SYSTEMS MODELING, SIMULATION AND OPTIMIZATION IN A HETEROGENEOUS WORLD

Johan Åkessson, CTO

Modelon

THANKS TO

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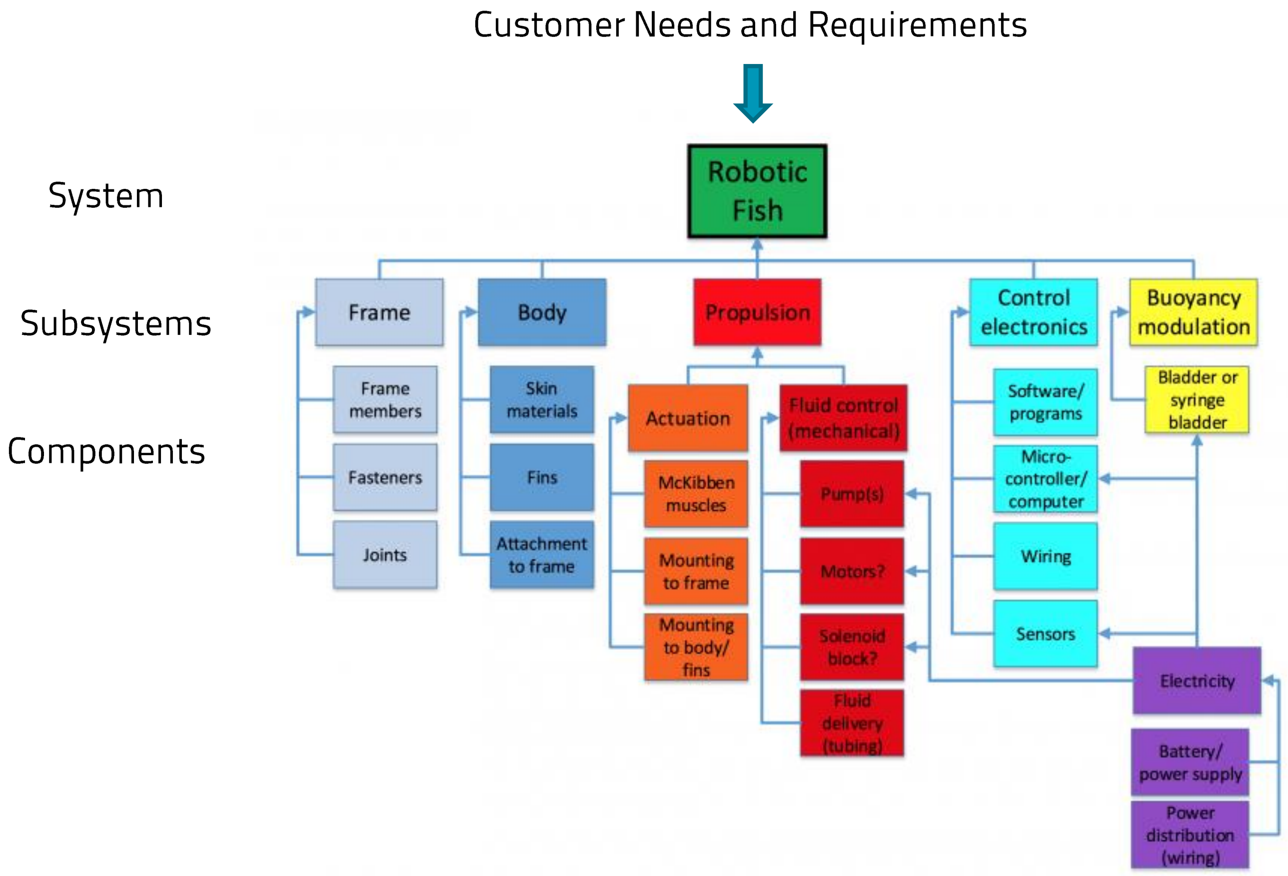
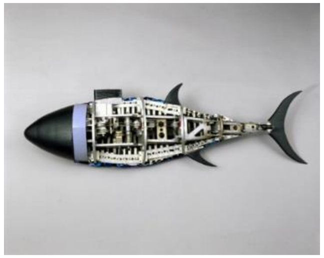
OUTLINE

- Model-based Systems Engineering
- Heterogeneity
- Application examples

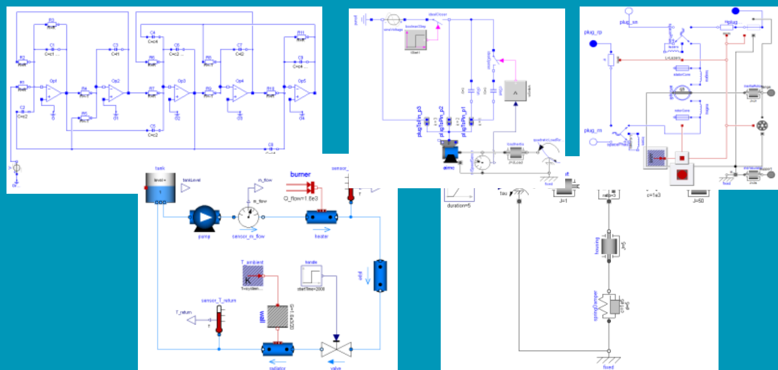
SYSTEMS ENGINEERING CHALLENGE





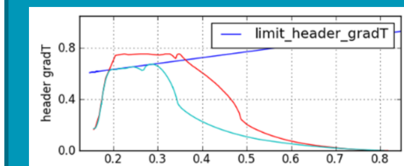
PRELUDE – HETEROGENEITY IN MBSE

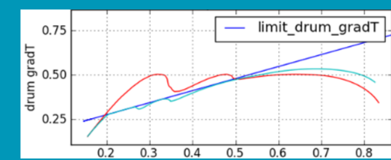
Physical domains



Analysis

$$F(\dot{x}, x, y) = 0, x(0) = x_0$$

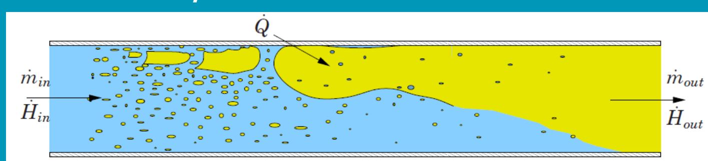


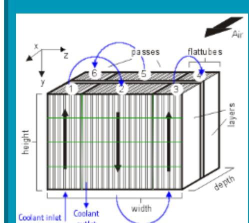


$$\min \int_{t_0}^{t_f} L(\dot{x}, x, y, u, p)dt$$

$$\text{s.t. } F(\dot{x}, x, y, u, p) = 0, x(0) = x_0$$

Model fidelity





$$\dot{\mathbf{x}} = \mathbf{f}_x(\mathbf{x}, \mathbf{m}, \mathbf{u}, \mathbf{p}, t)$$

$$F(x) = 0, \quad x_0 = x^0$$

Tools

Wolfram SystemModeler

SimulationX

Excel

IPG Automotive

MATLAB SIMULINK

SCADE SUITE

Adams

Dymola Multi-Engineering Modeling and Simulation

MapleSim

MSC Software

MODELON

Expert partner in open-standards solutions for computational model-based engineering

- Centered around **Modelica** and **FMI** open standards for model authoring, analysis, and deployment
- R&D and distribution of best-of-breed software components
- Services with excellence in domain expertise and industry applications

Modelon

MODELON BACKGROUND & PROFILE

- Product and service company: solutions
  - Dymola (Dassault Systèmes)
  - Modelica libraries (Modelon)
  - FMI Tools (Modelon)
  - Custom toolchains (Modelon)
- Expert profile: MSc + PhD
- Spin-off from Automatic Control @ Lund University
  - Origin of Modelica technology
  - Leaders in system control modeling and simulation since 1970s
- Modelica Association
  - Active in Modelica and FMI standards development
- Academic
  - Engagement in LCCC
  - MS thesis projects

Modelon

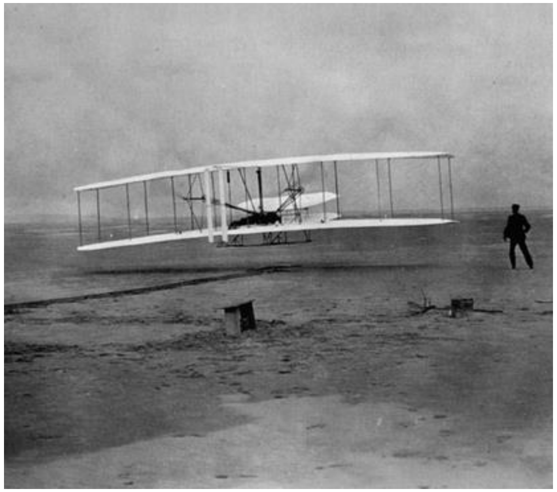
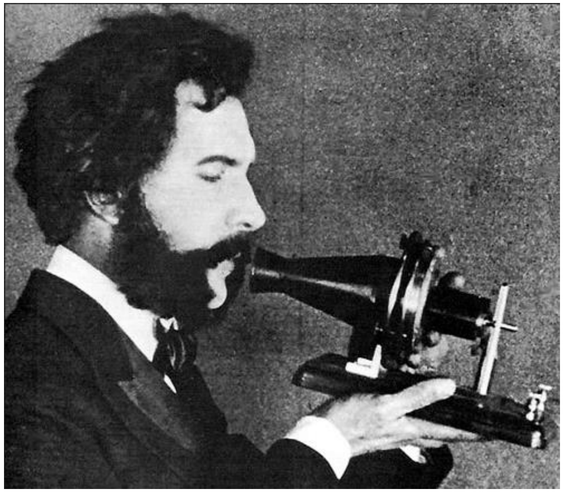
SOLUTIONS PARTNER 2013

