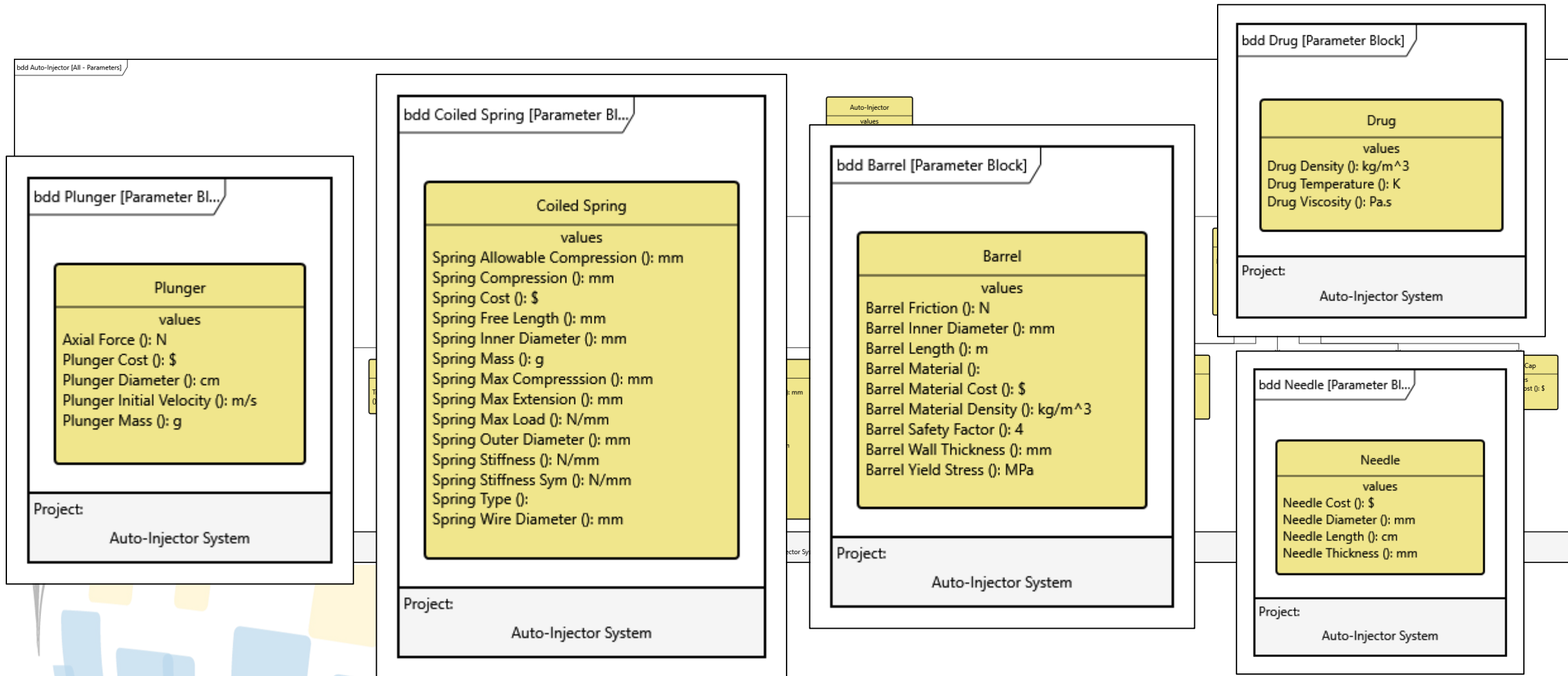


# Functional/Behavior Architecture – Functional Parameterization

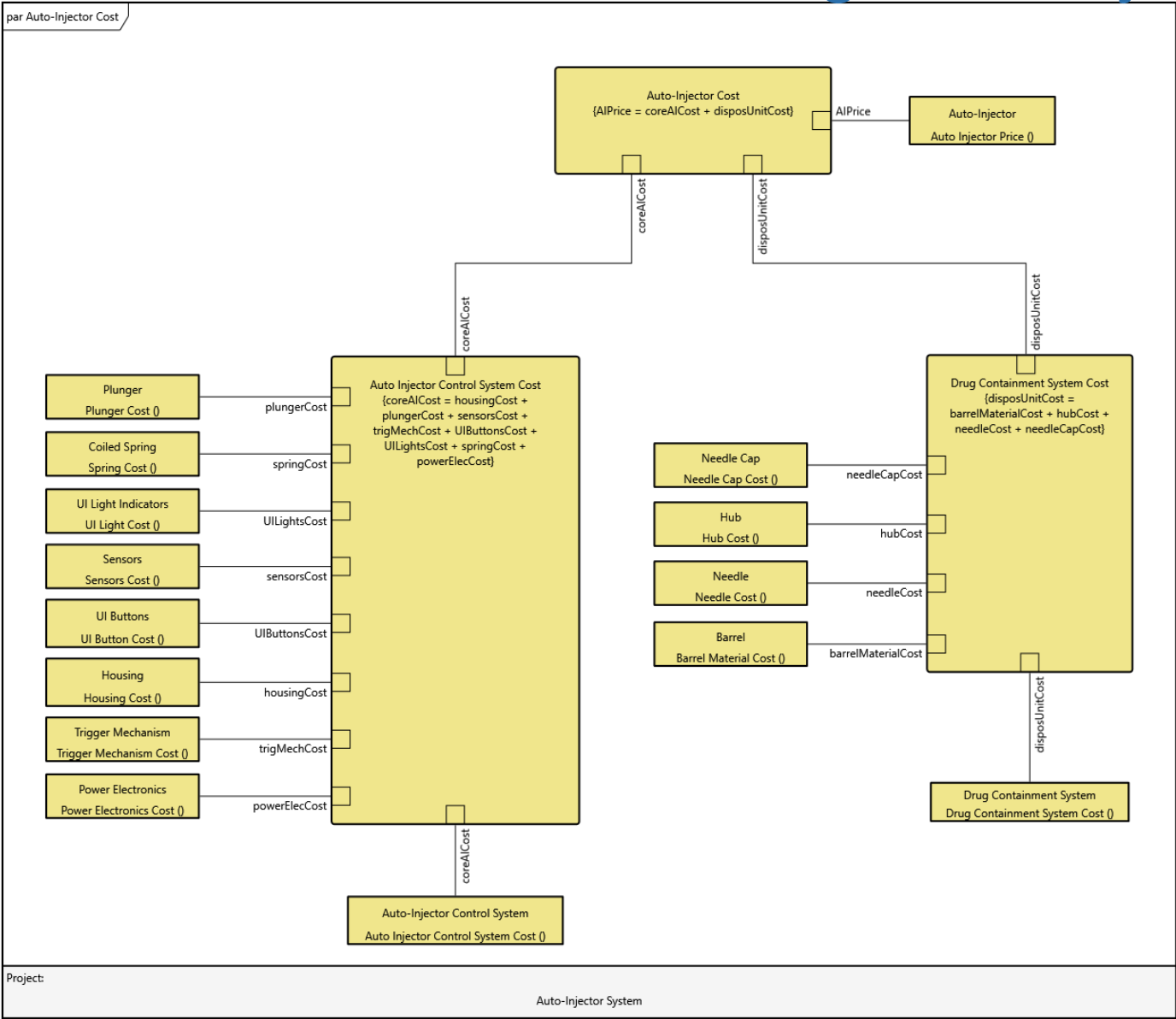




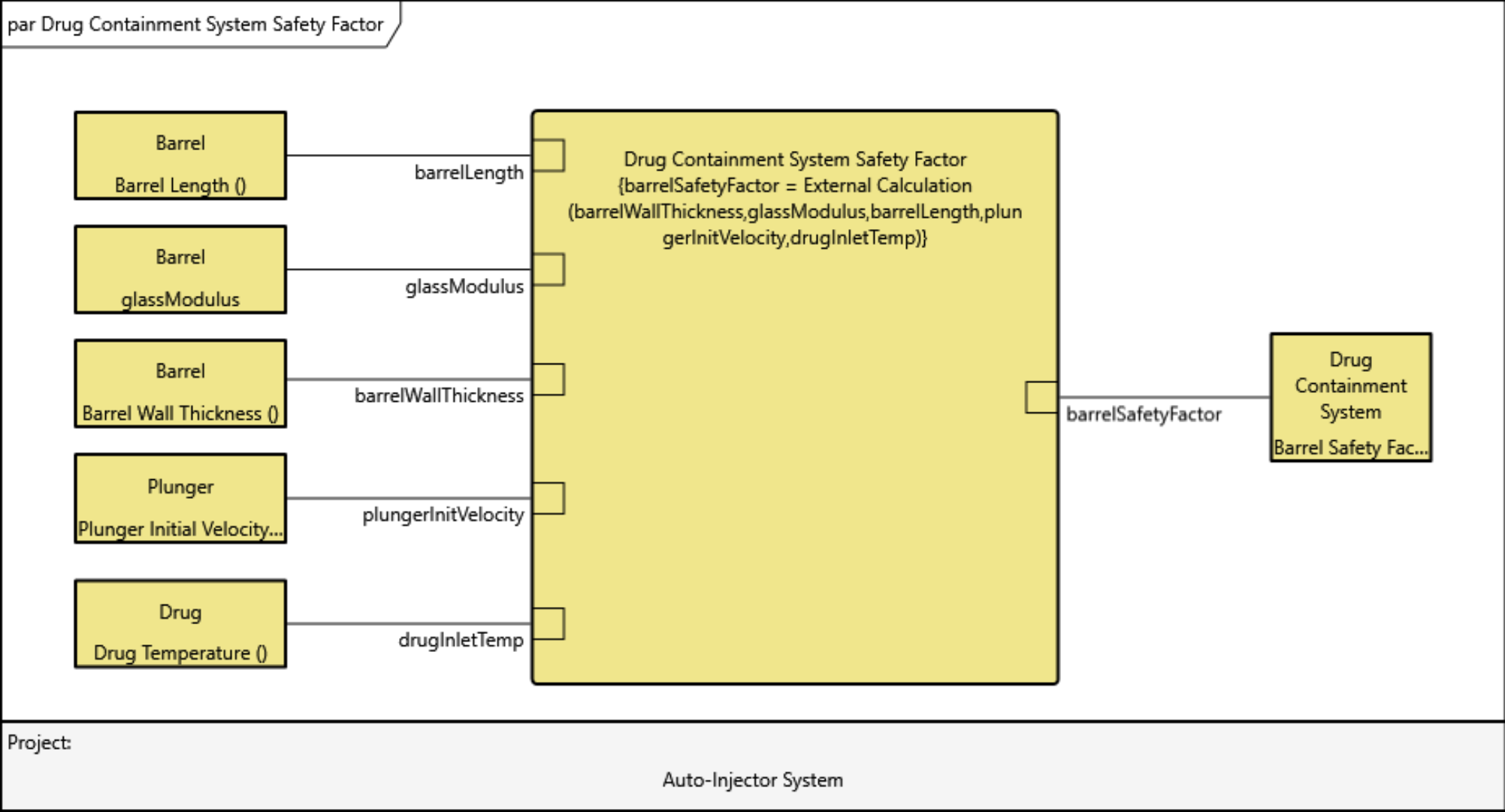
