INTO-CPS

Exploring the Cyber-Physical Design Space

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Horizon 2020 Programme

Structure

1. Introduction to INTO-CPS tool chain
2. How we support Design Space Exploration (DSE)
3. Working towards DSE guidance
4. Future directions and getting involved

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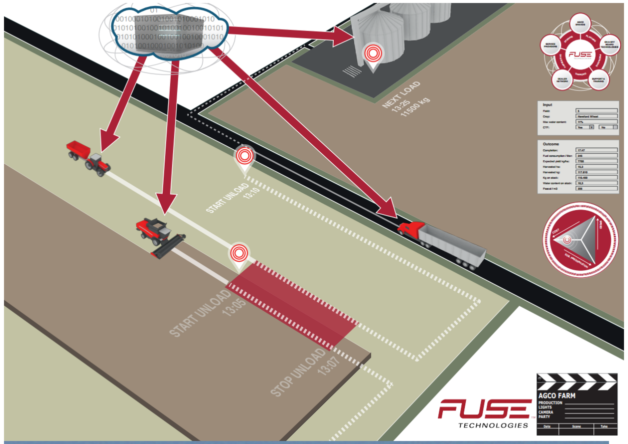
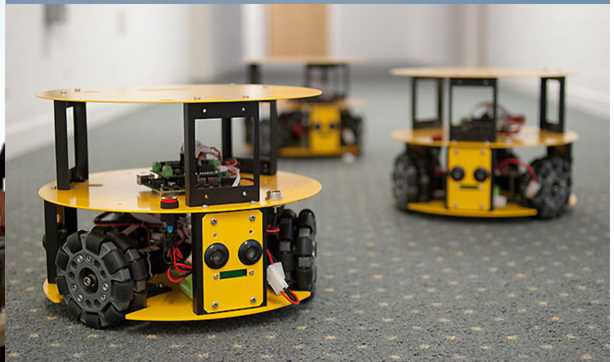
What is a Cyber-Physical System?

- Systems of interacting systems
  - Computing elements
  - Physical elements
  - Human interactions
- Complex, networked character
- Distributed control
- Error detection and recovery





Our position in a nutshell

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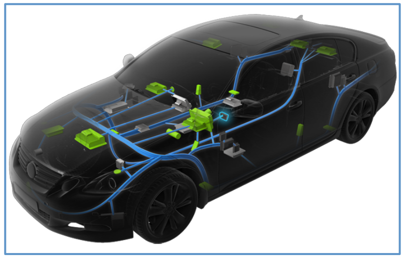
We advocate:

- Cyber-Physical Systems Engineering
  - The product is a system: software is not the end!
- Multidisciplinary collaborative modelling
- (Co-) simulation as well as verification
  - Promotes Design Space Exploration
  - Entails well-founded co-simulation orchestration

Our approach:

- Co-simulation of multiple Discrete Event and Continuous Time models
- A tool chain – not single tools
  - Requirements and Architectural models (in SysML)
  - Traceability support through development
- FMI interfaces constituent models
- Semantic foundations in Unifying Theories of Programming



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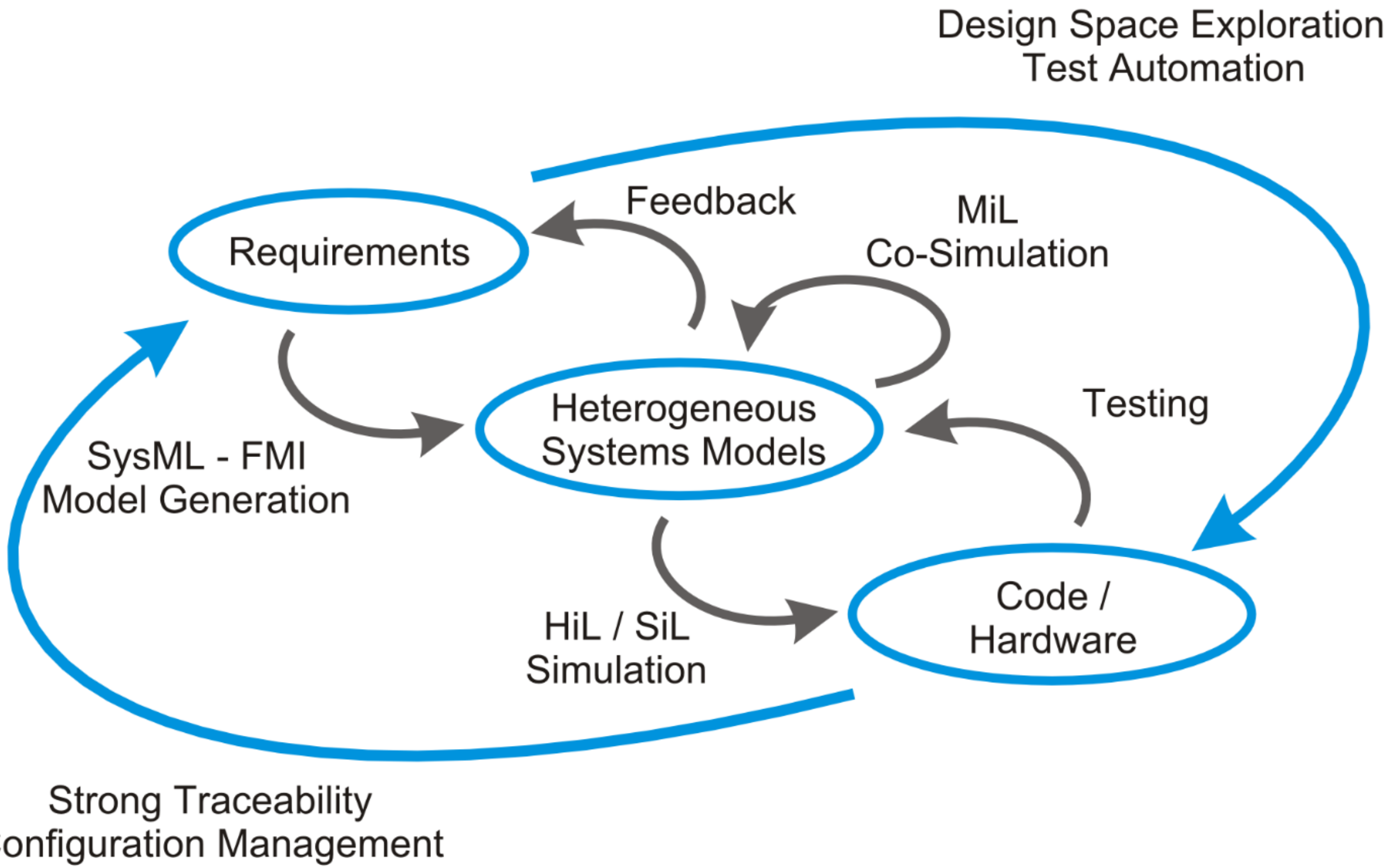
A New Toolchain for CPS Design



The INTO-CPS Tool Chain

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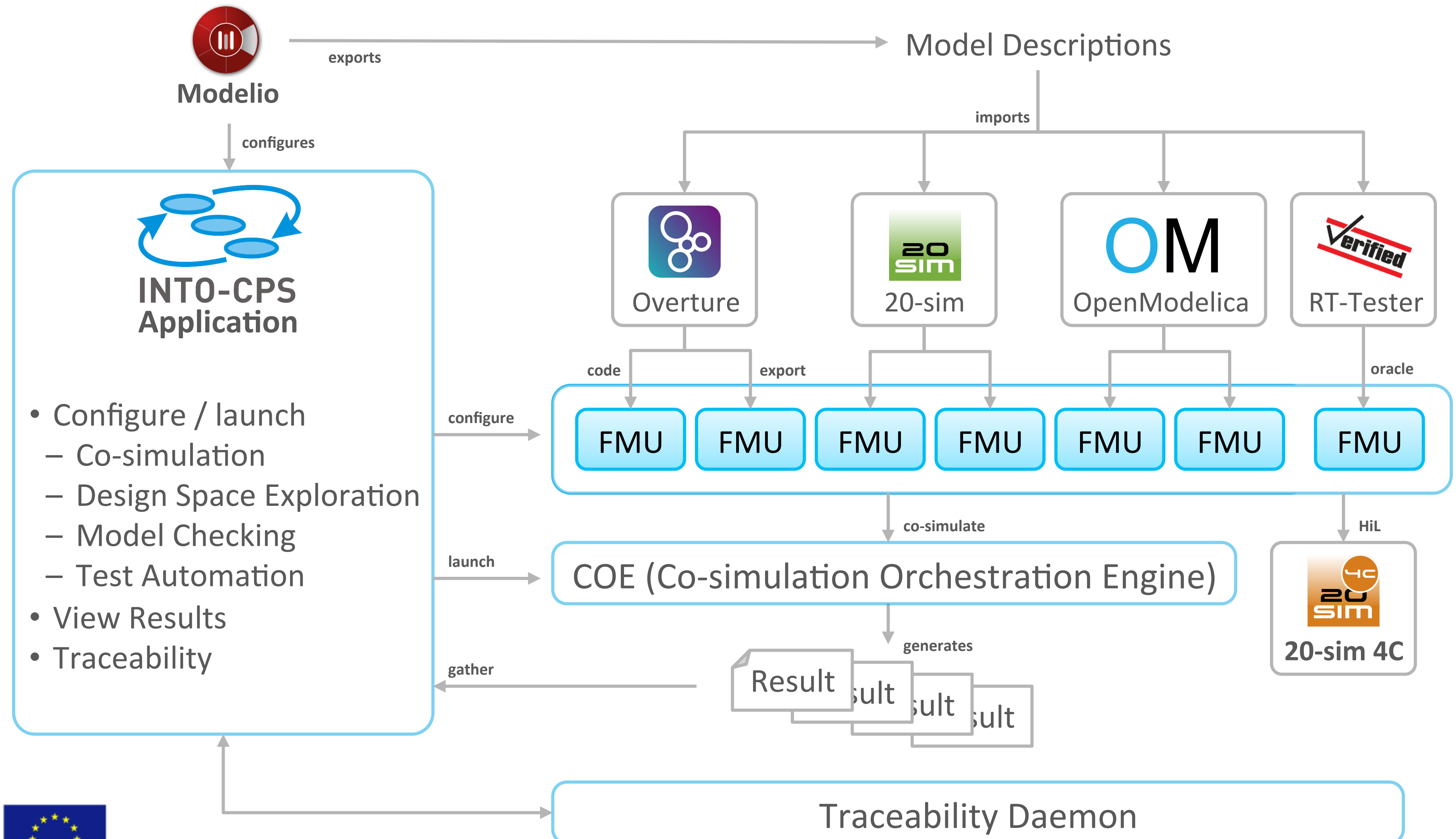
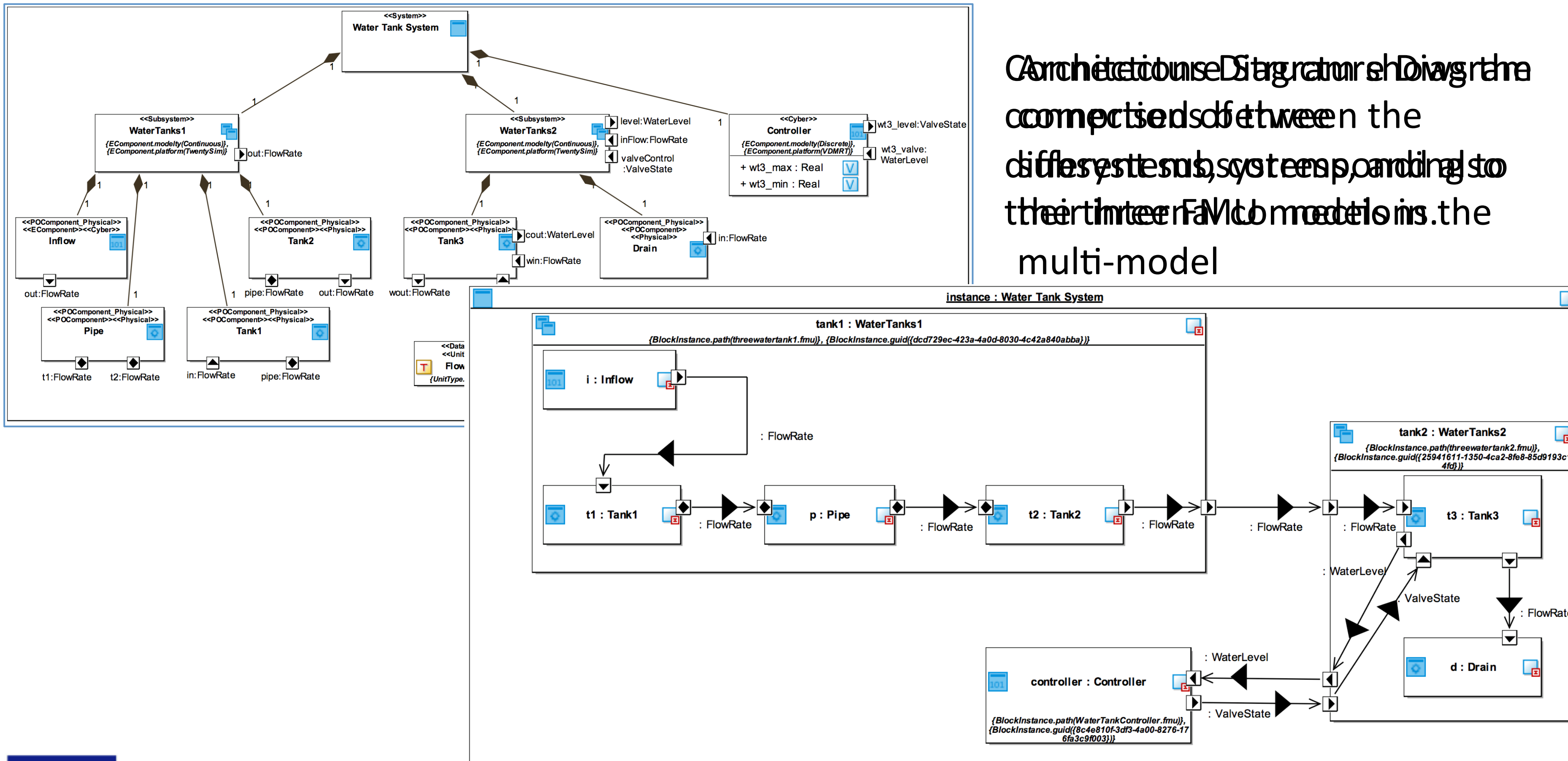