MathWorks Partner

PART I

MBSE

SYSTEMS: ADVANCING RELENTLESSLY

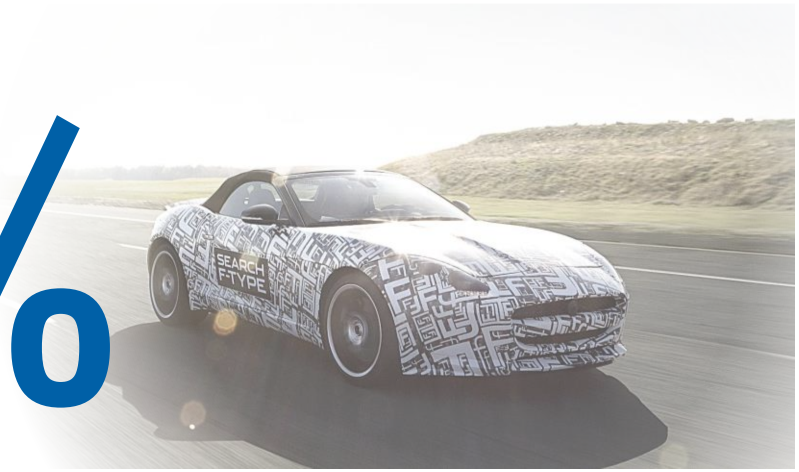





MOTIVATION

Source: 3D Experience Forum, Mannheim, June 26 2013

Approximately

60%



of development time no physical prototype is available!

How to achieve an earlier vehicle evaluation & validation?

MOTIVATION

Source: 3D Experience Forum, Mannheim, June 26 2013

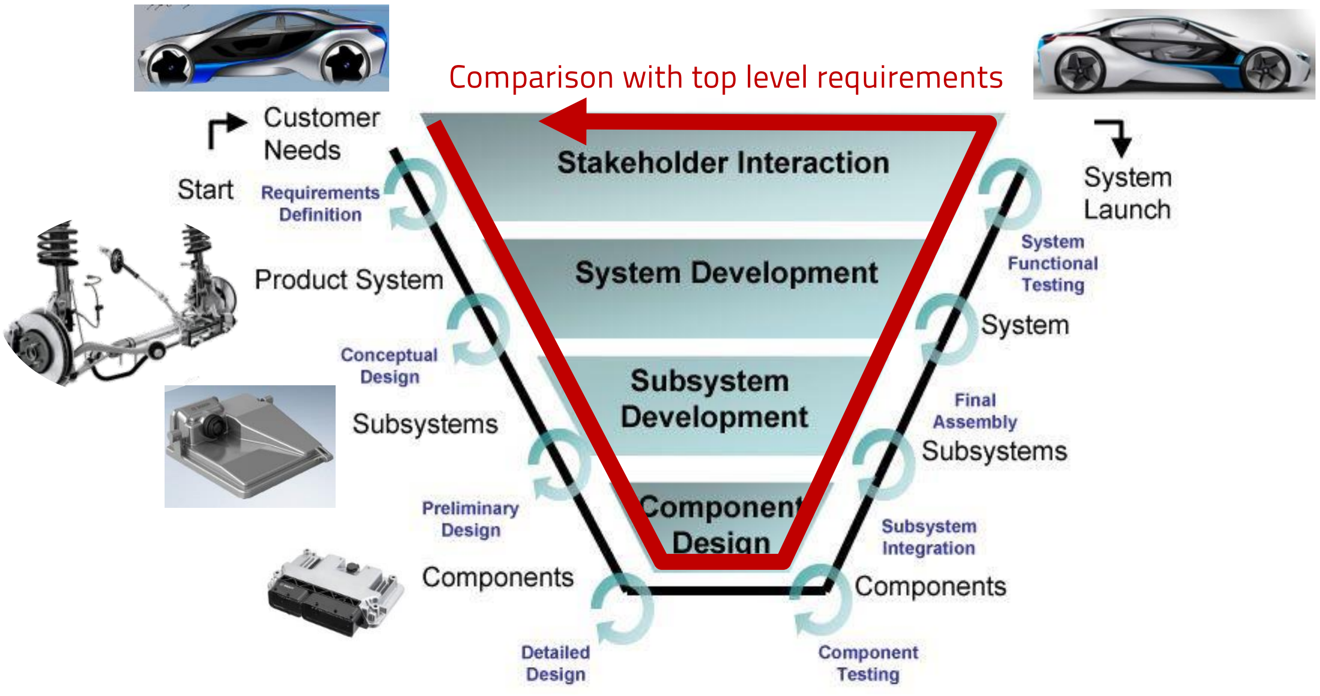
Less than

10%

of engineers get evaluation experience in the full vehicle.

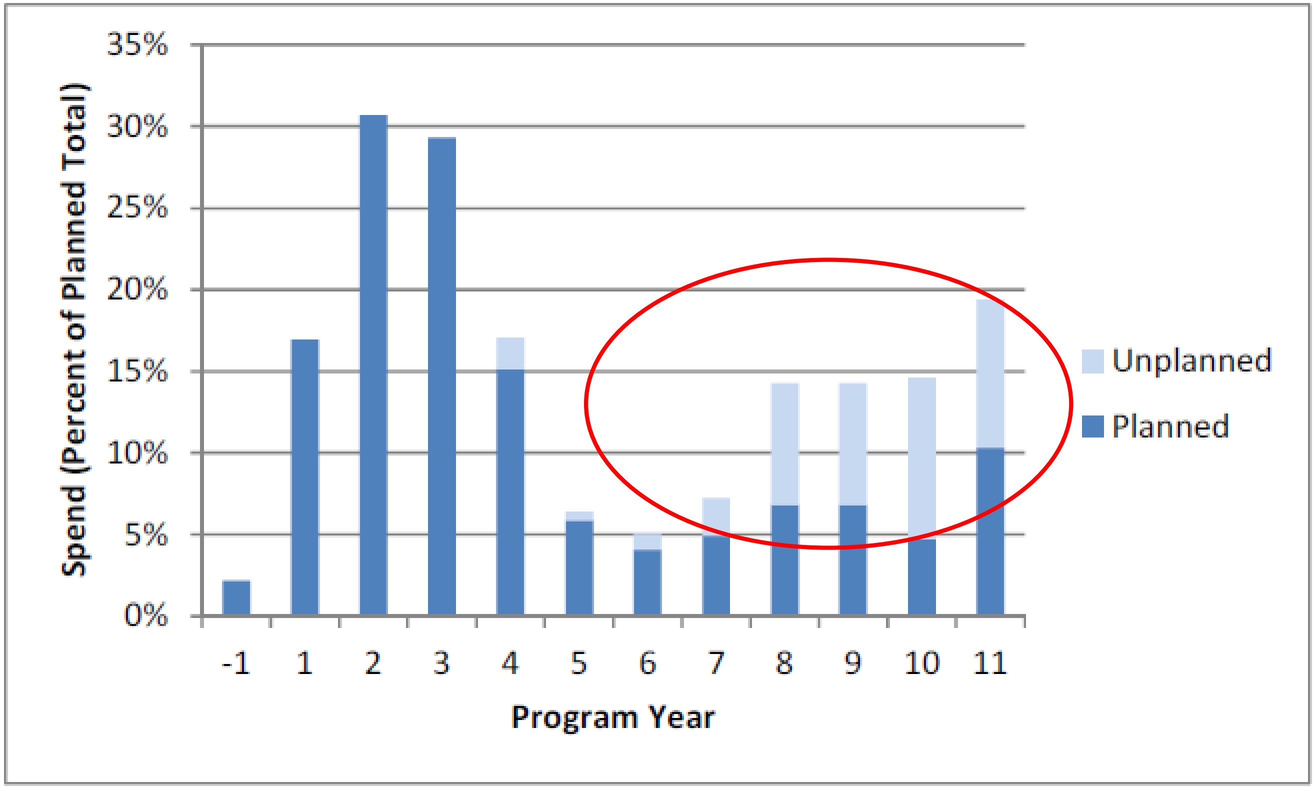
How can we enable engineers to validate in the full vehicle?

