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Integrated Multi-formalism Tool Support for the Design of Networked Embedded Control Systems

Bridging between different modeling formalisms - results from the MULTIFORM project

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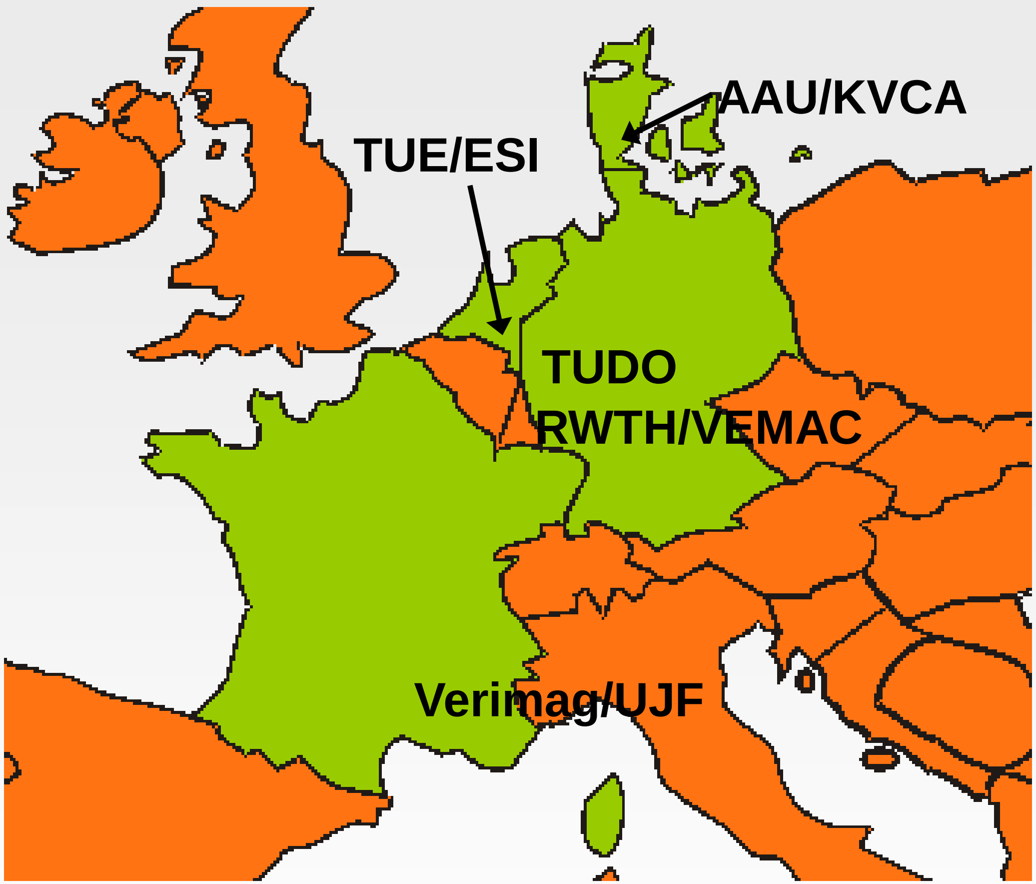
System Design meets Equation-based Languages, Sept. 19, 2012, Lund

Outline

- The MULTIFORM project
- Design flow example
- Tool developments
- Model exchange and model transformations
- Lessons learned