INTO-CPS SysML CPS Profile

- Three-tank Water Tank : INTO-CPS technology
  - Design architecture using INTO-CPS profile



Connections Diagram shows the connections between the different subsystems, corresponding to their internal FMU models in the multi-model

Test Automation

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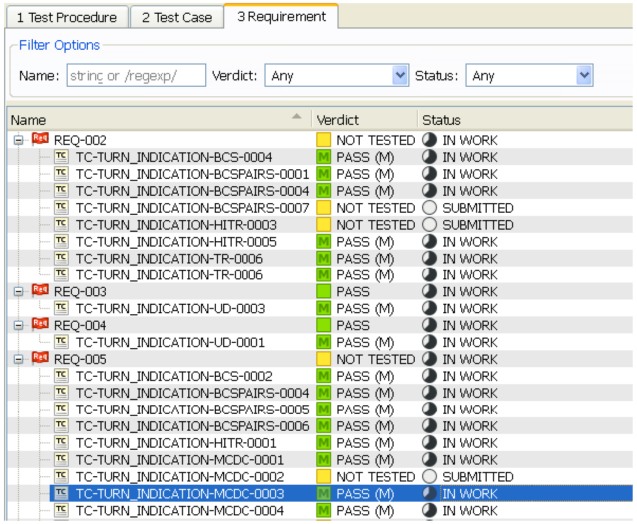
- Based on RT Tester tool suite
- Status:
  - Test sets generated from XMI import (from Modelio)
  - Test procedures are generated as FMUs, connected to Co-simulation
- Outlook:
  - Identify SuT in SysML profile, connect to Test Automation
  - Connect SysML requirements with LTL formulas



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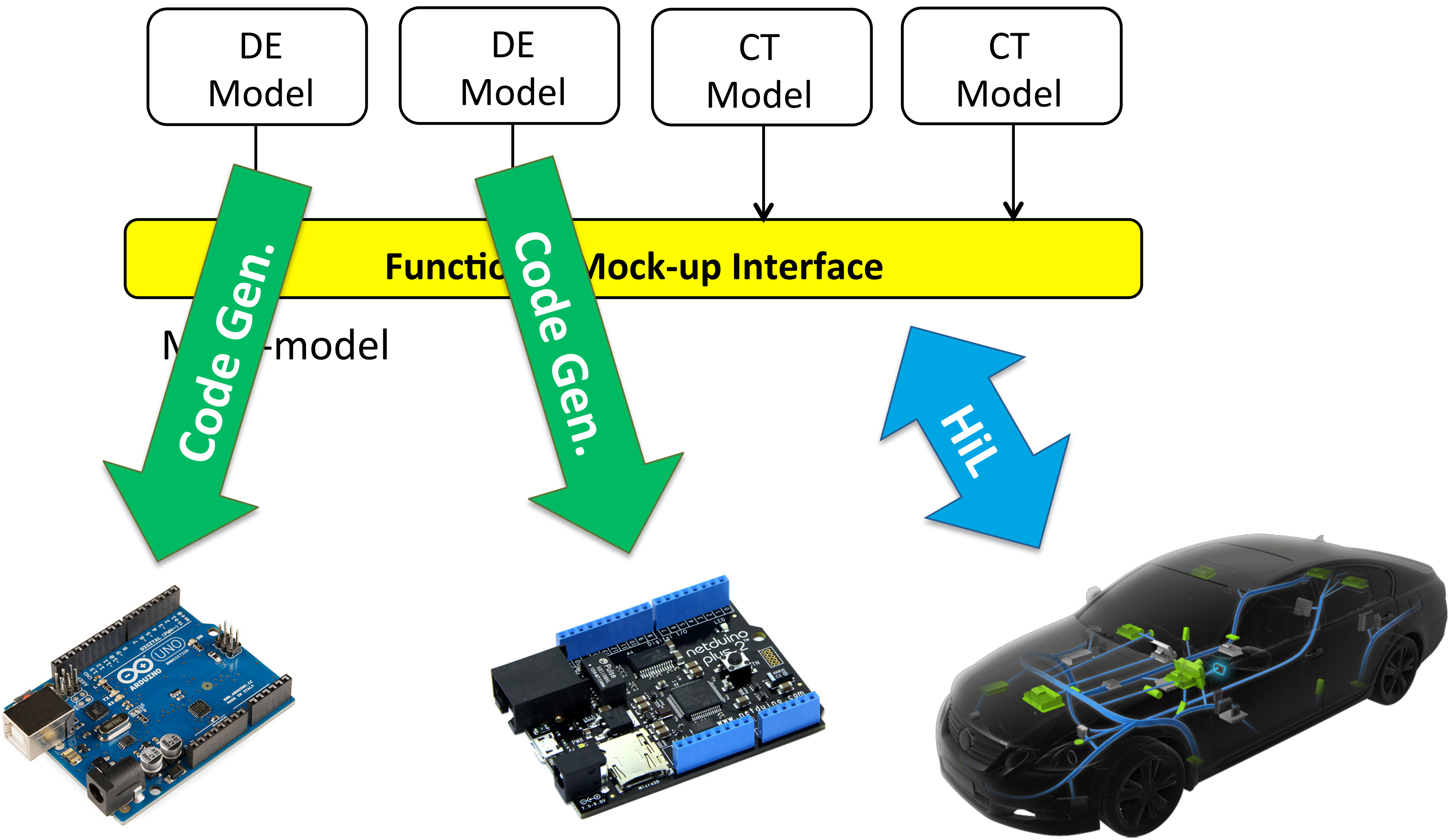
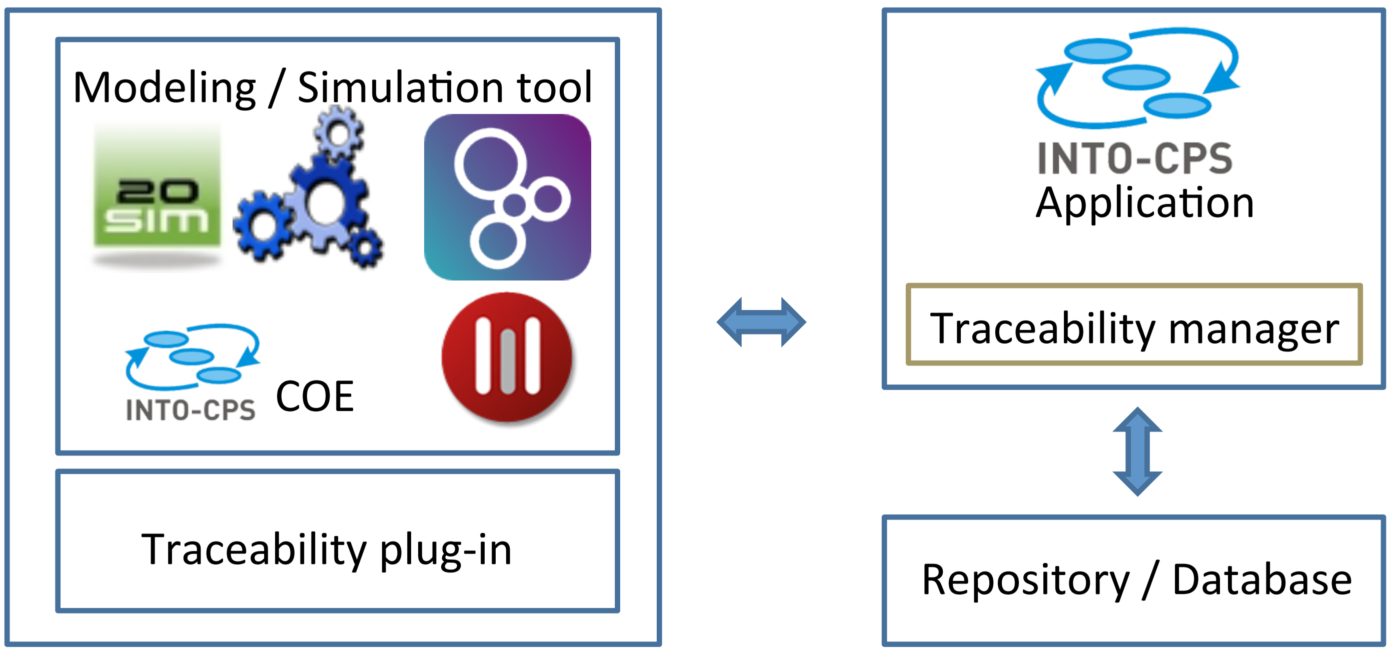
Hardware-in-the-Loop (HiL) and Code Generation