THE V MODEL



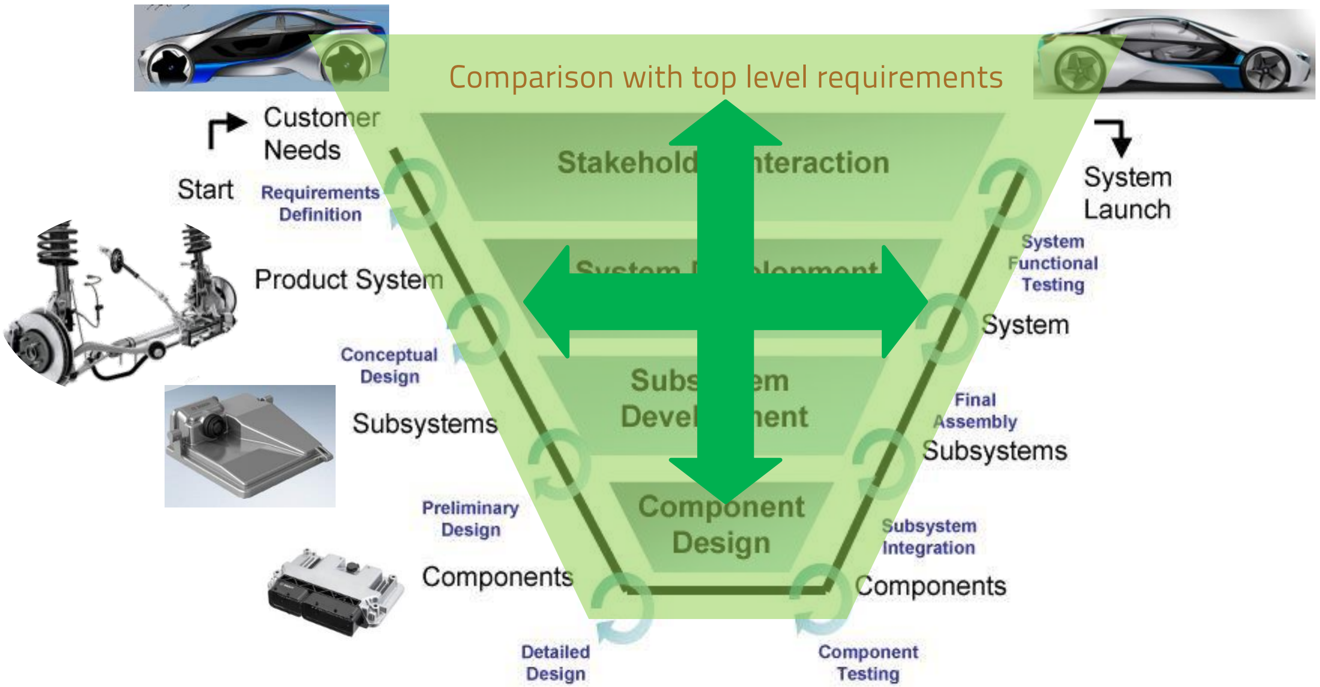
System verification very late or even too late!

COST OF POOR QUALITY



Kevin Otto: "Robust Design" Presentation Lund February 2012

THE V MODEL REVISED



ANY task at ANY level of the system can be verified against ANY requirement at ANY time!

Modelon

PART II

Modelica and FMI

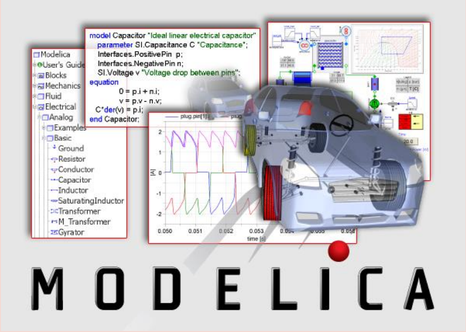
WHAT IS MODELICA ?

- Modelica is a free modeling language developed and owned by the Modelica Association
  - Non-profit organization
  - Over 100 members
  - Active development through the Modelica Design Group
  - Develops the largest, free library for multi-domain models, the Modelica Standard Library
- The Modelica language
  - Object-oriented modeling language
  - Acausal and equation based
  - First principles (mass, energy, momentum balances)
  - Supports multi-domain modeling

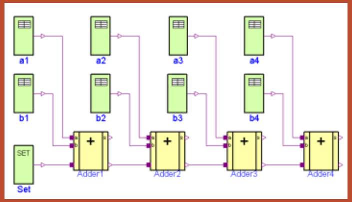
Think HTML for modeling

MODELICA LANGUAGE AND MODELICA STANDARD LIBRARY

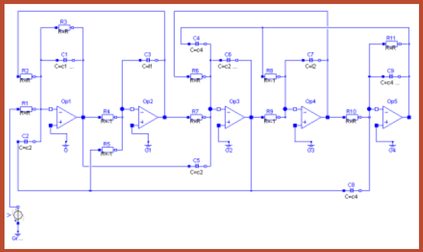
Modelica® is a non-proprietary, object-oriented, equation based language to conveniently model complex physical systems containing, e.g., mechanical, electrical, electronic, hydraulic, thermal, fluid, control, electric power or process-oriented subcomponents.



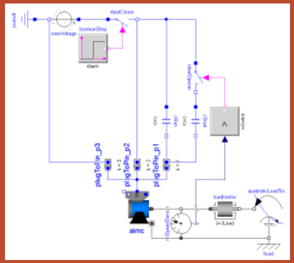
Electrical (Digital)

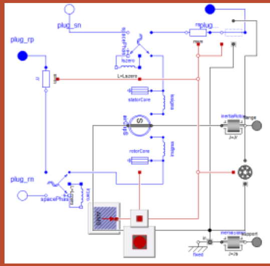


Electrical (Analog)

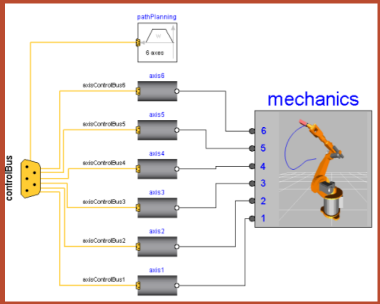


Electrical (Mechanical)

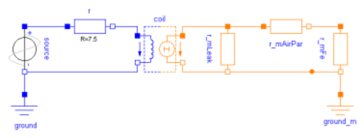




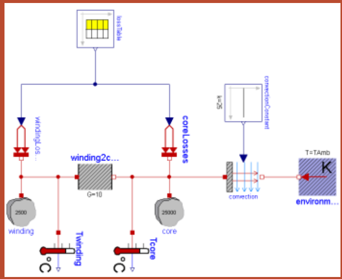
Mechanics (MultiBody)



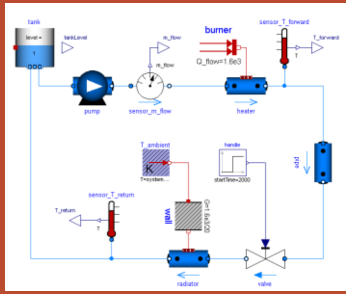
Magnetic



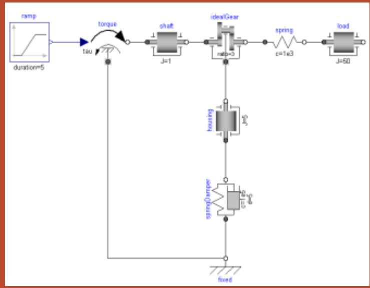
Thermal (Heat Transfer)



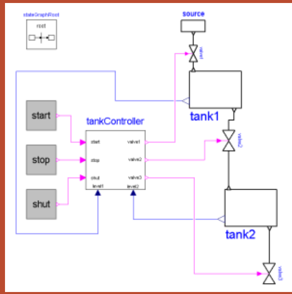
Fluid



Mechanics



StateGraph



- Object-oriented and equation based modeling language from non-profit Modelica Association
- Model structured like schematics with reusable objects and couplings
- Behavior defined by:
  - First principles (mass, energy, momentum balances)
  - Equations!
- www.modelica.org

Modelica Tools (Commercial and Open Source)