# Architectural Decomposition/Derivation – Parameterization



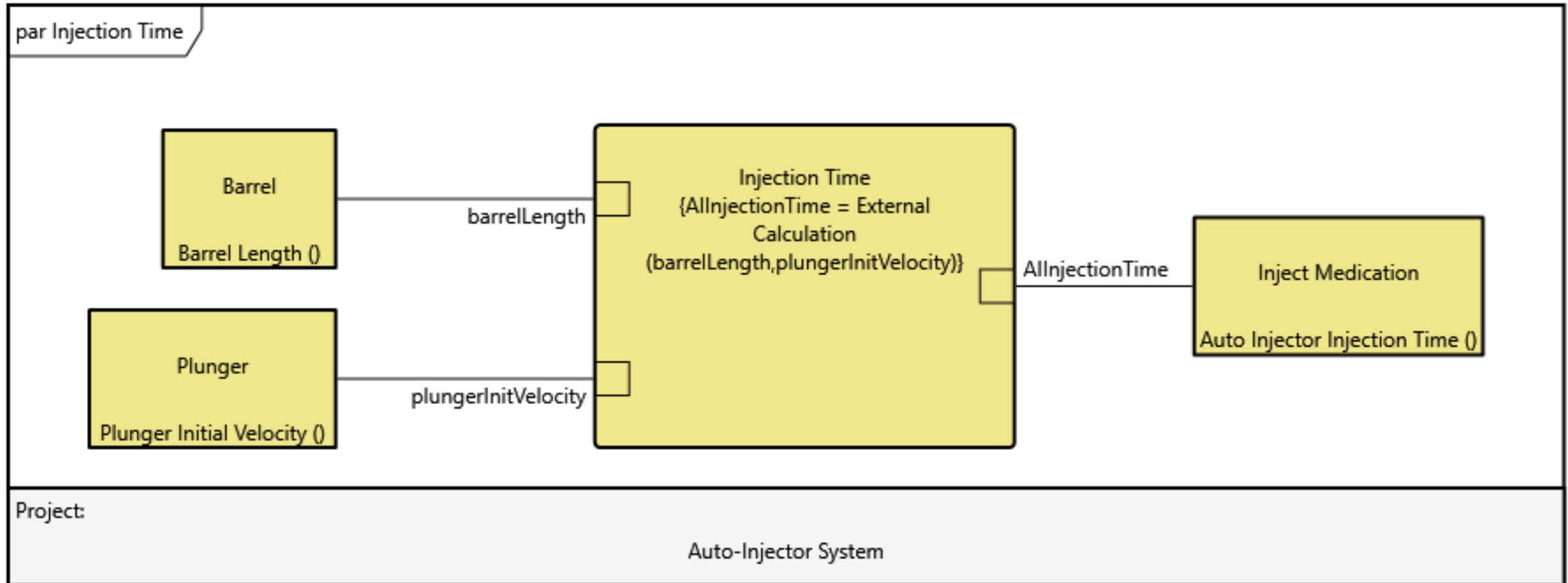
# Constraint Definition – Parametric Diagram – System Cost