Traceability & Provenance

- Goal: Ensure tracing between requirements, models, results, code
- Keep track of changes
- Uses OSLC / Prov-N standards



Industrial Case Studies

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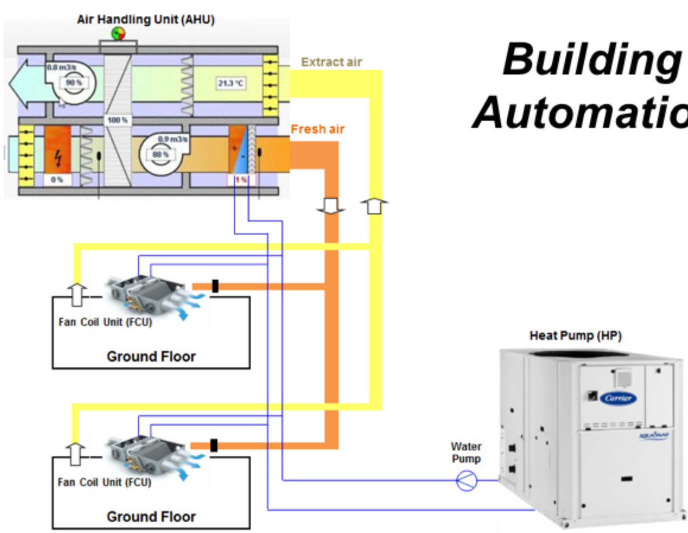

Building Automation

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Automotive

Programme

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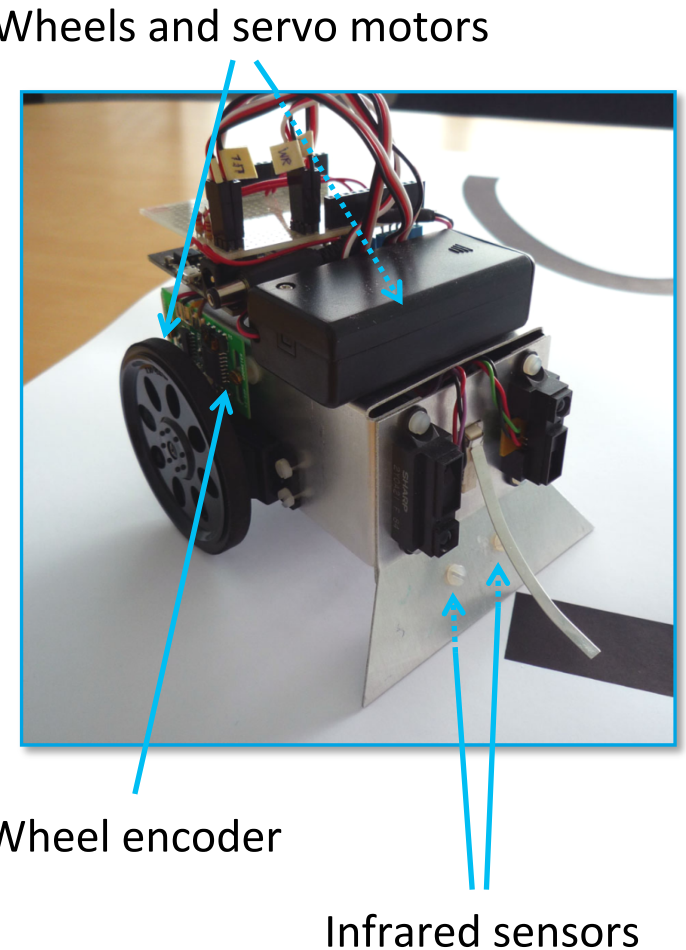
Line Follower Robot

- Small robot with:
  - Two wheels with servos
  - Two wheel encoders
  - Two infrared sensors
- Goal:
  - Use the sensors to follow the line
  - Handle a single sensor failure

Example path



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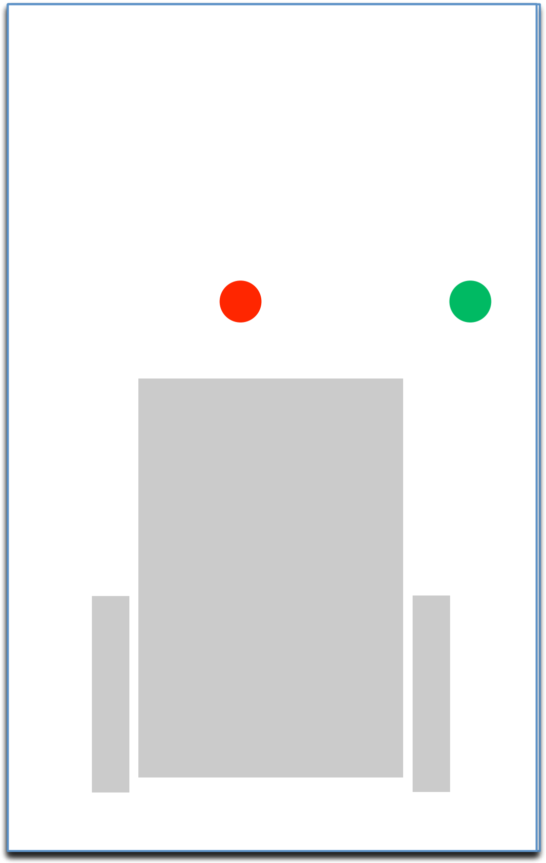
Design Space - Parameters

- Design parameters have numeric or token values that define some property of the CPS
- Parameters can define physical or cyber properties
- Multiplying the potential number of values for each parameter defines the architecture's design space.
- Line follow robot has 9 positions for each sensor -> 81 potential designs
- We may want constraints on parameters to yield only sensible combinations



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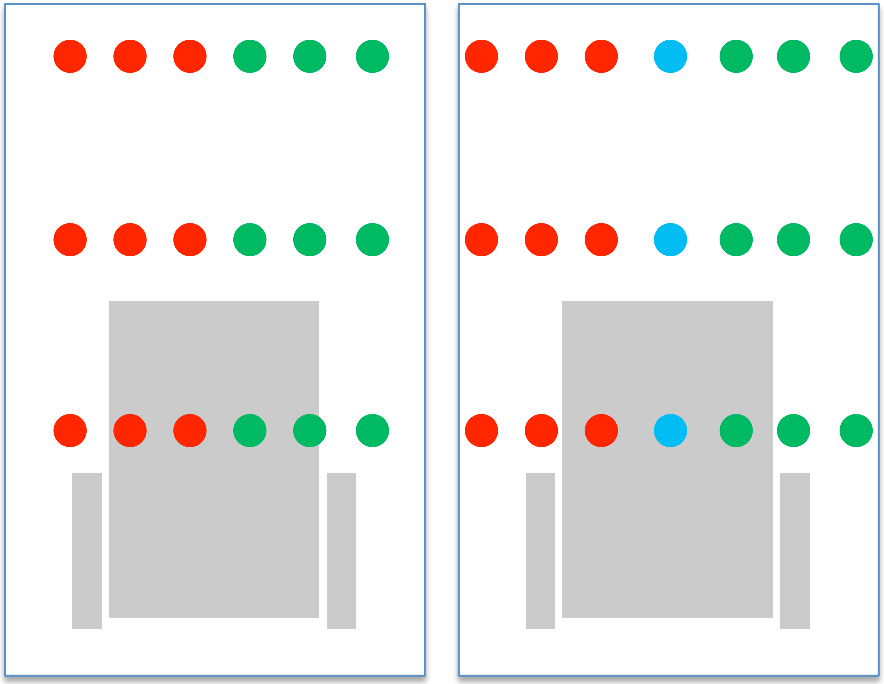
Design Space - Architecture

- Designs that differ in more than just parameter values
- Architectures may share some parameters
- Line follow robot could have different numbers of sensors



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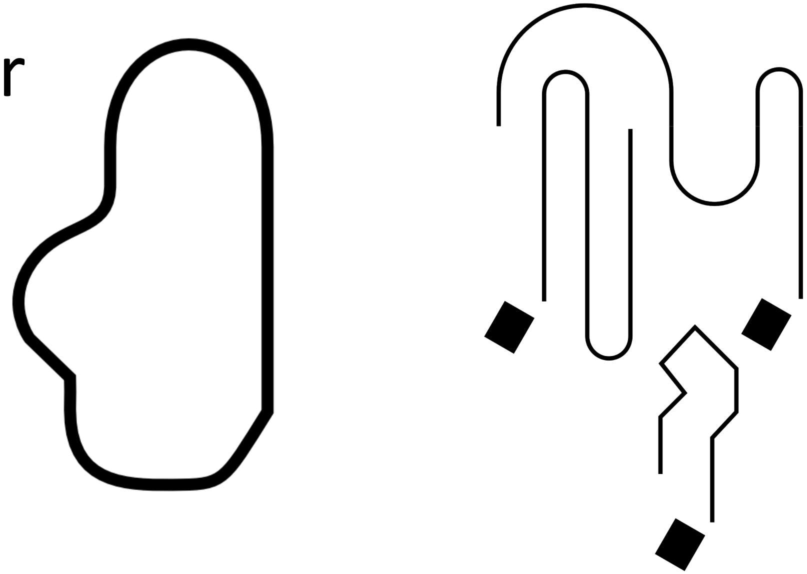
Design Space - Scenarios

- Scenarios describe the environment around the CPS
- Designs may be optimised for particular scenarios
- Need diversity in testing scenarios
- Scenarios can help assess different requirements
- This affects both simulation models and objective scripts