Dymola

DASSAULT SYSTEMES

Modelon

MapleSim 6

SimulationX
Powered by ITI

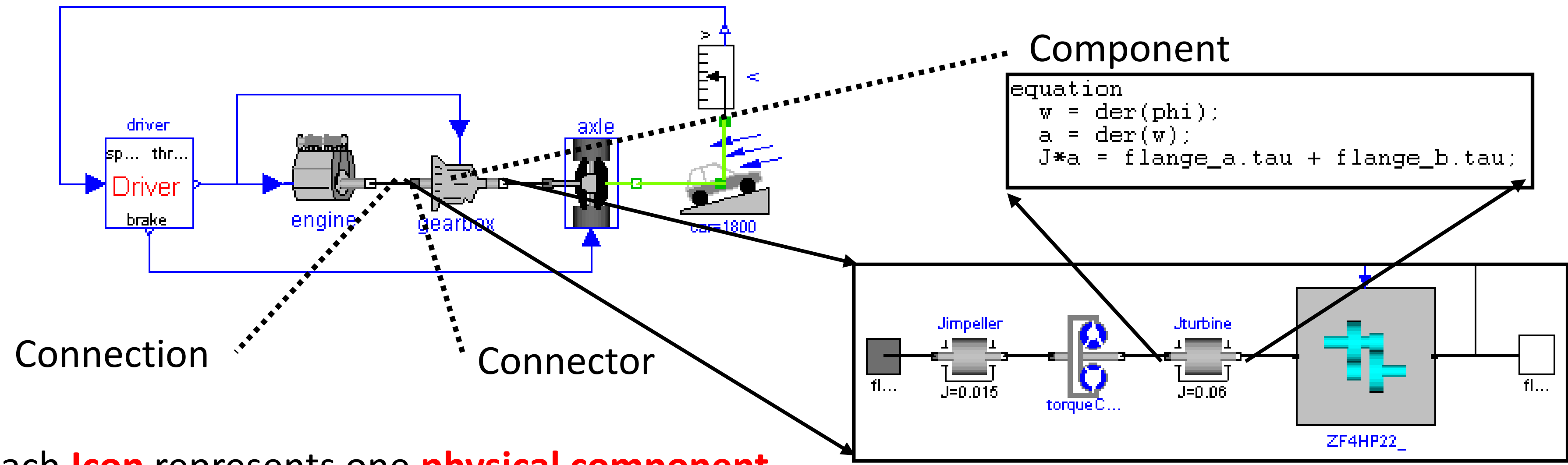
Wolfram SystemModeler

JModelica.org

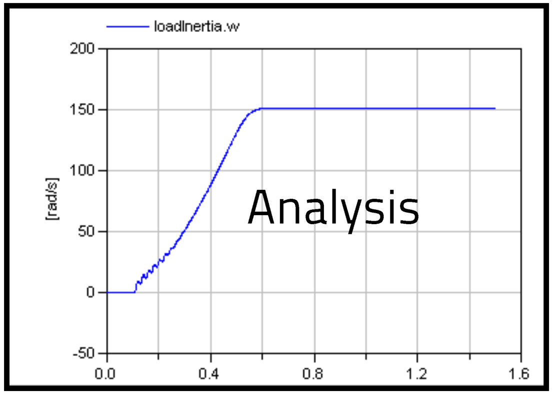
OpenModelica

Many tools – a single, standardized modeling language

OBJECT ORIENTED MODELING



- Each **Icon** represents one **physical component**.
  For example, electrical resistance, mechanical device, pump
- A **connection line** represent the actual physical **coupling**. For example, electrical wire, rigid mechanical coupling.
- **Variables** in the **connectors** define the **Interaction** to other objects
- A component consists of **connected** sub-components (= hierarchical structure) and/or is described by **equations**.

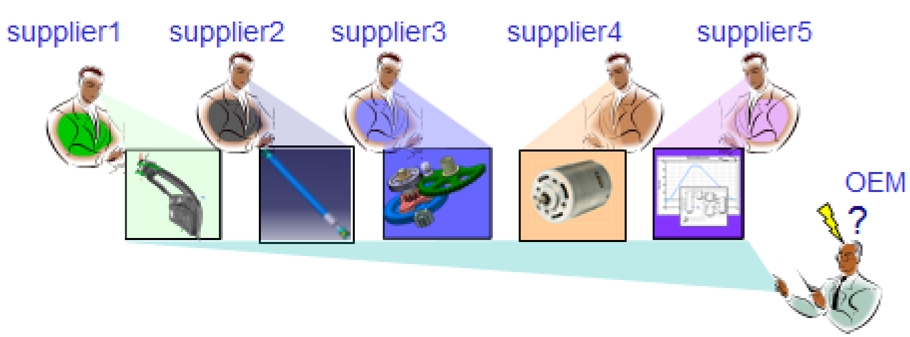


FUNCTIONAL MOCKUP INTERFACE (FMI)

- Tool independent standard to support both model exchange and co-simulation of dynamic models
- Original development of standard part of EU-funded MODELISAR project led and initiated by Daimler
- First version FMI 1.0 published in 2010
- ***FMI currently supported by more than 60 tools***
  (see www.fmi-standard.org for most up to date list)
- Active development as Modelica® Association project
- FMI 2.0 released July 2014 and brings additional functionality to FMI standard

Problems / Needs

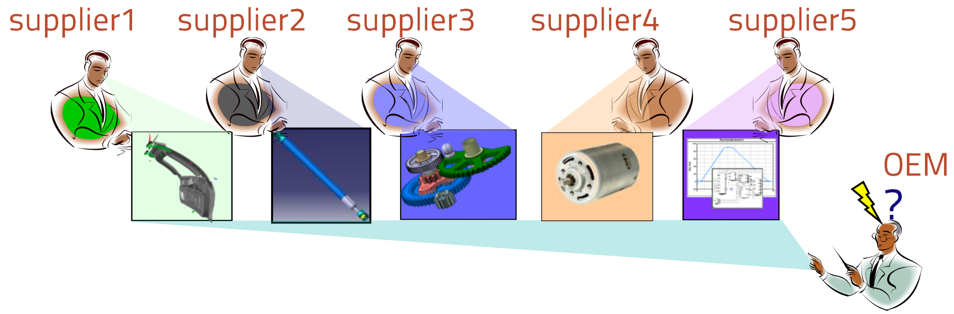
- Component development by supplier
- Integration by OEM
- **Many different simulation tools**



WHY FMI?

Problem

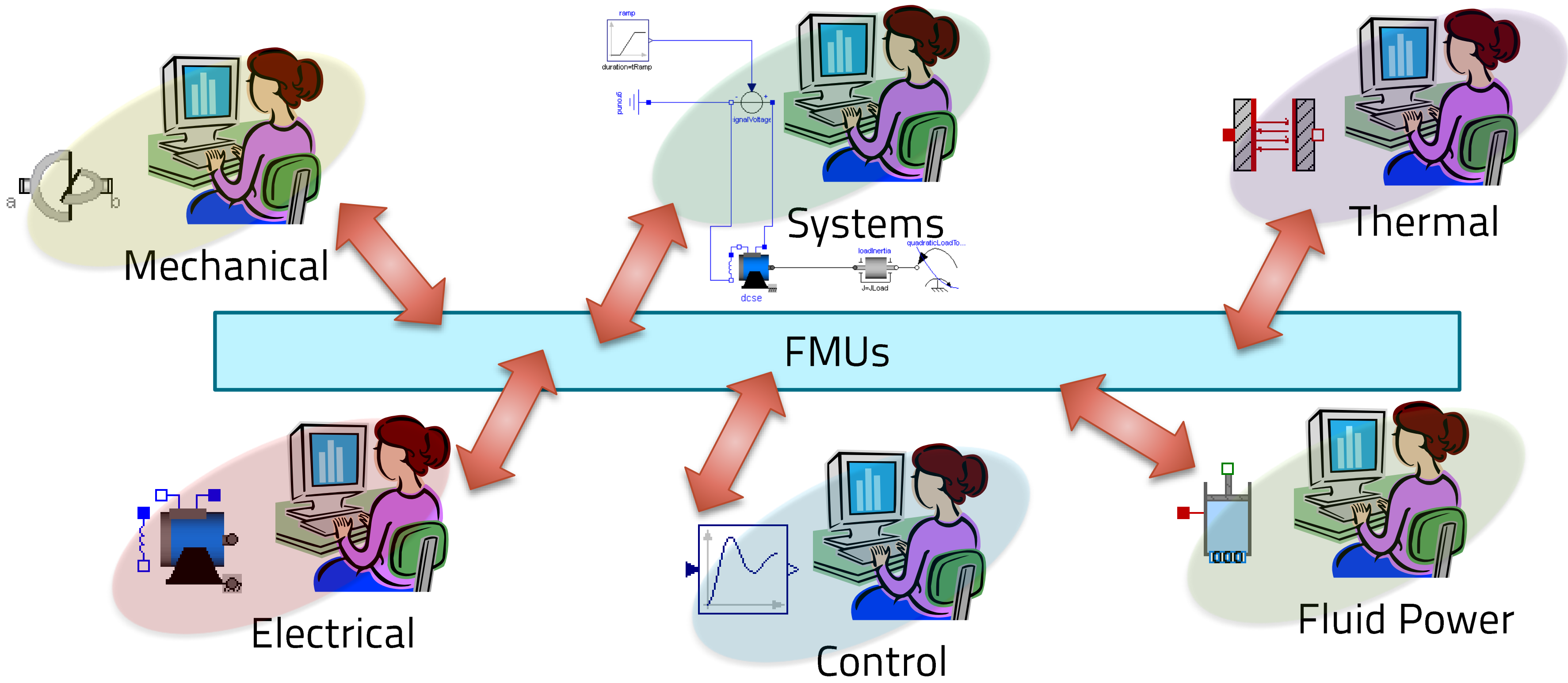
- Due to **different applications**, **models** of a system often have to be developed using **different programs** (modeling and simulation environments).