# Constraint Definition – Parametric Diagram – Drug Containment System Safety Factor



# Constraint Definition – Parametric Diagram – Injection Time





# Need for Multi-Fidelity Analytical Models

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# Step 2: Simulation Models Automation

Conceptual Phase

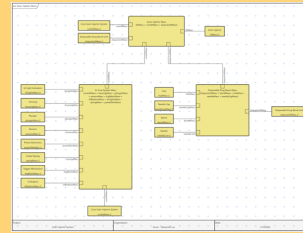
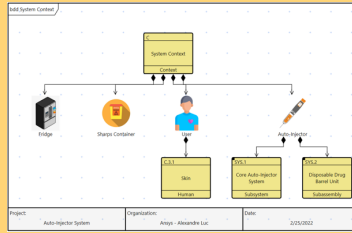
Preliminary Phase

Detailed Design Phase

Prototype & Test

## SAM\* Tool

**Step 1**  
System Model  
Creation



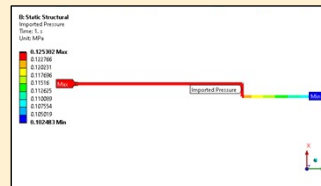
SAM\* = System  
Architecture Model

## Cost Analysis

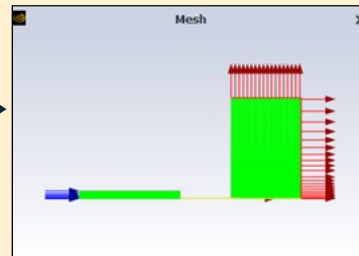
	A	B	C
1	<b>Barrel Design Properties</b>		
2	Barrel Inner Diameter		1 mm
3	Barrel Wall Thickness		0.5 mm
4	Barrel Length		0.05 m
5	Glass Volume		1.19381E-07 m <sup>3</sup>
6			
7	<b>Glass Cost</b>		
8	Glass Volumic Cost		97.05 \$/m <sup>3</sup>
9	Barrel Glass Cost		1.16E-05 \$

**Step 2**  
Simulation Models  
Automation

## 1-way FSI Workflow



CFD Analysis

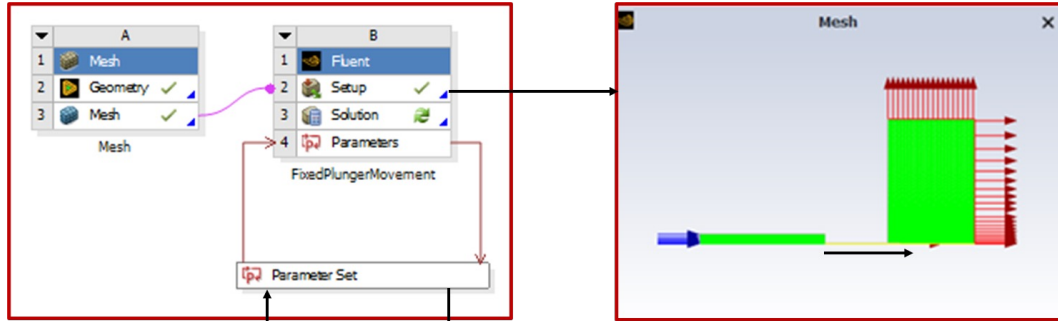


Structural Analysis

Simulation Models

# Simulation Models Creation and Parametrization

## CFD Analysis



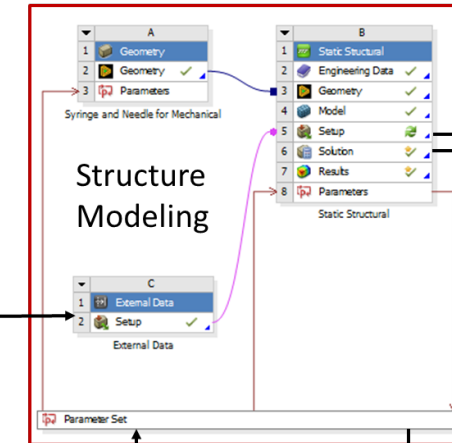
**Fluid Inputs:**  
Plunger Initial Velocity  
Drug Inlet Temperature

**Fluid Outputs:**  
Barrel Wall Pressure  
Drug Density  
Drug Injection Time  
Drug Viscosity

## Cost Analysis

	A	B	C
1	<b>Barrel Design Properties</b>		
2	Barrel Inner Diameter	9 mm	
3	Barrel Wall Thickness	0.3 mm	
4	Barrel Length	0.05 m	
5	Glass Volume	4.59967E-07 m <sup>3</sup>	
6			
7	<b>Glass Cost</b>		
8	Glass Volumic Cost	97.05 \$/m <sup>3</sup>	
9	Barrel Glass Cost	4.46E-05 \$	

Fluid Pressure

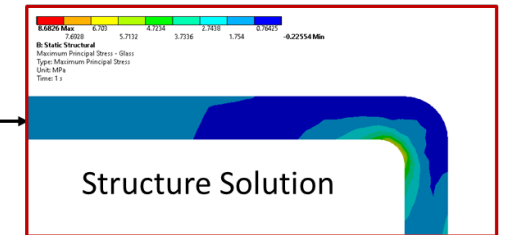
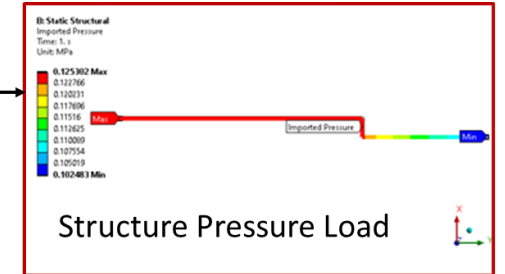