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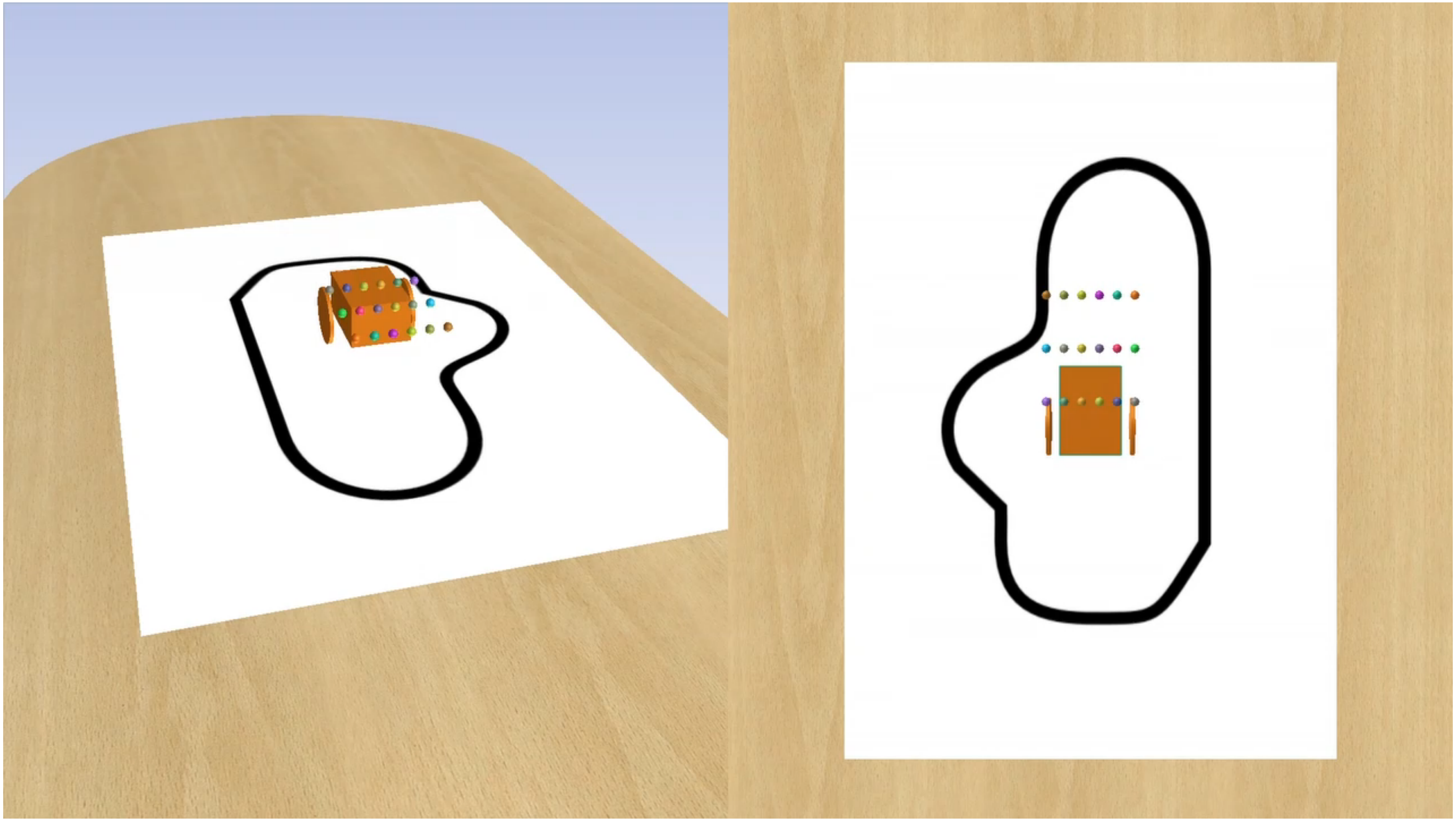
All Results



Objectives

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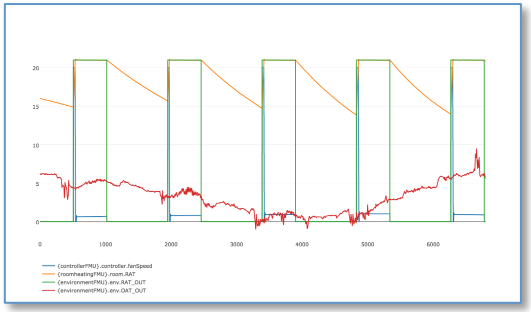
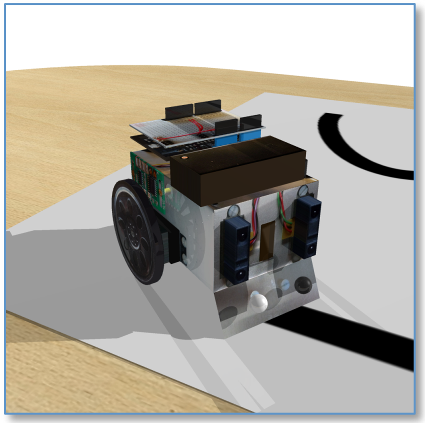
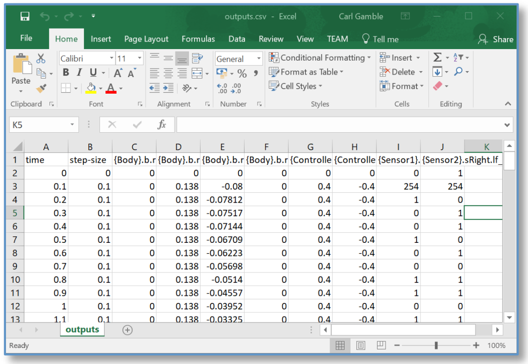






	A	B	C	D	E	F	G	H	I	J	K
1	time	step-size	{Body}.b.r	{Body}.b.r	{Body}.b.r	{Body}.b.r	{Controlle	{Controlle	{Sensor1}.	{Sensor2}.sRight.lf_	
2	0	0	0	0	0	0	0	0	0	1	
3	0.1	0.1	0	0.138	-0.08	0	0.4	-0.4	254	254	
4	0.2	0.1	0	0.138	-0.07812	0	0.4	-0.4	1	0	
5	0.3	0.1	0	0.138	-0.07517	0	0.4	-0.4	0	1	
6	0.4	0.1	0	0.138	-0.07144	0	0.4	-0.4	0	1	
7	0.5	0.1	0	0.138	-0.06709	0	0.4	-0.4	1	0	
8	0.6	0.1	0	0.138	-0.06223	0	0.4	-0.4	0	1	
9	0.7	0.1	0	0.138	-0.05698	0	0.4	-0.4	0	0	
10	0.8	0.1	0	0.138	-0.0514	0	0.4	-0.4	1	1	
11	0.9	0.1	0	0.138	-0.04557	0	0.4	-0.4	1	1	
12	1	0.1	0	0.138	-0.03952	0	0.4	-0.4	0	0	
13	1.1	0.1	0	0.138	-0.03325	0	0.4	-0.4	1	1	

Live graphs and raw results are good for debugging CPS design and understanding behaviour

They are not so good for automatically comparing two or more designs

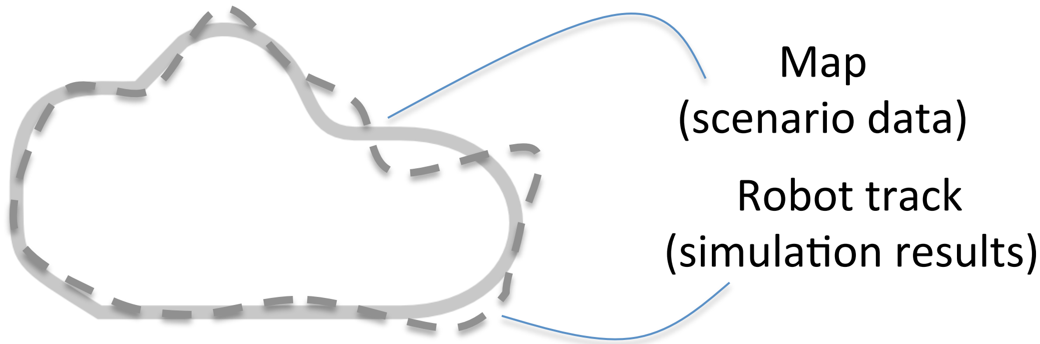
Need measures that characterise behaviour of the modelled system.

We call these 'objectives' and they process the raw simulation data to output measures that allow direct comparison of results.

For the line follower we have cross track error and lap time

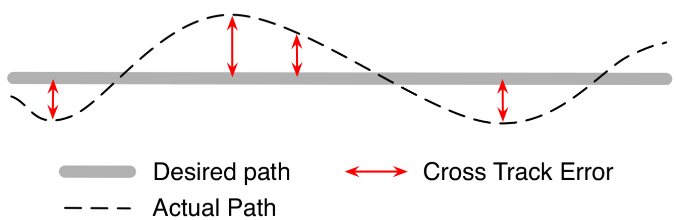
Objective Evaluation

Raw data:

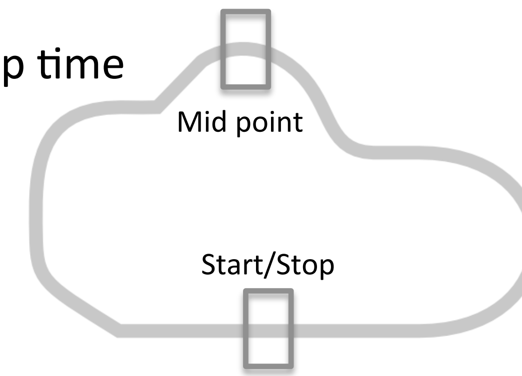


Objective evaluation:

Cross track error



Lap time



Objective values:


```
{
    "lapTime": 23.410000000001048,
    "maxCrossTrackError": 0.11212158578971308,
    "meanCrossTrackError": 0.014968210731969004,
    "meanSpeed": 0.05307078947255971
}
```

Ranking and Trade-off

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Trade-off preferences well understood:

Weighted additive method

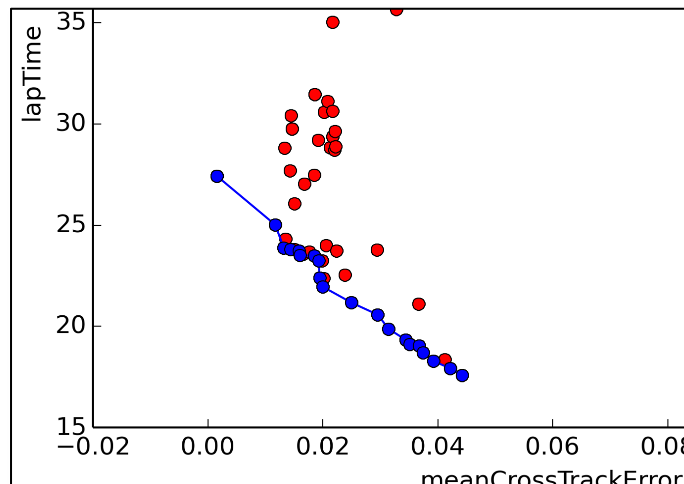
$$V_a = w_1^a v_1^a(x_1^a) + w_2^a v_2^a(x_2^a) + \dots + w_n^a v_n^a(x_n^a)$$