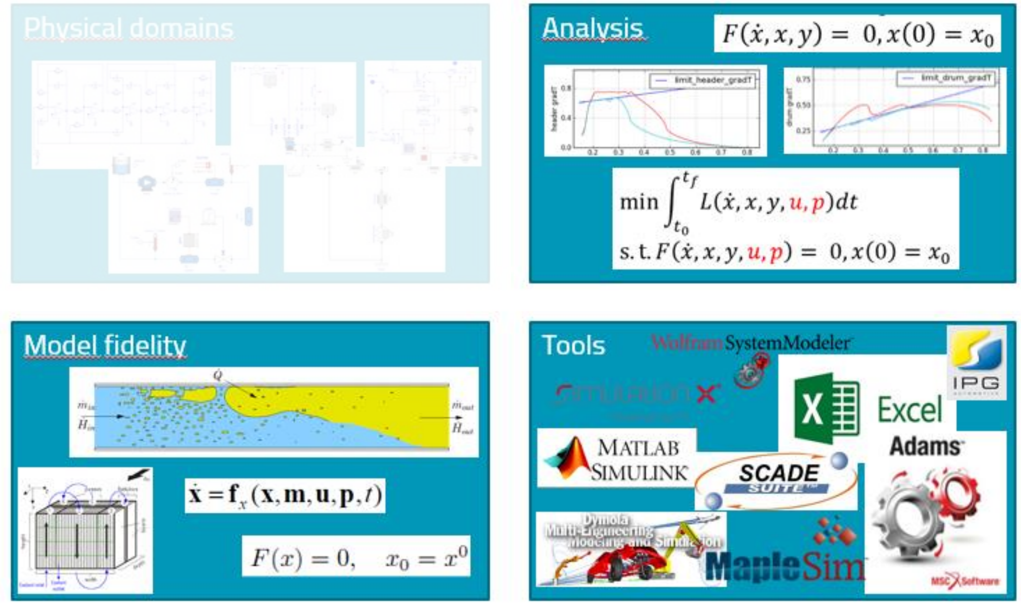
- In order to **simulate** the system, the different programs must somehow interact with each other.
- The system integrator must cope with simulation environments from many suppliers.
- This makes the **model exchange** a necessity. No current standardized interface.
- Even though **Modelica®** is tool independent, it cannot be used as such a standardized interface for model exchange.

MULTIDOMAN COLLABORATION

- Engineers in different domains work **with FMUs**
  - Share models, distributed collaboration, work in tool of choice, reduced license costs, protect IP, couple carefully!!



Modelon

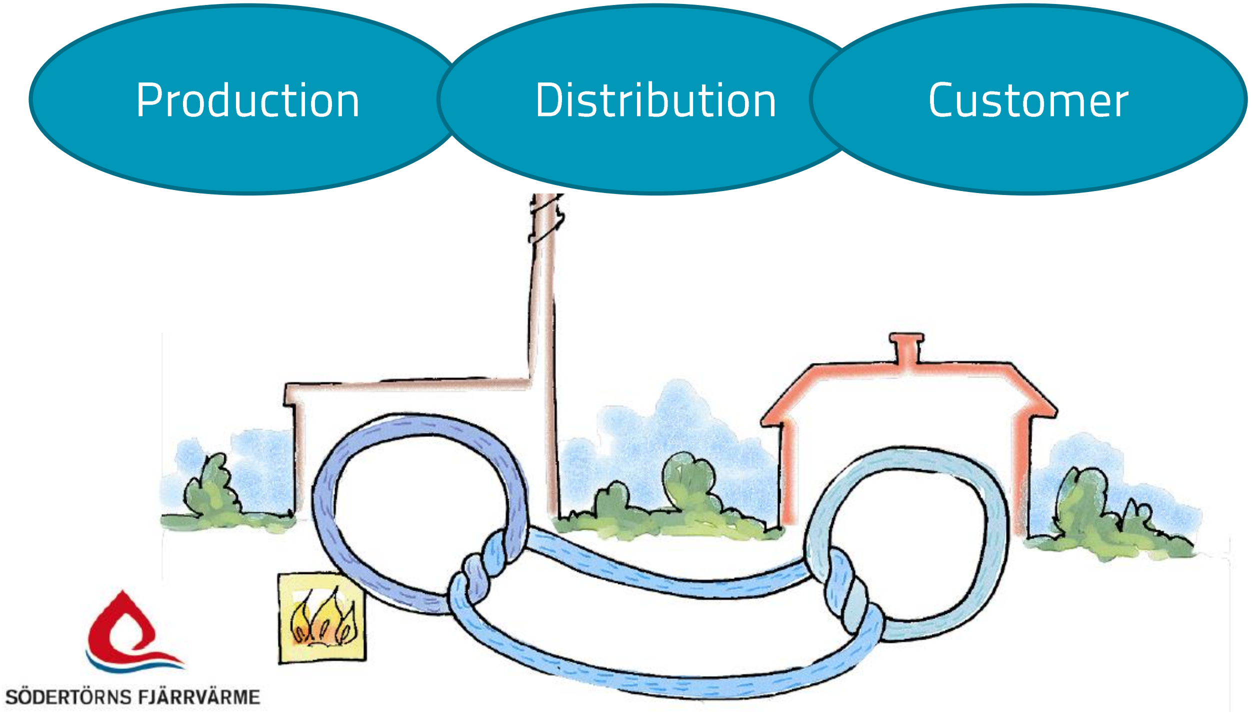


PART III

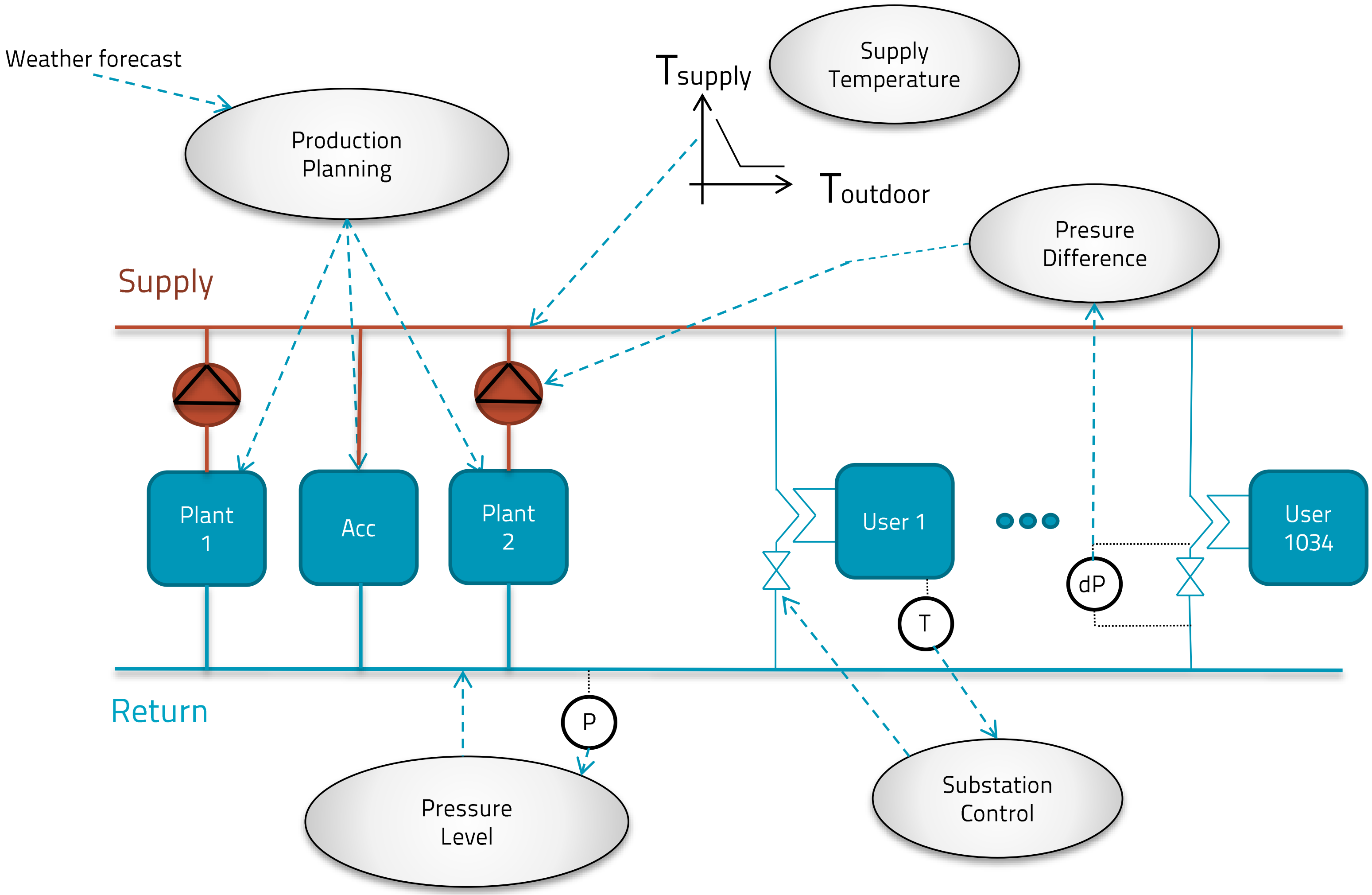
Short-term production planning in district heating networks