**Structure Inputs:**  
Material Modulus  
Barrel Wall Thickness

**Structure Outputs:**  
Max Tensile Stress  
Safety Factor

## Structural Analysis

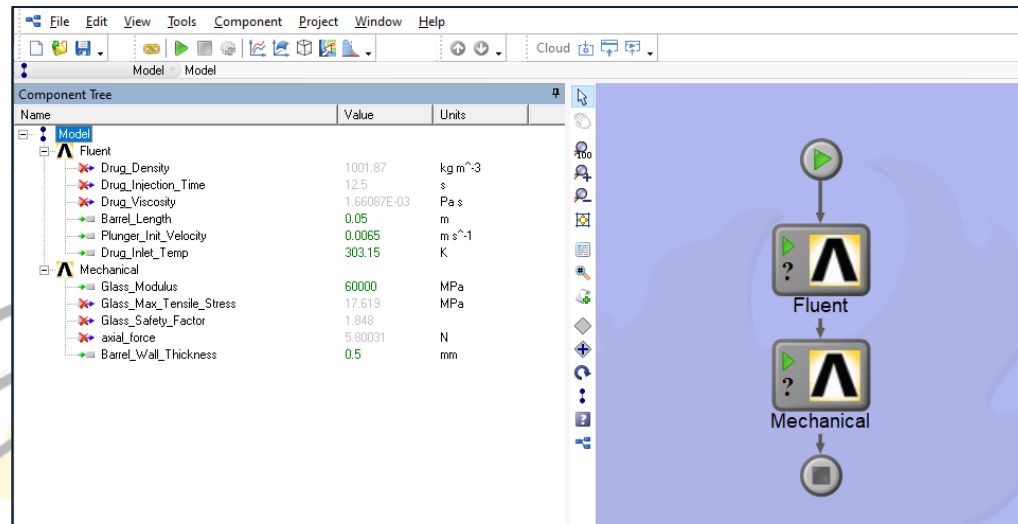
Barrel Pressure from Fluid



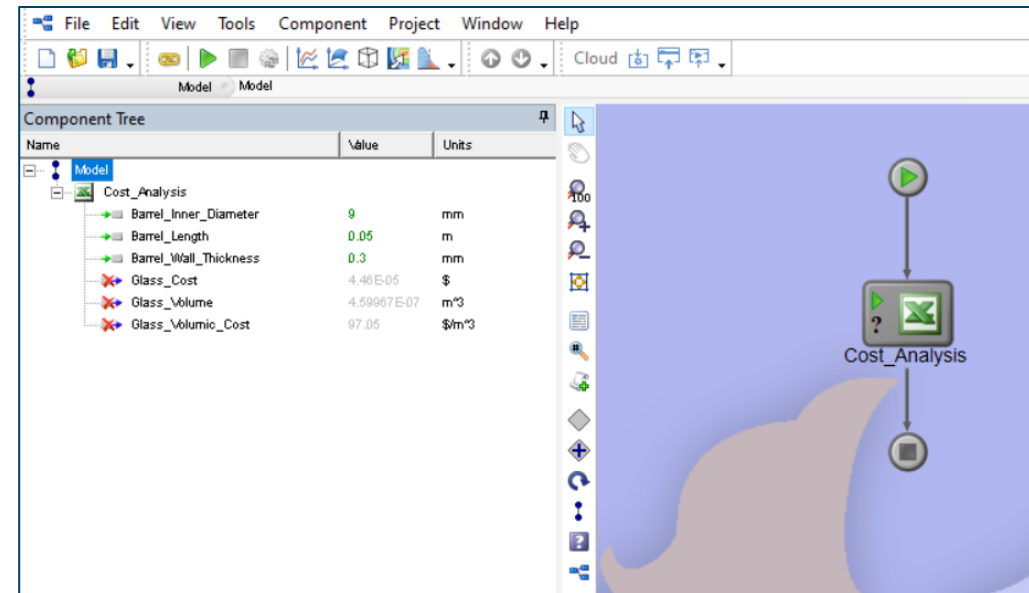
# Simulation Model Automation



1-way Fluid Structure Interaction Workflow



Cost Analysis Workflow





# Integrating Analyses with Systems Architecture Model

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# Step 3: Connect Simulation Models to the SAM



**SAM\* Tool**

**Step 1**  
System Model Creation

SAM\* = System Architecture Model

**Bi-directional Connector**

**Step 3**  
Connect Simulation Models to the SAM

**Cost Analysis**

	A	B	C
1	<b>Barrel Design Properties</b>		
2	Barrel Inner Diameter		1 mm
3	Barrel Wall Thickness		0.5 mm
4	Barrel Length		0.05 m
5	Glass Volume		1.19381E-07 m <sup>3</sup>
6			
7	<b>Glass Cost</b>		
8	Glass Volumic Cost		97.05 \$/m <sup>3</sup>
9	Barrel Glass Cost		1.16E-05 \$

**1-way FSI Workflow**

CFD Analysis

Structural Analysis

Simulation Models

**Step 2**  
Simulation Models Automation



# Step 3: Connect Simulation Models to the SAM

Server Address to access Simulation Workflows

The screenshot shows the Analysis Editor interface with the following components:

- Server Address:** mcre://localhost
- Current Path:** mcre://localhost/AIAnalyses/Cost\_Analysis
- Server Browser:** A tree view showing the project structure under mcre://localhost, including AI\_Analyses, Cost\_Analysis, AS\_Files, AS\_Webinar\_Trade\_Offs, GENESYS7, and Genesis.
- Systems Model Structure:** A table listing the model structure.
- Analysis Variables:** A table listing the analysis variables.
- Parametric Mapping:** A central area where arrows connect variables from the Systems Model Structure to the Analysis Variables table.

Name	Type	Units
C.3 User		
SYS Auto-Injector		
AIHeight		cm
AIInjectionTime	Real	s
AILength		cm
AIMass	Real	g
AIPrice	Real	€
AIWidth		cm
SYS.1 Core Auto-Inject		
SYS.2 Disposable Drug		

Name	Type	Units
Cost_Analysis		
barrelInnerDiameter	Real	mm
barrelWallThickness	Real	mm
barrelLength	Real	m
glassCost	Real	\$

Parametrized Architectural Entities

Analysis Variables

Parametric Mapping

# Step 3: Connect Simulation Models to the SAM

Analyses mapped with Component Entities

Name	Value	Type	Units	Associated Analyses
Barrel_Inner_Diameter	1.0000	Real	mm	Cost_Analysis_PACZ
Barrel_Wall_Thickness	0.500000	Real	mm	Cost_Analysis_PACZ, Aut
Glass_Modulus	68534	Real	MPa	Auto_Injector_FSI
Glass_Safety_Factor	4.0977	Real		Stress Limit, Auto_Injector
axial_force	0.0	Real	N	Auto_Injector_FSI
Barrel_Length	5.0000E-2	Real	m	Cost_Analysis_PACZ, Aut
Glass_Max_Tensile_Stress	7.9460	Real	MPa	Auto_Injector_FSI
Glass_Cost	0.0	Real	\$	Cost_Analysis_PACZ
Plunger_Init_Velocity	5.8000E-3	Real	m s <sup>-1</sup>	Auto_Injector_FSI

Name	Associated Analyses
1.2.1 Injection Time Min	Injection Time Min
1.2.2 Injection Time Max	Injection Time Max
1.1 Stress Limit	Stress Limit