Enumeration and scoring

$$\begin{aligned} &order_a \\ &\{ \\ &\qquad s_1^{\ a} = \{ g_1^{\ 1}\!:\ g_2^{\ 1}\!:\ \dots,\ g_n^{\ 1} \};\ score\_s_1^{\ a} = w; \\ &\qquad s_2^{\ a} = \{ g_1^{\ 2}\!:\ g_2^{\ 2}\!:\ \dots,\ g_n^{\ 2} \};\ score\_s_2^{\ a} = y; \\ &\qquad s \dots \\ &\qquad s_n^{\ a} = \{ g_1^{\ n}\!:\ g_2^{\ n}\!:\ \dots,\ g_3^{\ n} \};\ score\_s_n^{\ a} = z; \\ &\} \end{aligned}$$

Trade off preferences Not well understood:

Pareto analysis



Search Algorithms

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Open Loop: Exhaustive search:

- *Pro:* simulates all combinations and so the global optimum will be found
- *Con:* attempts to simulate all combinations and so may not complete in a realistic time

Closed Loop: Genetic Search, Simulated Annealing:

- *Pro:* makes use of ranking information and iteration to attempt to home in on better designs
- *Con:* Generally includes random elements so not repeatable and may find local rather than global optimum

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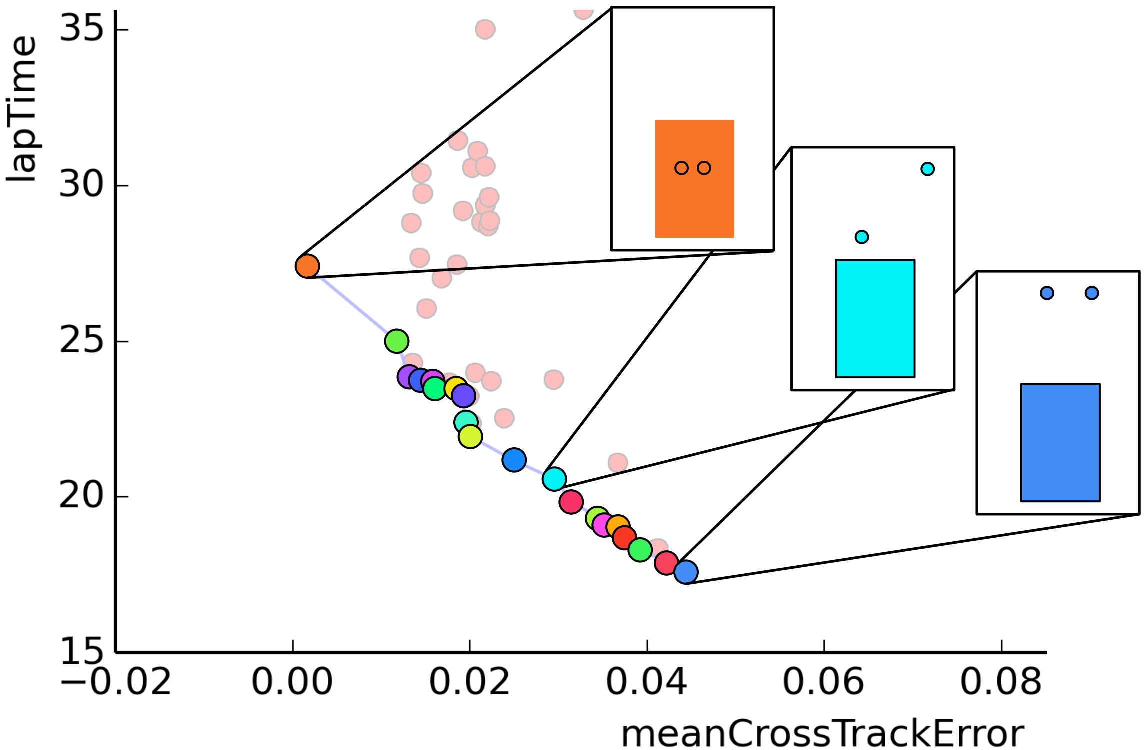
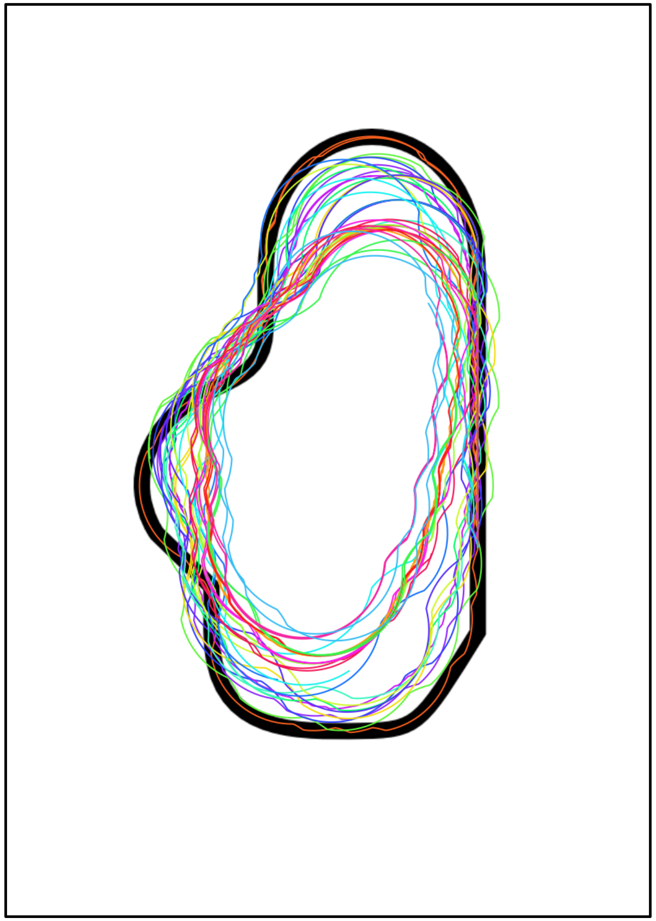
Pareto Front





Pareto Front (Speed vs Error)

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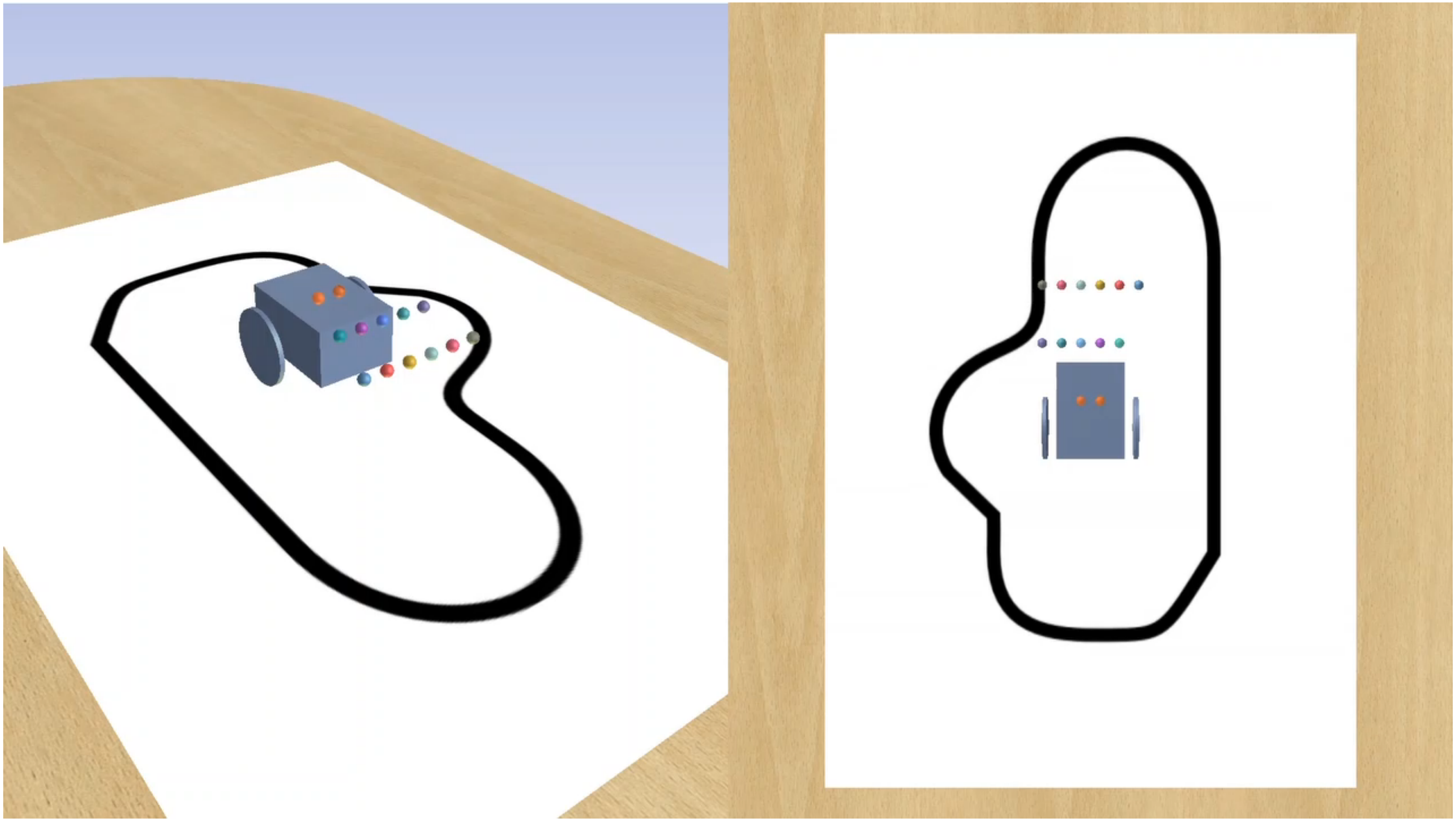

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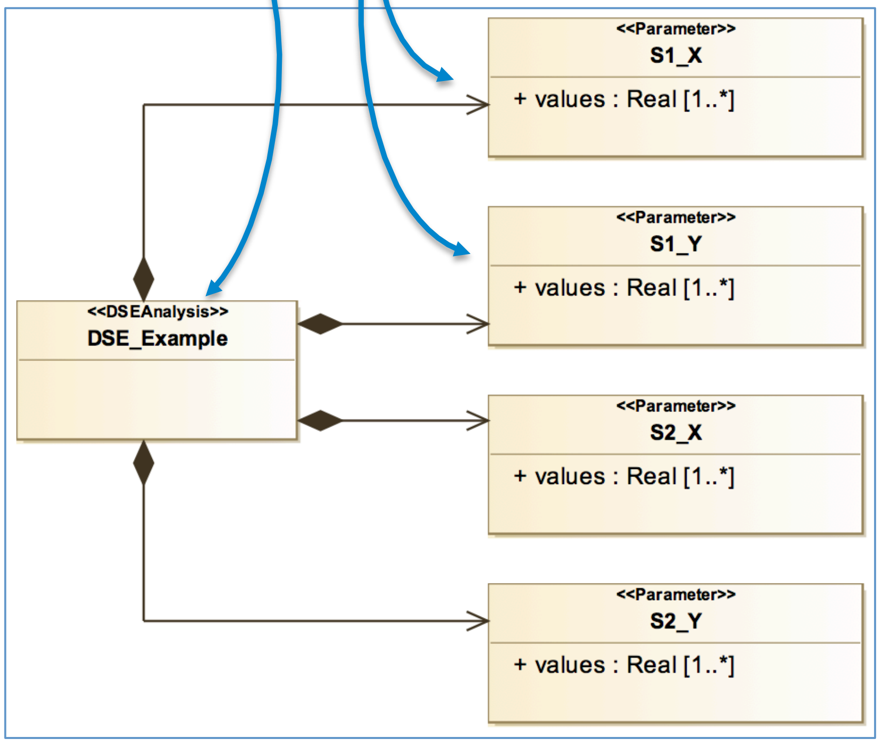
DSE in SysML - Parameters