MULTIFORM: EU ICT STREP 9/2008 – 5/2012



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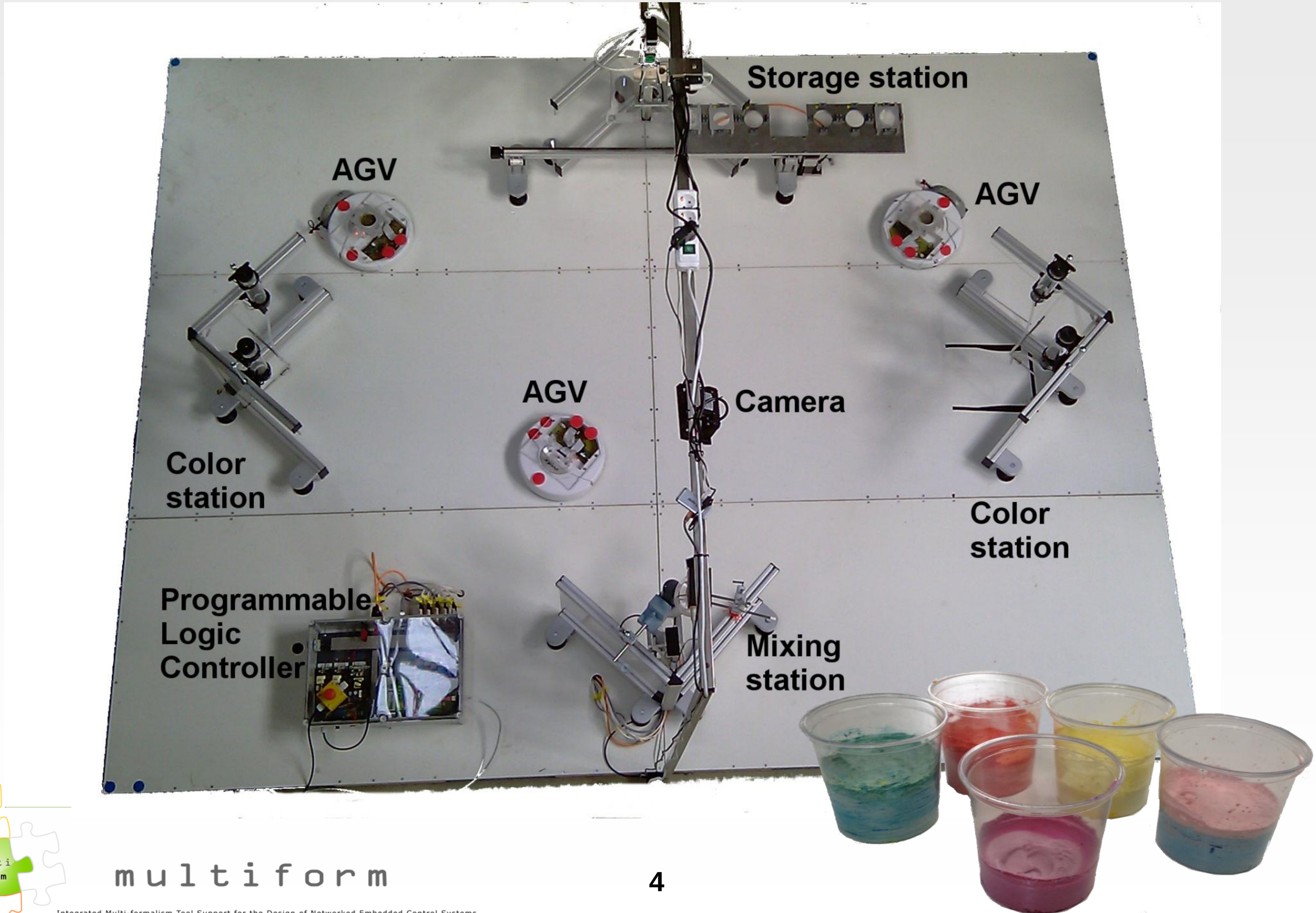
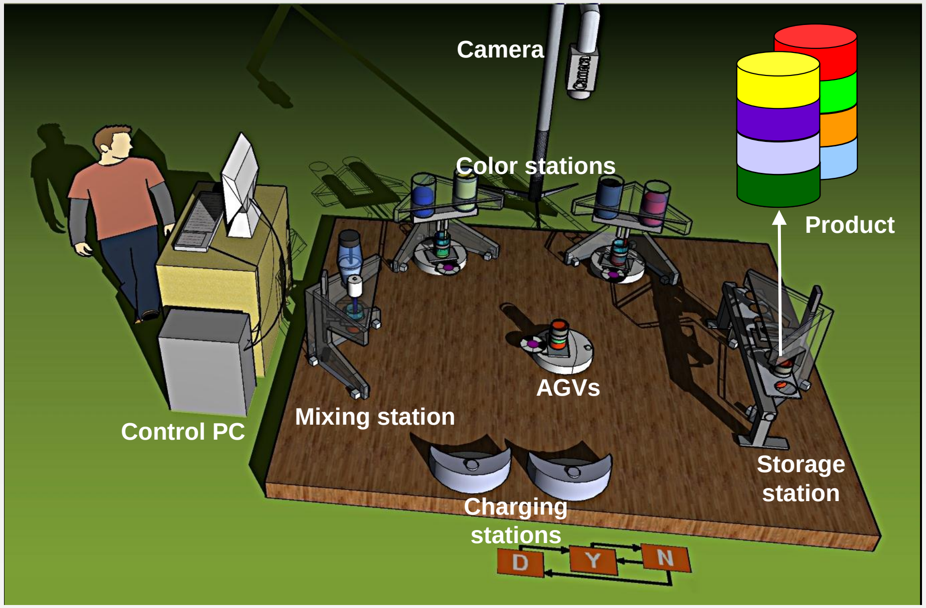
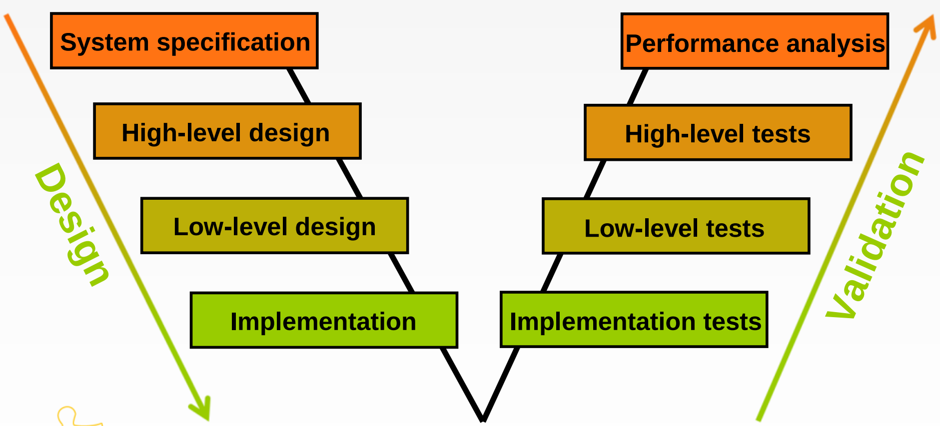
  - Closely working with DANFOSS