Analyses mapped with Requirement Entities

Name	Baseline	Value	Units	Change	Delta	Delta %
Barrel_Inner_Diameter	0.0	0.0		=	0.0	
Barrel_Wall_Thickness	0.45000	0.45000		=	0.0	0.0
Glass_Modulus	68534	68534		=	0.0	0.0
Glass_Safety_Factor	4.0977	3.3544		↓	0.74328	18.139
axial_force	0.0	6.2411		↑	6.2411	
Barrel_Length	5.0000E-2	5.0000E-2		=	0.0	0.0
Glass_Max_Tensile_Stress	7.9460	9.7067		↑	1.7607	22.159
Glass_Cost	0.0	3.1147E-6		↑	3.1147E-6	
Plunger_Init_Velocity	5.8000E-3	5.8000E-3		=	0.0	0.0
Drug_Viscosity	1.0000E-3	1.5262E-3		↑	5.2619E-4	52.619
Drug_Inlet_Temp	277.60	277.60		=	0.0	0.0
Drug_Density	998.18	1001.3		↑	3.1341	0.31398
Drug_Injection_Time	12.195	8.6207		↓	3.5744	29.310

Name	Satisfied	Margin
1.2.1 Injection Time Min	✓	0.62069
1.2.2 Injection Time Max	✓	1.3793
1.1 Stress Limit	✗	-0.14561

Change Analysis & Requirement Status



# Run Trade Studies in the SAM

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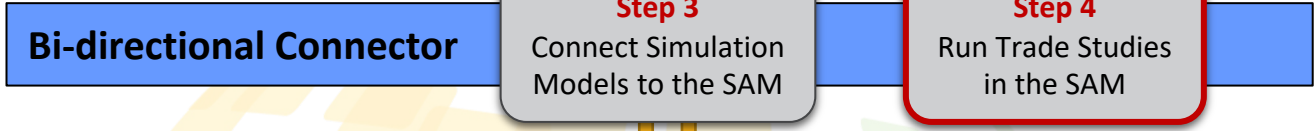
# Step 4: Run Trade Studies in the SAM



**SAM\* Tool**

**Step 1**  
System Model Creation

SAM\* = System Architecture Model



**Cost Analysis**

	A	B	C
1	<b>Barrel Design Properties</b>		
2	Barrel Inner Diameter		1 mm
3	Barrel Wall Thickness		0.5 mm
4	Barrel Length		0.05 m
5	Glass Volume		1.19381E-07 m <sup>3</sup>
6			
7	<b>Glass Cost</b>		
8	Glass Volumic Cost		97.05 \$/m <sup>3</sup>
9	Barrel Glass Cost		1.16E-05 \$

**1-way FSI Workflow**

**CFD Analysis**

**Structural Analysis**

Simulation Models

# Configure and Run Trade Studies in the SAM

- Design of Experiments set up in the SAM directly
- Specify Design/Response Variables and DoE method
- Results gathered in a Data Explorer Table
- Save Results back to the SAM

DOE Tool 14.2.2

TradeStudy\_OA\_plus\_LHS

Design Variables

Name	Values
Model.Auto_Injector_1422_10_19.Model.Fluent.Drug_Init_Velocity	Low: 0.004 High: 0.00625
Model.Auto_Injector_1422_10_19.Model.Fluent.Drug_Inlet_Temp	Low: 275 High: 303
Model.Auto_Injector_1422_10_19.Model.Mechanical.Glass_Modulus	Low: 60000 High: 74000
Model.Auto_Injector_1422_10_19.Model.Mechanical.Glass_Thickness	Low: 0.25 High: 0.5

Response Variables

- Model.Cost\_Analysis\_Excel\_10\_29.Model.Excel.Glass\_Cost
- Model.Cost\_Analysis\_Excel\_10\_29.Model.Excel.Glass\_Volume
- Model.Auto\_Injector\_1422\_10\_19.Model.Fluent.Drug\_Density
- Model.Auto\_Injector\_1422\_10\_19.Model.Fluent.Drug\_Injection\_Time
- Model.Auto\_Injector\_1422\_10\_19.Model.Fluent.Drug\_Viscosity

Number of Runs: 81

Show Data Explorer

Run... Options... Help...

Table - LHC200\_11\_8.tstudy - Data Explorer

File Chart Help

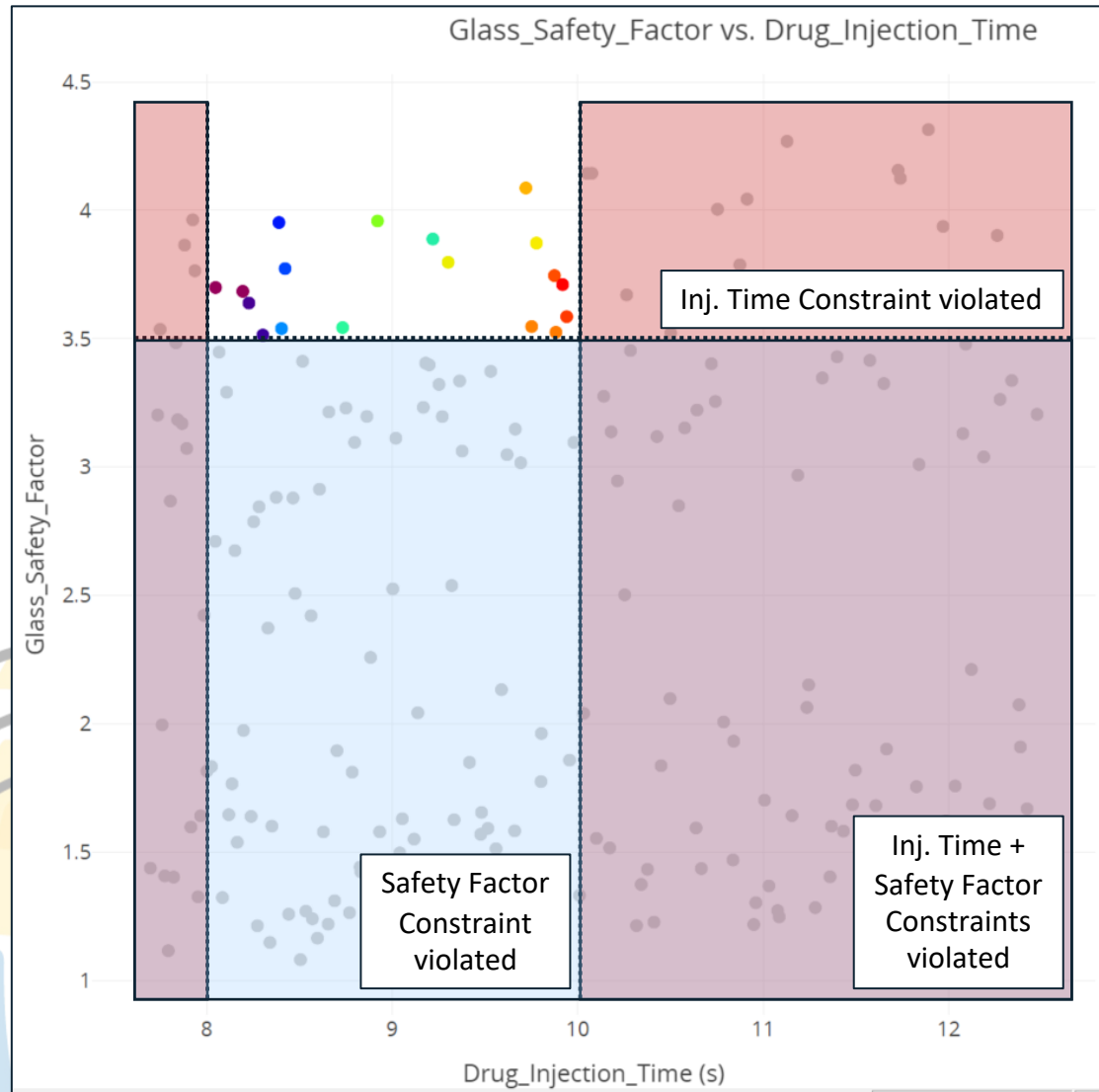
Legend: input valid output invalid output modified value