DSE object

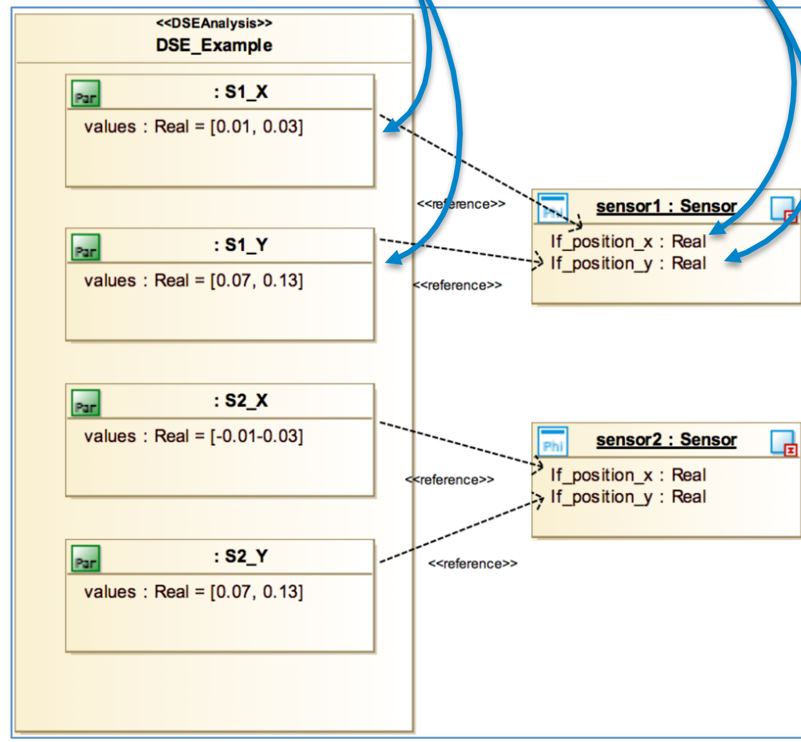
Parameter definitions
- ID
- Type
- List of values

Parameter instances

Mapped to FMU instance parameters



Parameters definition



Mapping to Multi-model

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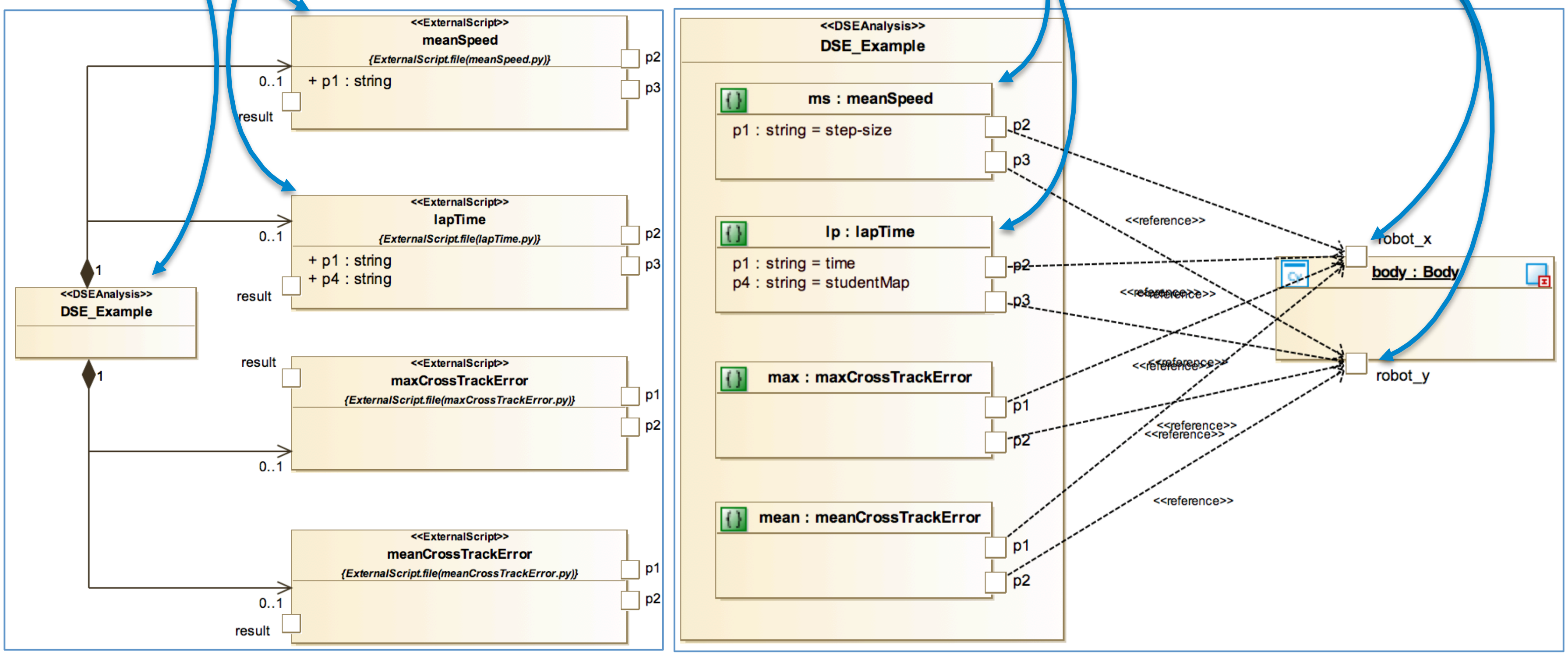
DSE in SysML - Objectives

DSE object

Objective definitions
- ID
- Script file
- List of required data

Objective instances

Variable inputs Mapped to FMU instance outputs



Objectives definition

Mapping to Multi-model

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DSE in SysML - Ranking

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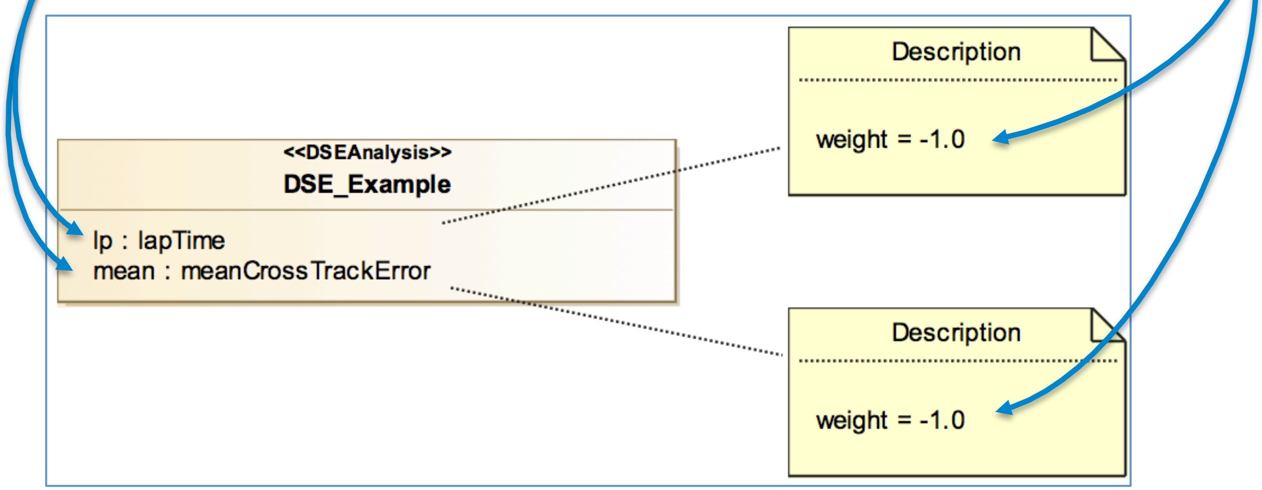
Objective IDs

Weighting defines preference:

- -1 = lower preferred
- +1 = higher values preferred



Ranking defines what to include in Pareto analysis

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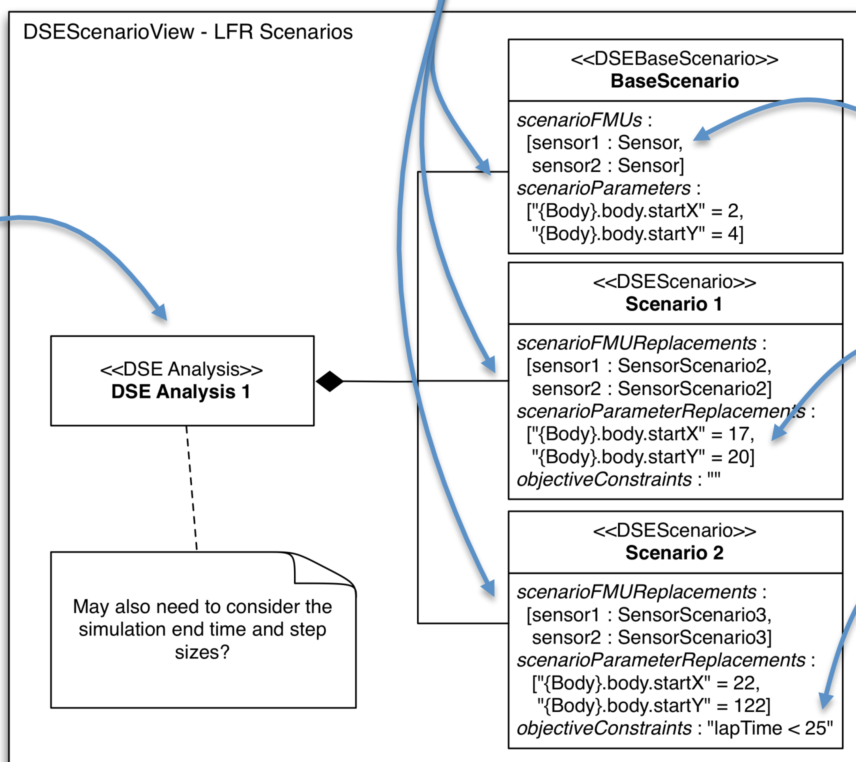
DSE in SysML