Modelon

DISTRICT HEATING NETWORK



NETWORK



Energy Management and Control in Buildings

OPTIMIZATION PROBLEM

Objectives

- Heat balance (supply = demand)
- Economy
  - Maximize electricity production
  - Minimize production and operation cost
  - Minimize heat loss
- Safety and availability
- Environment and sustainability

Degrees of freedom

- Production units
- Supply temperature and flow
- Storage (accumulator, network, buildings)

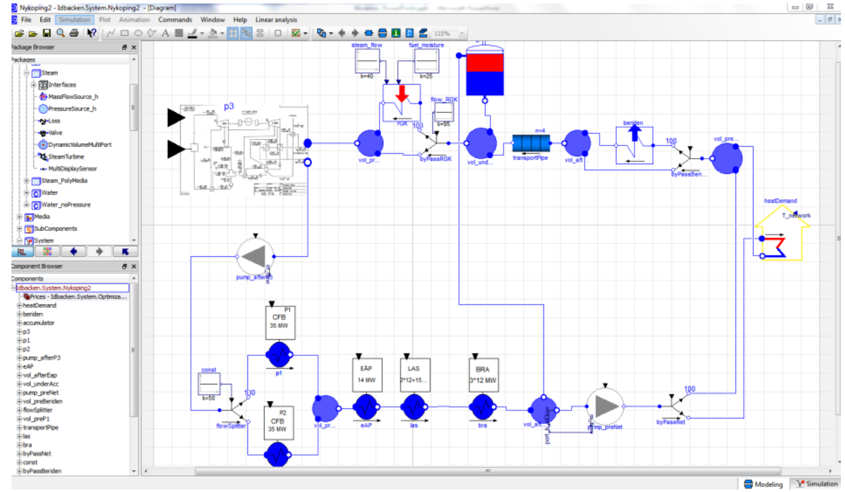
PROPOSED SOLUTION IN 2 STEPS

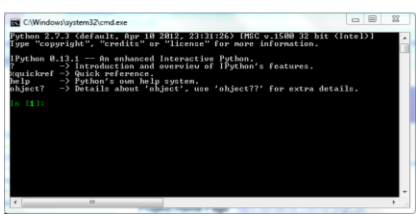
- **Step1: Unit Commitment**
  - Simple, linear, discrete-time plant models
  - Mixed Integer Linear Programming
  - Optimized status (on/off) of plants (and heatflows)
- **Step 2: Economic Dispatch**
  - Known status (on/off) from Step 1
  - Physical plant models
  - Nonlinear dynamic optimization, initialized by Step 1
  - Optimized temperature, flows, electricity, storage

Base-line approach:
Mixed integer linear programs

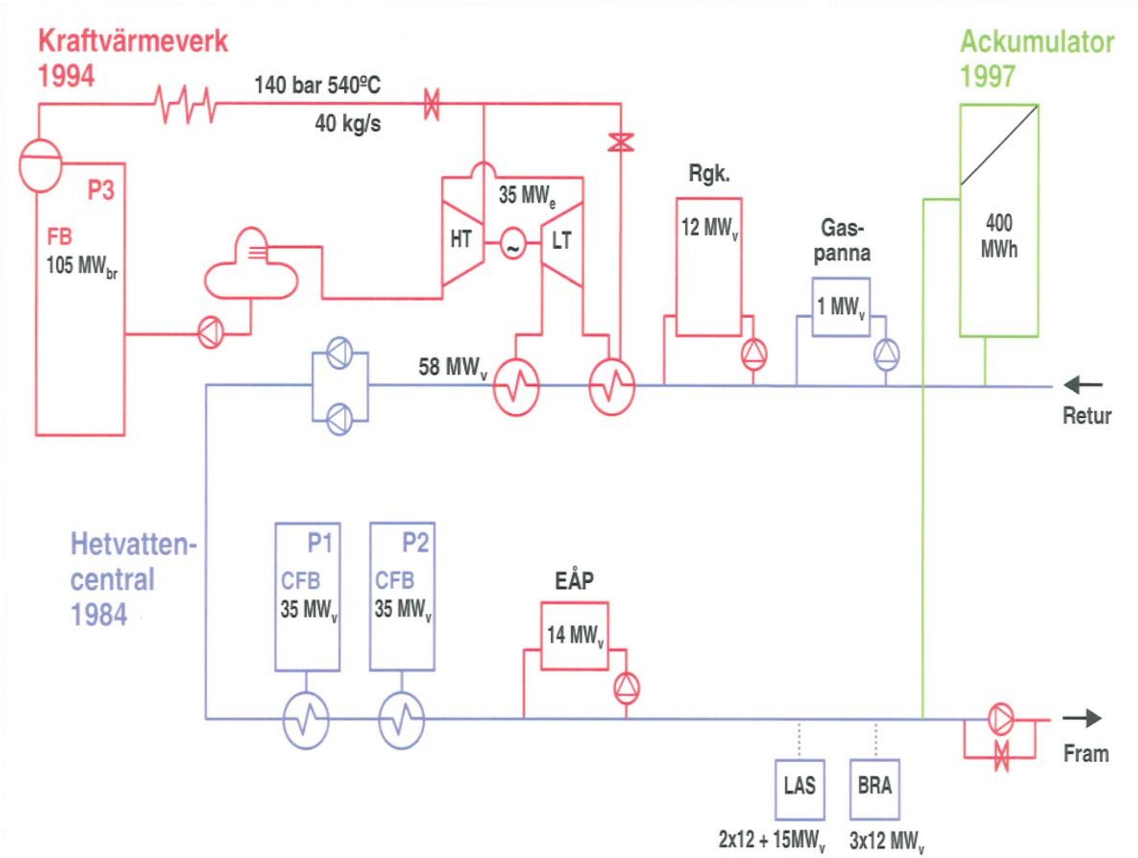
TOOLS

- Model development in **Dymola**
  - Optimization-friendly models
- **Gurobi** for solving MILPs (UCP)
- Dynamic optimization with **JModelica.org** (EDP)
  - Collocation
  - Time delay support
- **Python** to interact with models and results





CASE STUDY: IDBÄCKEN, VATTENFALL AB



Main DOF

- 8 production units
- 1 accumulator
- 1 cogeneration plant
- 1 external cooler
- Distribution pump
- Circulation pump

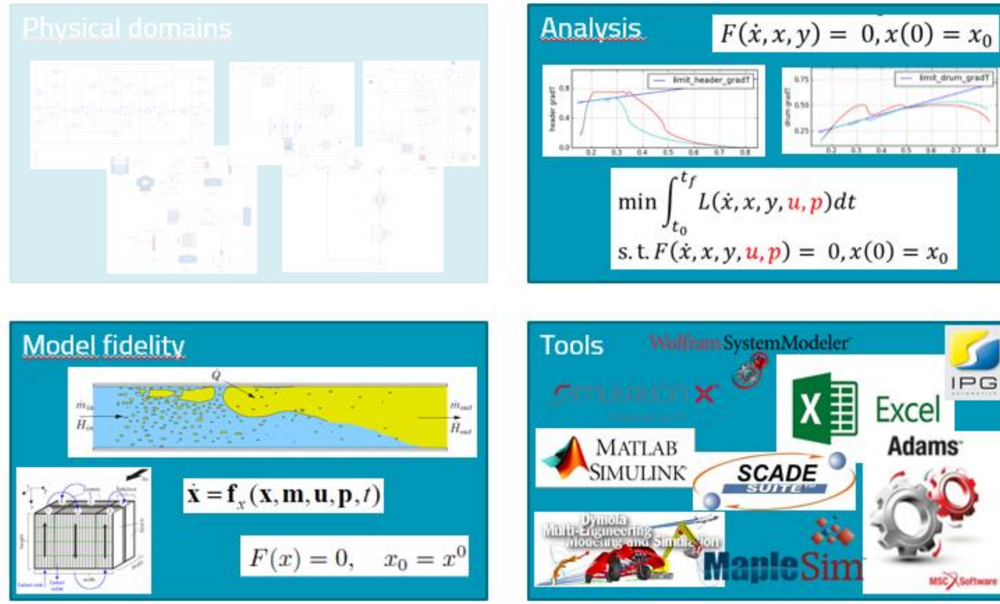
Physical model

- Cogeneration plant
- Accumulator
- DH water

Economic optimization for both UCP and EDP

Results

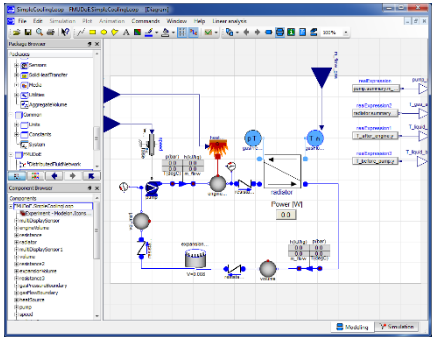
- Feasible to integrate physical models in economic dispatch problem
- Higher quality of plans (compared to MILP-based & measurement data)



PART IV

DOE with FMI in MATLAB

SIZING AND CONTROL DESIGN

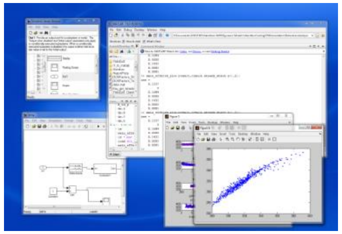


Modelica models

- Complex models
- Nonlinear
- Many parameters

Design and implementation of controllers in Matlab / Simulink

- Prefer simpler models
- Linearizations
- Understanding dominating parameter effects
- Understanding system variability
- Identify worst cases



HOW to get the answers?