	188	189	190	191	192	193	194	195	196	197	198	199	200
design variable(Model.Auto_Injector_1422_10_19.Model.Fluent.Drug_Injection_Velocity)	0.00435	0.00465	0.00429	0.00402	0.00439	0.00431	0.00496	0.00451	0.00404	0.00466	0.0044	0.00621	0.00473
design variable(Model.Auto_Injector_1422_10_19.Model.Fluent.Drug_Temperature)	283.684	282.966	290.837	291.336	285.482	286.556	276.825	276.982	292.693	285.167	275.975	288.022	282.215
design variable(Model.Auto_Injector_1422_10_19.Model.Mechanical.Glass_Modulus)	60309.1	64836.8	66113.9	64280	71016.6	73374.2	72278.3	71191.8	71445.2	62689.5	60766.7	61445.8	60574.7
design variable(Model.Auto_Injector_1422_10_19.Model.Mechanical.Glass_Thickness)	0.3497	0.43337	0.43453	0.32853	0.44119	0.33143	0.49319	0.2695	0.35499	0.40686	0.32442	0.40959	0.39121
response(Model.Cost_Analysis_Excel_10_29.Model.Excel.Glass_Cost)	5.23E-05	6.55E-05	6.57E-05	4.91E-05	6.68E-05	4.95E-05	7.51E-05	4.00E-05	5.32E-05	6.13E-05	4.84E-05	6.18E-05	5.89E-05
response(Model.Auto_Injector_1422_10_19.Model.Mechanical.Glass_Safety_Factor)	1.8191	3.25549	3.32506	1.66844	3.42963	1.68108	4.14427	1.27204	1.90949	3.40216	1.60069	2.71038	3.15235
response(Model.Auto_Injector_1422_10_19.Model.Mechanical.Glass_Max_Tensile_Stress)	17.8989	10.0016	9.79231	19.5152	9.49373	19.3685	7.85662	25.5967	17.0517	9.57038	20.3412	12.0131	10.3288
response(Model.Auto_Injector_1422_10_19.Model.Mechanical.axial_force)	5.88007	5.95226	5.86686	5.8059	5.8889	5.87055	6.02699	5.91874	5.80861	5.95455	5.89155	6.35256	5.96971
response(Model.Auto_Injector_1422_10_19.Model.Fluent.Drug_Density)	1000.09	1000.24	998.662	998.562	999.733	999.518	1001.47	1001.44	998.291	999.796	1001.64	999.225	1000.39
response(Model.Auto_Injector_1422_10_19.Model.Fluent.Drug_Injection_Time)	11.4968	10.7423	11.6504	12.4226	11.3985	11.6074	10.0767	11.0782	12.3867	10.7209	11.3684	8.04705	10.5773
response(Model.Auto_Injector_1422_10_19.Model.Fluent.Drug_Viscosity)	1.30622E-...	1.06065E-...	1.04751E-...	1.21910E-...	1.18457E-...	1.56247E-...	1.55500E-...	1.01299E-...	1.22953E-...	1.60370E-...	1.13975E-...	1.33404E-...	

Objective	Minimum	Maximum	Units	Design
AllInjectionTime ()	9.00000000	8.00000000	10.00000000	s
				9.9409508

Source Binding: REQ Auto-Injector System Injection Time

# Get Design Insights and Identify Solution Space



- Highly-constrained Design Space
- Useful to get Design Space Insights from the Conceptual Stage
- Help relaxing/refining requirements and narrowing down the Design Space



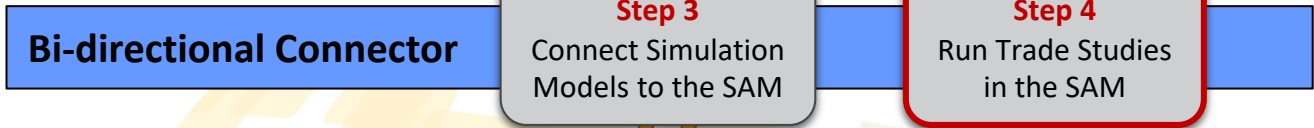
# Step 4: Run Trade Studies in the SAM



**SAM\* Tool**

**Step 1**  
System Model Creation

SAM\* = System Architecture Model



**Cost Analysis**

	A	B	C
1	<b>Barrel Design Properties</b>		
2	Barrel Inner Diameter		1 mm
3	Barrel Wall Thickness		0.5 mm
4	Barrel Length		0.05 m
5	Glass Volume		1.19381E-07 m <sup>3</sup>
6			
7	<b>Glass Cost</b>		
8	Glass Volumic Cost		97.05 \$/m <sup>3</sup>
9	Barrel Glass Cost		1.16E-05 \$