Additional view in DSE profile for scenario sweeping

3 Scenarios

DSE object



Each may define:

- FMUs – these change which fmu is used for part of the multi-model
- Parameter values – set specific parameters for FMU instances
- Objective constraints – used to defined acceptance criteria specific to a scenario

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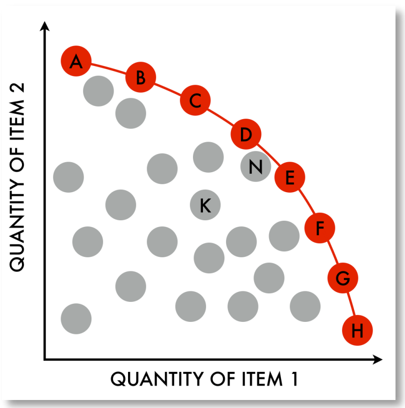
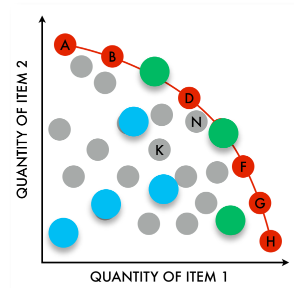
Measurement of closed loop

Run exhaustive search to obtain ground truth and objective measures



Run multiple genetic searches using exhaustive results lookup for speed



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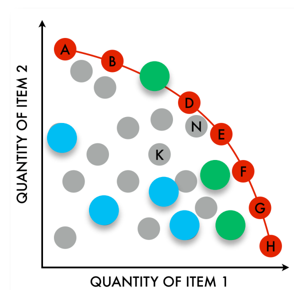

Compute results metrics

- Cost
- Accuracy
- Generational distance

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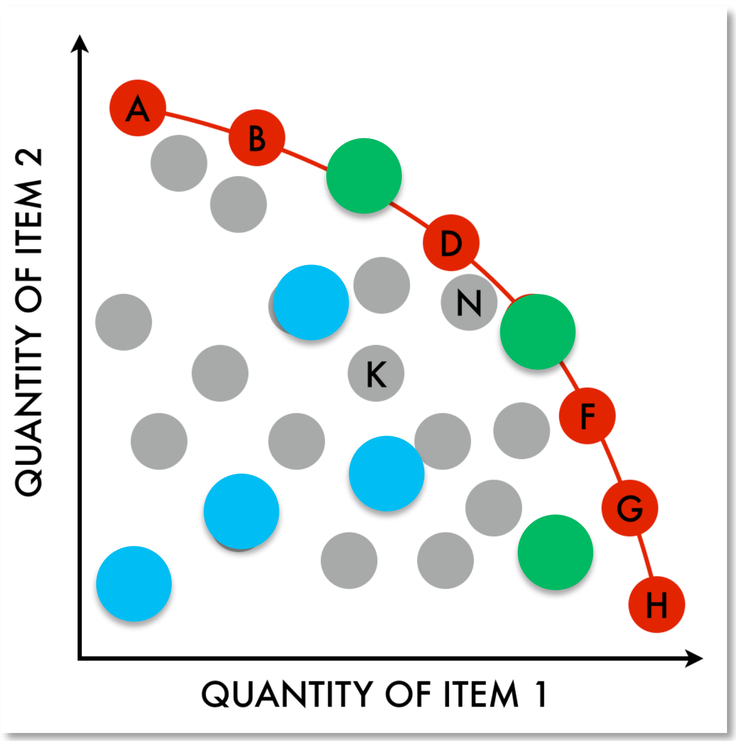
Measurement of closed loop



Cost of search : the number simulations run as a proportion of exhaustive simulations run.

Here genetic search performed 7 simulations and the exhaustive 27 simulations

Measurement of closed loop

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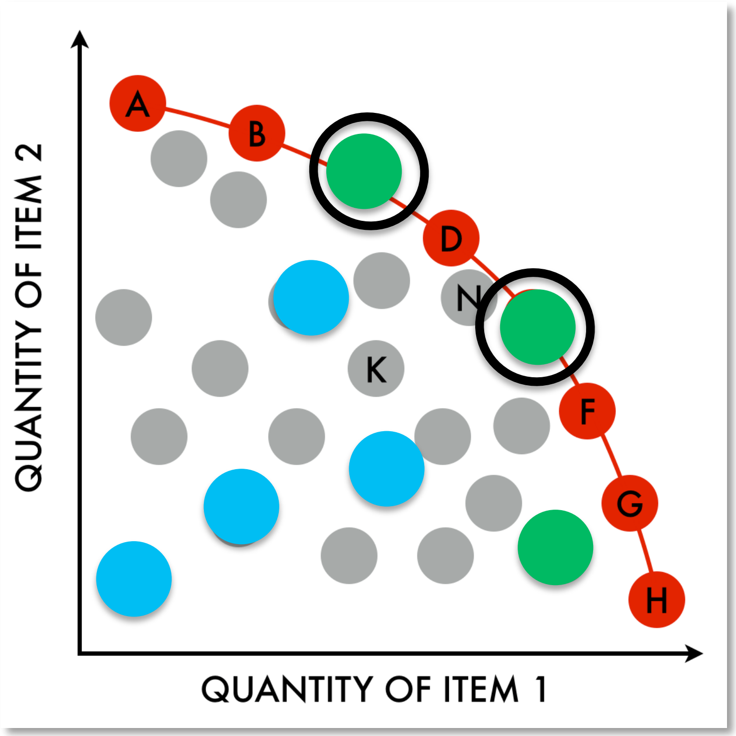
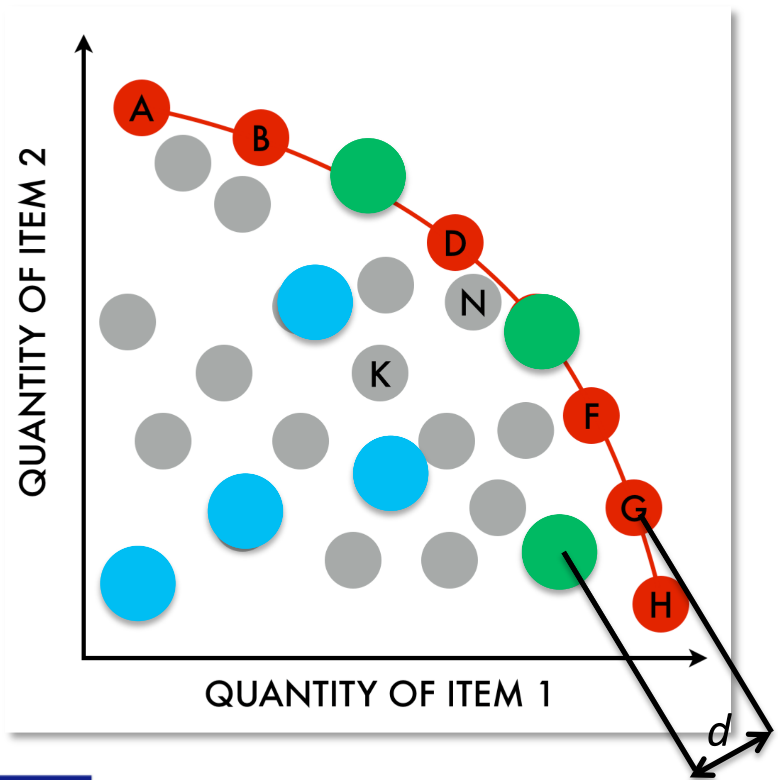


Accuracy : Probability a result in a genetic non-dominated set can be found in the exhaustive Pareto front

Here 2 of the 3 genetic NDS results are found on the exhaustive Pareto front

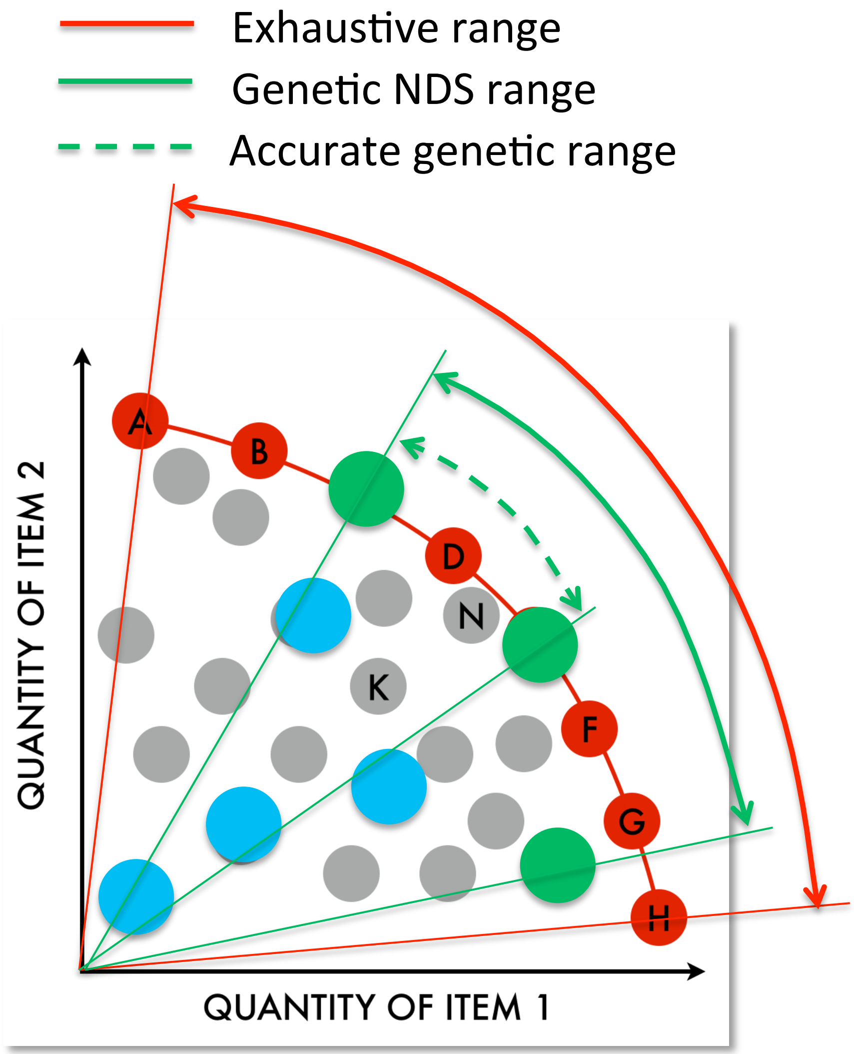
Measurement of closed loop



Generational Distance : the mean distance between genetic non-dominated set and the exhaustive Pareto front

Combines both the number of results not on pareto front and their distance from the front, we need to reconsider its use

Measurement of closed loop



Coverage : the range of results returned by a genetic search as a proportion of the exhaustive range.

Could consider the whole non-dominated set or just the accurate range.