COMBINING TWO PARADIGMS

Quality science/ Robust design / Six-sigma / Design-of-experiments

- Steady-state models
- Many parameters
- Data-driven models
- Focus on workflows, processes and tools

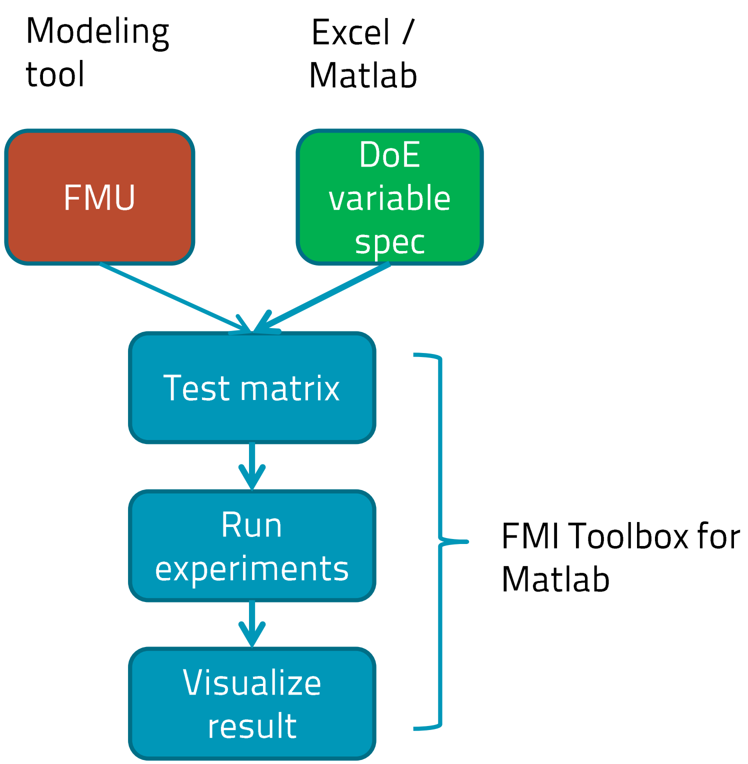
Control engineering

- Dynamic models
- Few parameters
- Physics-based or data-driven models
- Focus on mathematical rigor

➢ Large potential in combining approaches

➢ Modelica and FMI is a suitable platform

DOE IN MATLAB WITH FMI



FMUDoESetup class

constructor input:

- FMU file name
- Excel file name
- [Excel sheet]
- [options]

methods:

- **qmc**
- **mc**
- **fullfact**
- **custom**

FMUDoEResult class

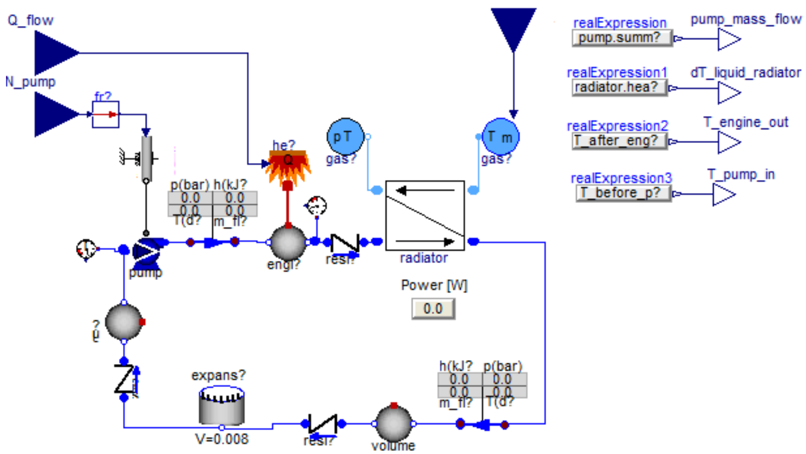
properties:

- **generation_date**
- **model_data**
- **doe**
- **constants**
- **experiment_status**
- **steady_state**
- **linsys**
- **options**
- **comp_time**

visualization methods:

- **main_effects**
- **bode**
- **step**

EXAMPLE: ENGINE COOLING SYSTEM



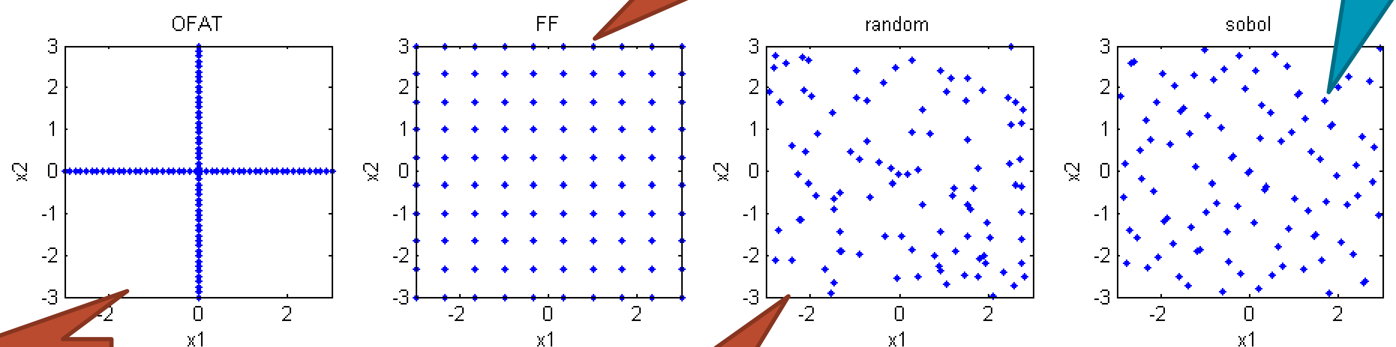
- Demo model from Modelon’s Liquid Cooling Library
- Design variables:
  - Maximum pump speed
  - Radiator efficiency
  - Minimum air mass flow
- Requirements:
  - Engine-out coolant temp < 100C
  - Handle heat load of 100 kW
  - Ambient temperature operating range [-20C, 45C]