**1-way FSI Workflow**

**CFD Analysis**

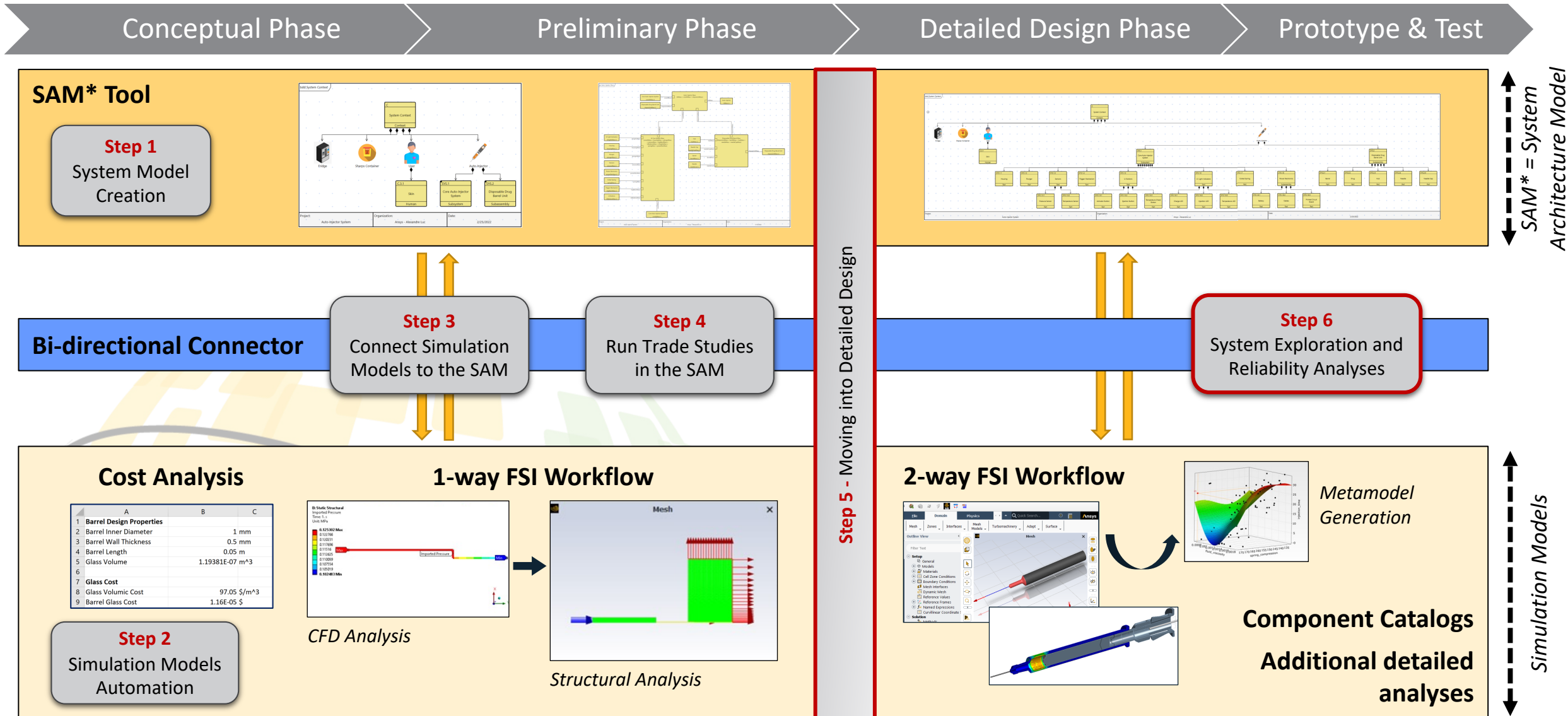
**Structural Analysis**

**Step 2**  
Simulation Models Automation

Simulation Models

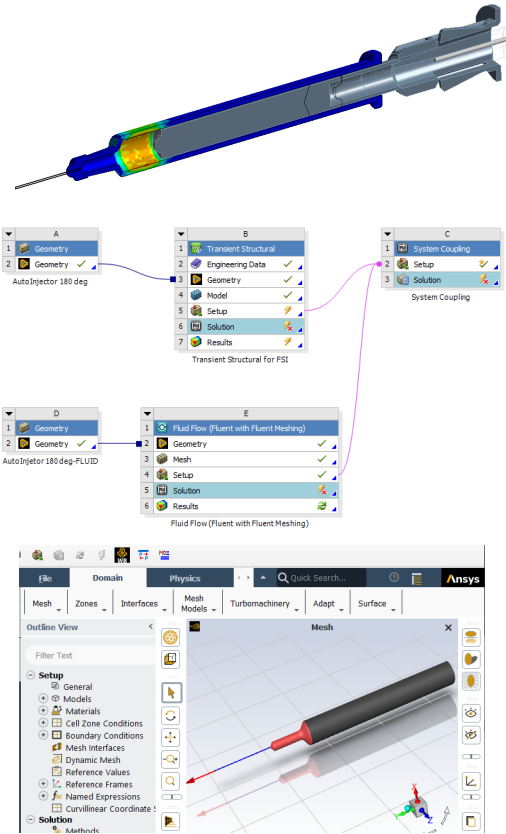


# Step 5: Moving into Detailed Design

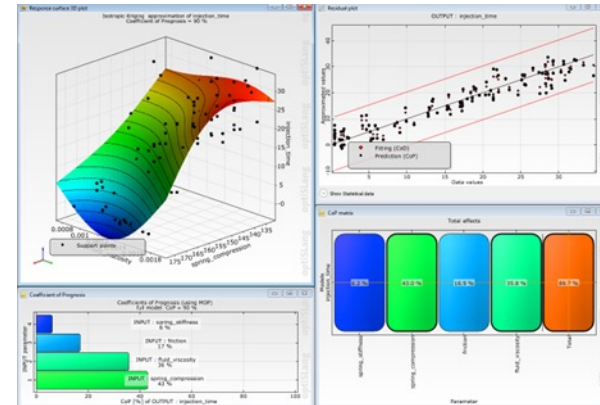


# Surrogate Model Generation

## 2-way FSI Model



## Surrogate Model



# Detailed Analyses Integration in the SAM



Low-Fidelity Analyses replaced by higher fidelity models



Additional Simulation Models connected to the SAM



Further Design Exploration Studies

Execution Plan 1\* x

Structure Elements					
Name	Value	Type	Units	Associated Analyses	
SYs.2.1 Barrel					
barrelFriction	5.0000E-2	Real	N	2-way FSI Metamodel_AI 2.0	
barrelInnerDiameter	6.3500	Real	mm	Safety Factor Workflow_AI 2.0, Material Catalog Workflow_AI 2.0, 1-way FSI Workflow_AI 1.0	
barrelLength	5.0000E-2	Real	m	Material Catalog Workflow_AI 2.0	
barrelMaterial	Polycarbonate	String		Material Catalog Workflow_AI 2.0	
barrelMaterialCost			\$	Auto-Injector System_Auto-Injector Cost, Material Catalog Workflow_AI 2.0	
barrelMaterialDensity			kg/m <sup>3</sup>	Material Catalog Workflow_AI 2.0	
barrelSafetyFactor				Safety Factor Workflow_AI 2.0, Barrel_barrelSafetyFactor_gte_3_5	
barrelWallThickness			mm	Safety Factor Workflow_AI 2.0, Material Catalog Workflow_AI 2.0	
barrelYieldStress			MPa	Safety Factor Workflow_AI 2.0, Material Catalog Workflow_AI 2.0	
SYs.2.2 Drug					
drugDensity	999.80	Real		1-way FSI Workflow_AI 1.0	
drugInletTemp	293.15	Real	K	1-way FSI Workflow_AI 1.0, Temperature Viscosity Formula_AI 2.0	
drugViscosity	1.0000E-3	Real	Pa.s	2-way FSI Metamodel_AI 2.0, 1-way FSI Workflow_AI 1.0, Temp	
SYs.2.3 Hub					
hubCost	0.10000	Real	\$	Auto-Injector System_Auto-Injector Cost	
SYs.2.4 Needle					

Analyses (9 of 10 selected)

- 1-way FSI Workflow\_AI 1.0
- 2-way FSI Metamodel\_AI 2.0
- Auto-Injector System\_Auto-Injector Cost
- Auto-Injector\_AllInjectionTime\_gte\_8\_Ite\_10
- Barrel\_barrelSafetyFactor\_gte\_3\_5
- Material Catalog Workflow\_AI 2.0
- Safety Factor Workflow\_AI 2.0
- Spring Catalog Workflow\_AI 2.0
- Spring Compression Feasibility Check\_AI 2.0
- Temperature Viscosity Formula\_AI 2.0