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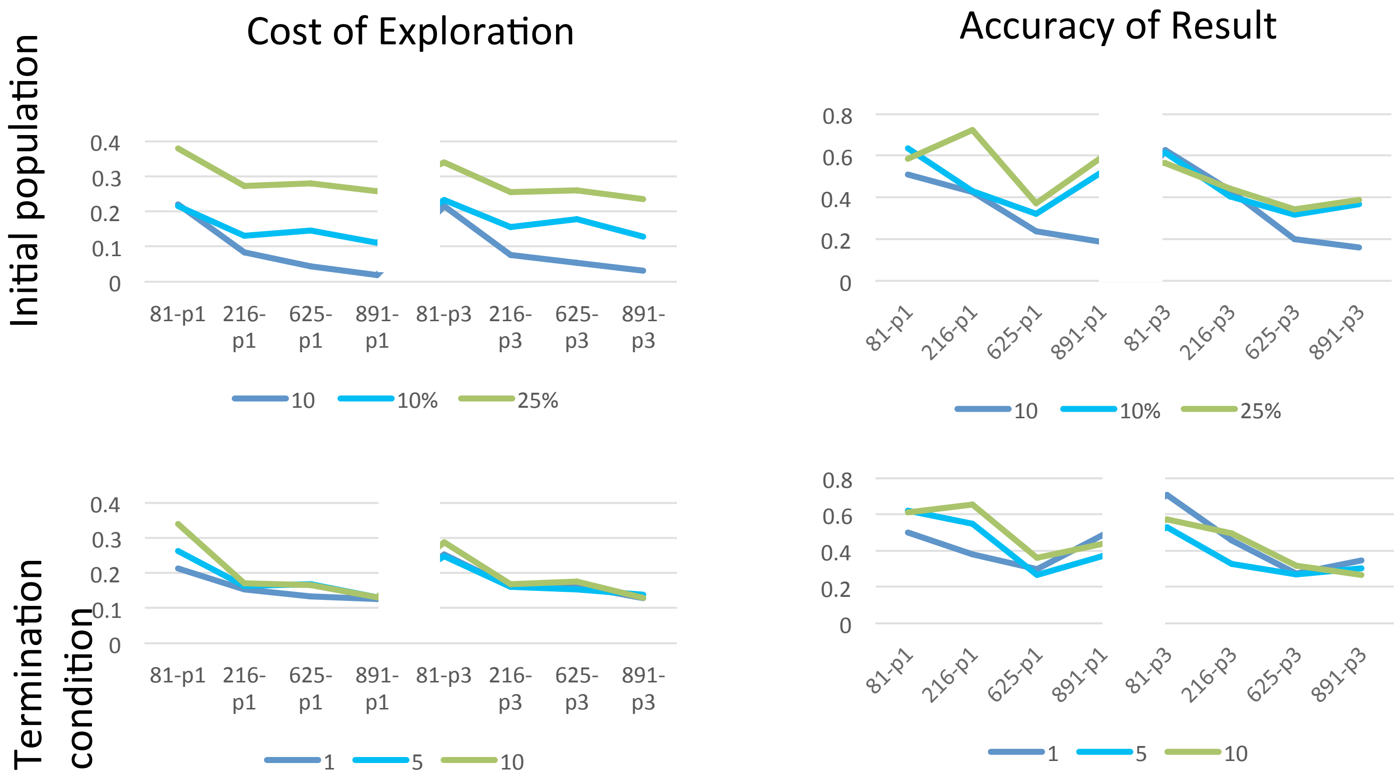
Measurement of closed Loop



Brief summary from a very small initial study:

- As design space size increases, genetic becomes more efficient (Good)
- Accuracy decreases as design space size increases (Not so good)

Naming : ”<design space size> - <variant of genetic algorithm>”

P1 = initial population randomly spread over design space

P3 = initial population evenly distributed over design space.

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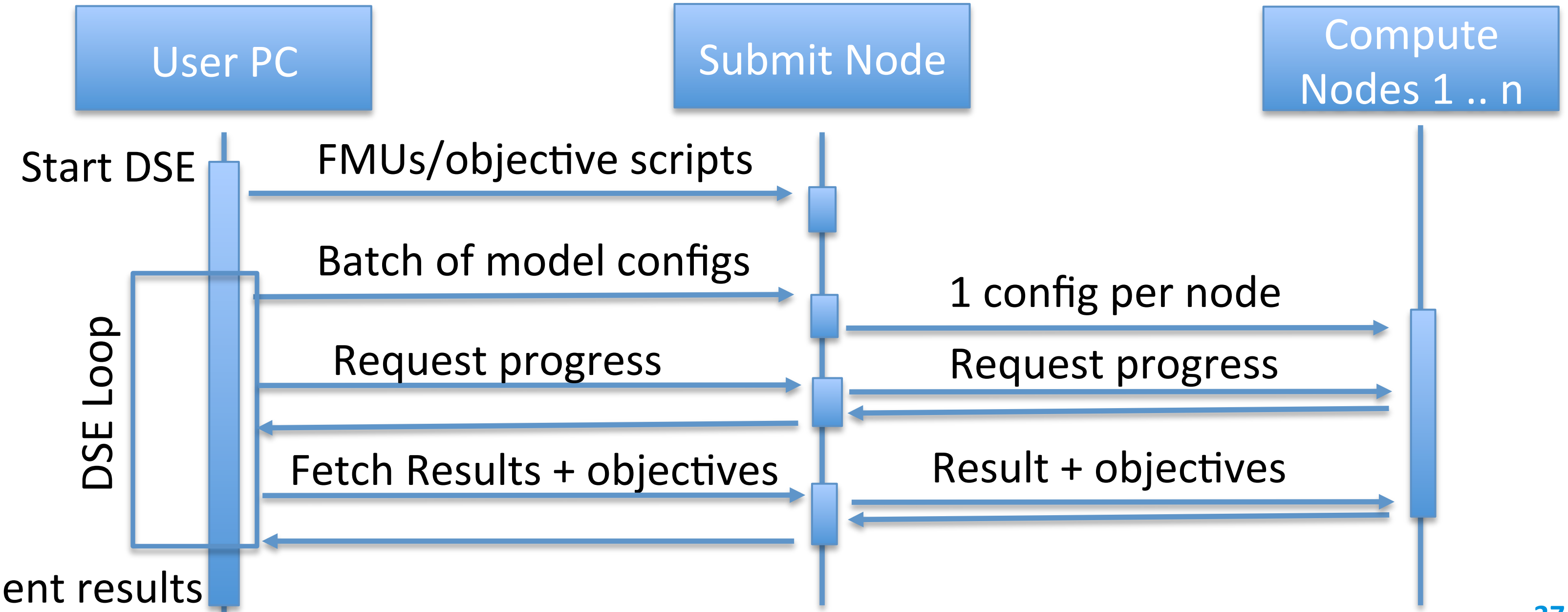
Future Directions - Search

- Modifications to genetic search
  - Initial population
    - Current: randomly generated
    - Future: allow structured initial population to evenly cover design space or follow user preferences
  - Parent selection:
    - Current: random selection influenced by ranking
    - Future: allow parent selection to be also influenced by location and grouping in designs space and/or objective space
- Add a simulated annealing search algorithm
- Allow architecture and scenario sweeping with results presented in a sensible manner

Future Directions - Cloud

- DSE can require much CPU time, even with genetic search
- DSE may be democratised by supporting the use of cloud resources
- Making used of HTCondor we have automated much of the process already and aim to automate the remainder over the summer

https://research.cs.wisc.edu/htcondor/



Future Directions - Cloud

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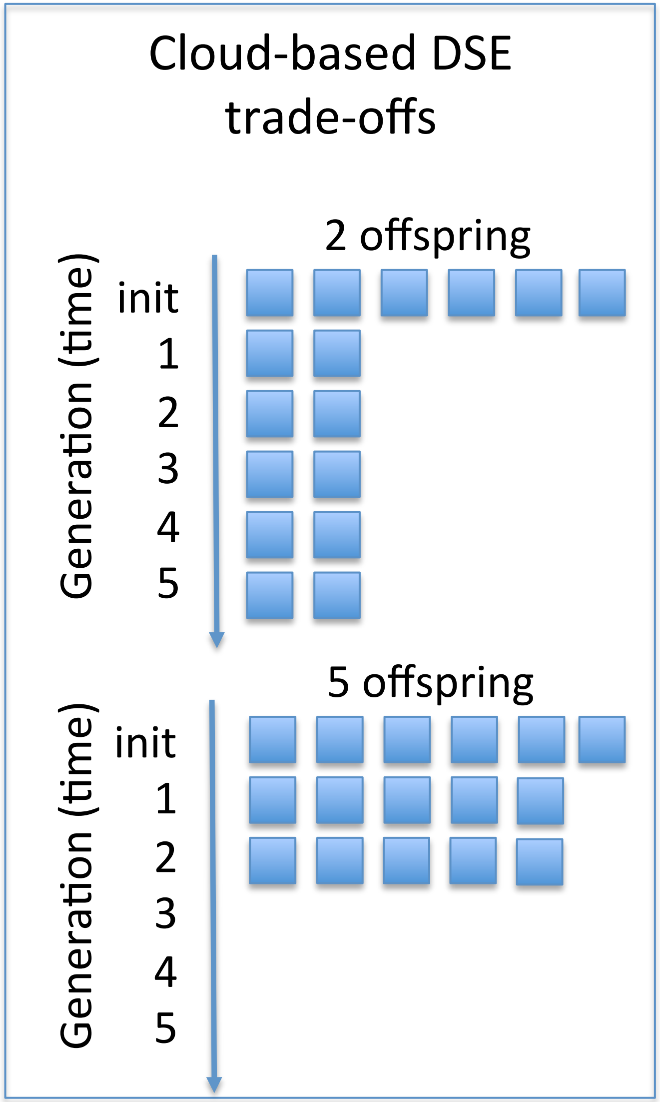
- Users are charged for both cpu time and data transferred
- Organisations may have different goals in terms of design cost, time and diversity
- We aim to provide guidance on how to employ cloud parallelism to meet organisational needs



INTO-CPS association - purpose

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- Maintain and develop further software that was created in the project
- Enable the widespread use of the software through open source licenses
- Promote its usage in academic and industrial settings
- Allow members to steer direction of development and incorporate software into products
- Kick-off meeting 14th November, Aarhus, Denmark

INTO-CPS association - technology

SysML profile
- Abstract modelling of CPS
- Builds on top of the Modelio tool (Open Source)
- Export of configurations for multi-models and DSE
- Traceability support

INTO-CPS application
- User Interface for setting up and executing Co-Simulation runs
- Integrates many elements of the INTO-CPS tool chain

Co-Simulation Orchestration engine
- FMI 2.0 compliant master algorithm
- Supports Windows, Linux, Mac
- Parallelization support

Design Space Exploration tools
- Algorithms for defining DSE runs and ranking the results
- Uses DSE configurations from Modelio
- Integrates well with the INTO-CPS application

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Thank you for your attention

IFG page:

http://projects.au.dk/into-cps/industry/industry-follower-group/

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