DOE DESIGNS

100 test points, two factors

Space-filling algorithms
Good coverage, also in higher dimensions

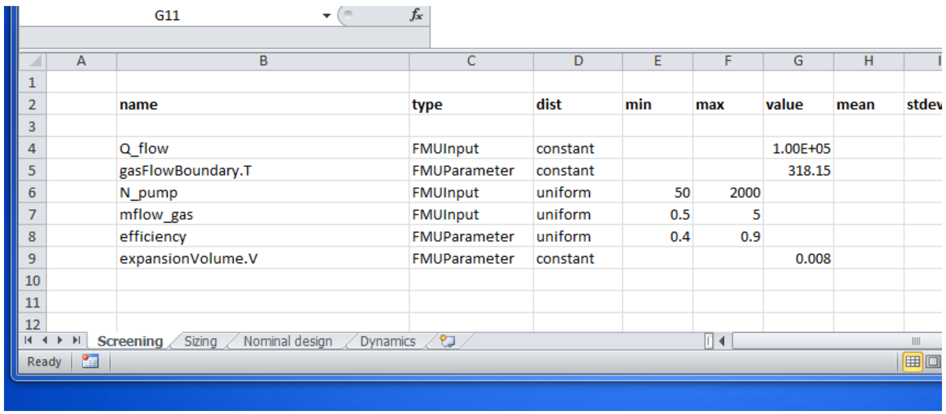
Scales poorly with nbr of factors



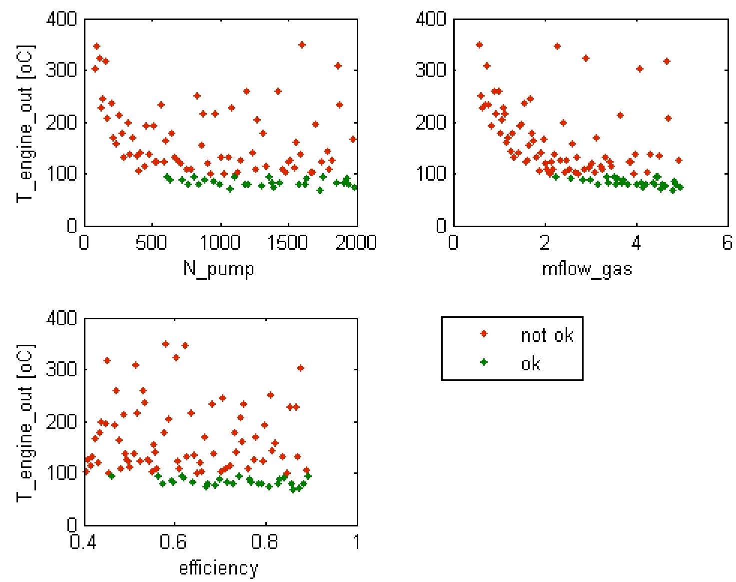
Common ad-hoc approach

Corner cases poorly covered in higher dimensions

SIZING: SCREENING DESIGN SPACE



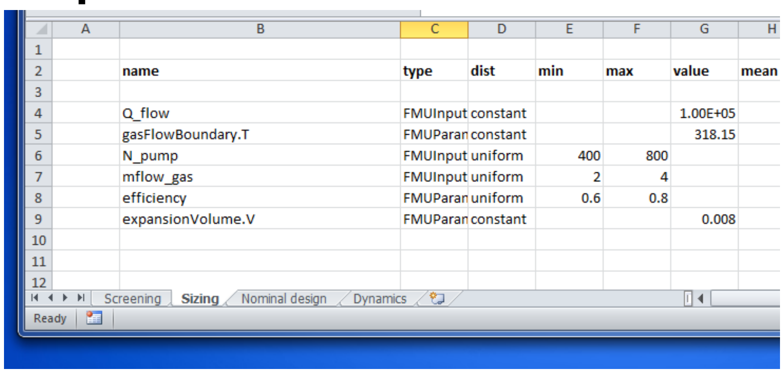
	A	B	C	D	E	F	G	H	I
1									
2		**name**	**type**	**dist**	**min**	**max**	**value**	**mean**	**stdev**
3									
4		Q_flow	FMUInput	constant			1.00E+05		
5		gasFlowBoundary.T	FMUParameter	constant			318.15		
6		N_pump	FMUInput	uniform	50	2000			
7		mflow_gas	FMUInput	uniform	0.5	5			
8		efficiency	FMUParameter	uniform	0.4	0.9			
9		expansionVolume.V	FMUParameter	constant			0.008		
10									
11									
12									




```
>> doe_setup = FMUDoESetup('CoolingLoop.fmu', 'DesignParameters.xlsx', 'Screening');
>> nbr_of_experiments = 100;
>> result = doe_setup.qmc(nbr_of_experiments);
>> T_engine_out = result.steady_state.y( : , 3)
>> result.main_effects(result, 'T_liquid_ae', T_engine_out > 100);
```

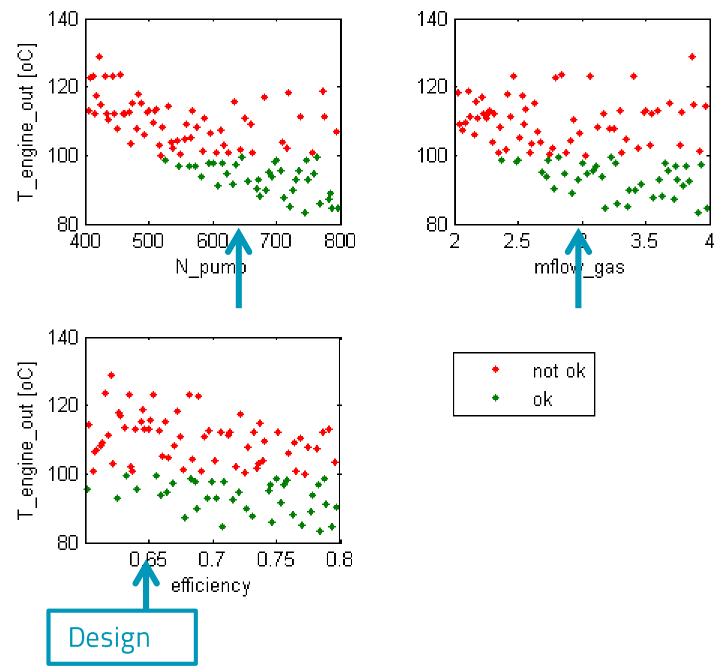
SIZING: DETERMINING A DESIGN

Zooming in to a smaller region of the design space:



	A	B	C	D	E	F	G	H
1								
2		name	type	dist	min	max	value	mean
3								
4		Q_flow	FMUInput	constant			1.00E+05	
5		gasFlowBoundary.T	FMUParan	constant			318.15	
6		N_pump	FMUInput	uniform	400	800		
7		mflow_gas	FMUInput	uniform	2	4		
8		efficiency	FMUParan	uniform	0.6	0.8		
9		expansionVolume.V	FMUParan	constant			0.008	
10								
11								
12								

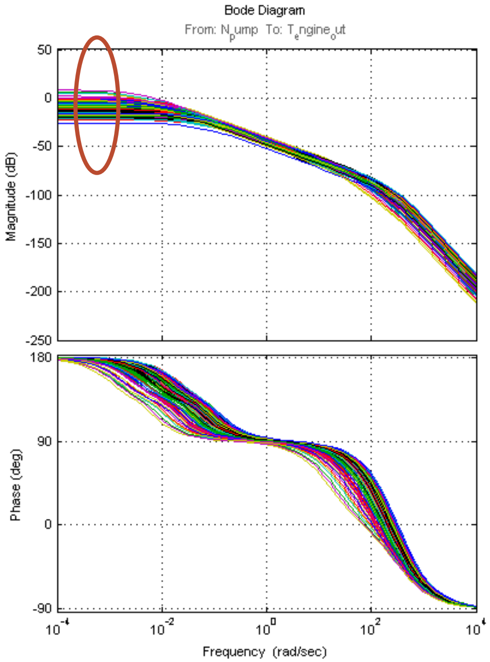

```
>> doe_setup = FMUDoESetup('CoolingLoop.fmu', 'DesignParameters.xlsx', 'Sizing');
>> nbr_of_experiments = 100;
>> result = doe_setup.qmc(nbr_of_experiments);
>> T_engine_out = result.steady_state.y( : , 3)
>> result.main_effects(result, 'T_liquid_ae', T_engine_out > 100);
```

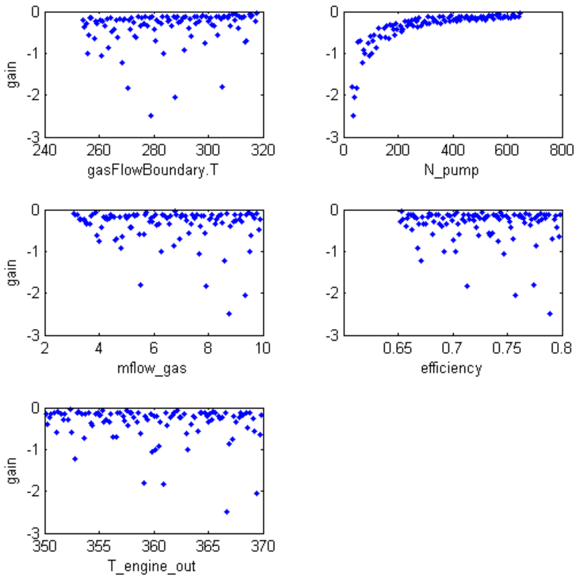


DYNAMICS: WHERE IS THE NONLINEARITY?

- Correlate feature of Bode plot with DoE factors

```
>> N = result.doe.nbr_of_experiments;
>> ss_gain = zeros(N,1);
>> for k = 1:1:N
>>       ss_gain(k) = dcgain(result.linsys.sys{k} (1,
1));
>> end
>> result.main_effects(ss_gain, 'gain');
```

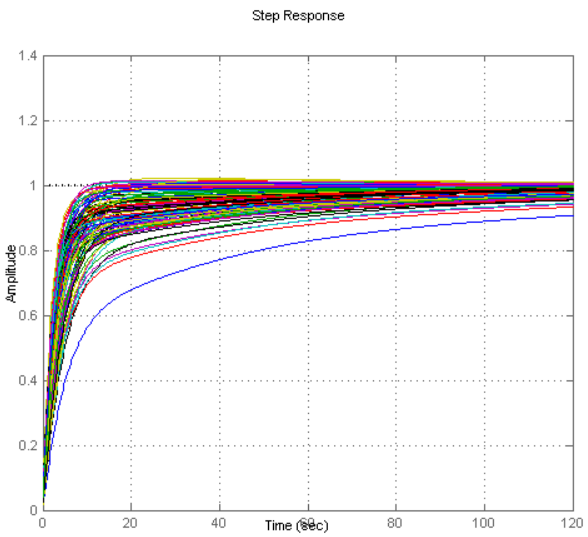




CONTROLLER EVALUATION

- Loop-shaping: PI-controller with K = -50, Ti = 100

- Closed-loop step response




```
>> s = tf('s');
>> Gc = -50*(1+1/(100*s));
>> cl_sys = cell(N,1);
>> for k = 1:1:N
>>      Gp = result.linsys.sys{k}(1, 1);
>>      cl_sys{k} = minreal(Gp*Gc/(1+Gp*Gc));
>> end
>> batch_step(cl_sys);
```

CONCLUSIONS

- Heterogeneity is a challenge in MBSE
  - Physical domains
  - Analysis
  - Model fidelity
  - Tools
- Modelica and FMI can help
- Unresolved challenges remains !