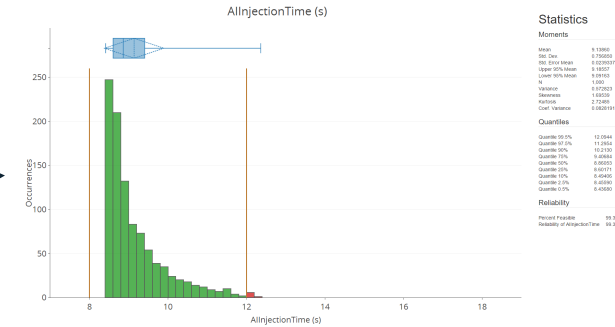
MaterialType	Yield Stress (MPa)	Ave Price (Eur/kg)	Density (kg/m <sup>3</sup> )
16 Polycarbonate	62.5	1.76	1200
19 Polypropylene	34.6	0.8	931
20 Polyethelene (high density)	28.4	1.05	954
21 Polyethelene (low density)	11.0	0.79	921
22 Soda Glass	7.0	0.70	2520

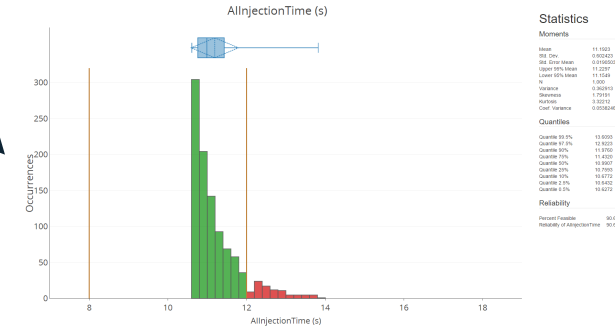
Requirements	
Name	Associated Analyses
R.0 R.0 Auto-Injector System Description	
R.0.3 R.0.3 Auto-Injector System Injection Capability	
R.0.3.4 R.0.3.4 Spring Compression Range	Spring Compression Feasibility Check_AI 2.0
ParameterRequirements	
Barrel.barrelSafetyFactor_gte_3_5	Barrel_barrelSafetyFactor_gte_3_5
Auto-Injector.AllInjectionTime_gte_8_Ite_10	Auto-Injector_AllInjectionTime_gte_8_Ite_10

# Step 6: Trade Study Results and Reliability Check

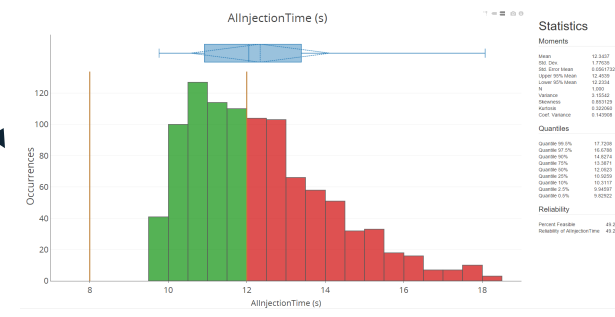
Spring Type	Spring Compression (mm)	Barrel Wall Thickness (mm)	Barrel Material Type	Barrel Friction (N)	Barrel Safety Factor	AI Price (\$)	AI Injection Time (s)
PC965-12065	132	0.8	Polycarbonate	0.0362	21.78	1.29	11.96
PC1143-25400	132	0.8	Polycarbonate	0.029	21.78	1.29	11.55
PC965-12065	132	0.8	Polycarbonate	0.0344	21.78	1.29	10.92
PC965-12065	132	0.8	Polycarbonate	0.0326	21.78	1.29	9.89
PC965-12065	137.6	0.8	Polycarbonate	0.038	21.78	1.29	9.87
PC965-12065	132	0.8	Polycarbonate	0.0308	21.78	1.29	8.91
PC965-12065	137.6	0.8	Polycarbonate	0.0362	21.78	1.29	8.77



**Optimal Design Candidate 1**  
*Reliab: 99.30%*



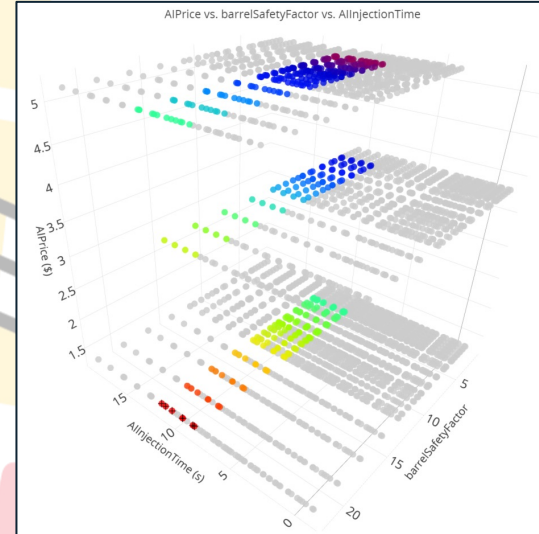
**Optimal Design Candidate 2**  
*Reliab: 90.60%*



**Optimal Design Candidate 3**  
*Reliab: 49.20%*

Trade studies identified a set of potential optimal design configurations

Monte Carlo analysis was then used to check the reliability of select design configurations against drug temperature variation



# Benefits & Challenges



## Keys Benefits

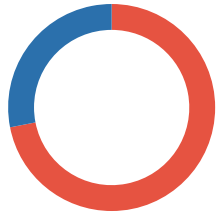
- Tooling and methodology to **support collaboration** between Systems Engineers and SMEs
- **Gain** in productivity & **Reduce risks**
- **More time** spent on Trades from early Conceptual Stage
- Drive **innovation**



## Challenges

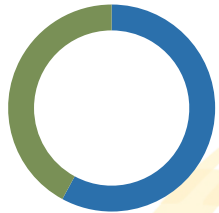
- **Accessibility** to analytical models from experts
- **Complexity** going into detailed design: need to reduce models.
  - Where to stop the integration?
- **Process change** required for companies having SMEs and Systems Engineers working in silos.
- Architectural Trade-Off: Implies having a 150% model.
  - How to handle **variation points** in simulations?
  - Requires creation of customized workflows for now.
- In this study, integration with Physical Architecture only, not with the **Functional Architecture**.
  - Potential topic to address next.

# Take-aways



## **Keys - Parameterization and Constraint Definition**

The key to successful integration of Systems Models and Multi-Fidelity Analytical Models is proper parameterization and constraint definition.



## **Unlocking the promise of MBSE**

Bridge the gap between Systems Engineering and Domain / Disciplinary Engineering by connecting System Models to Simulation and Analytical Models.



## **Verifying Requirements and Trading off Cost, Performance & Risk**

Leverage Simulation to perform Requirements Verification, and to trade between several architectures / design configurations, from the early stages of the Development Process.





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