Example: Design of a Pipeless Plant



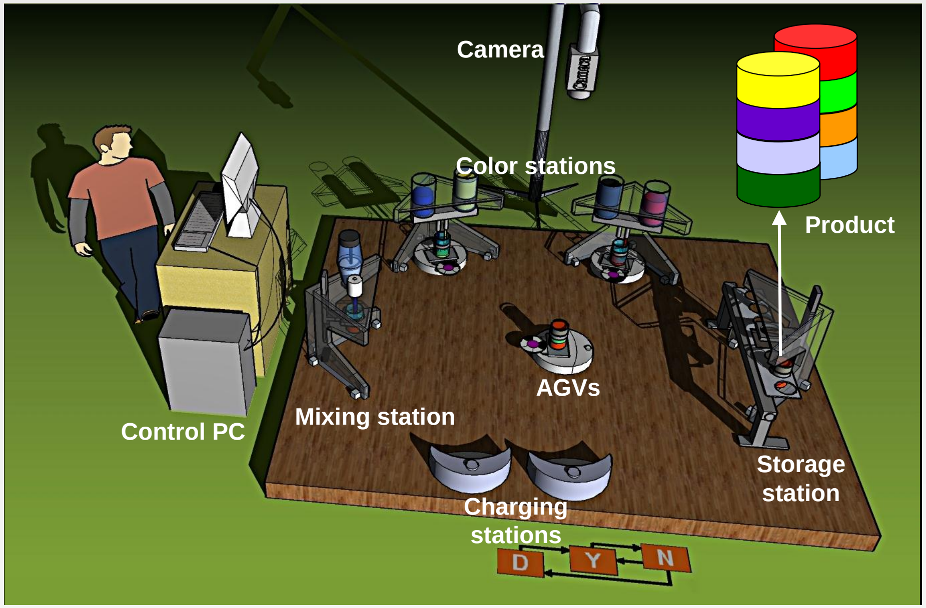
Challenges for Model-based Design (1)

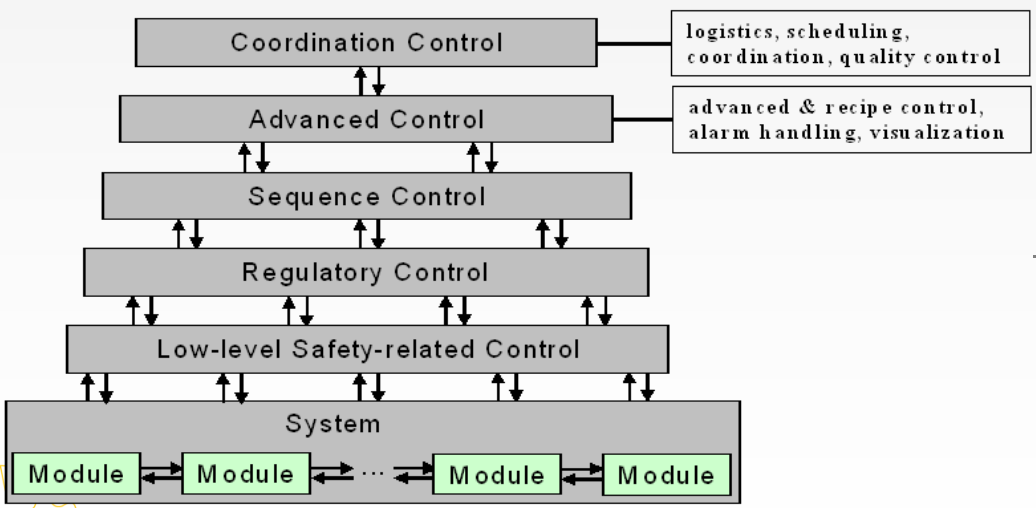




- Design and validation on different levels of abstraction
  - Specification
    - Specification of the tasks and of the performance of the system
  - High-level design
    - Choice of the equipment, feasibility and bottleneck analysis, throughput maximization, plant layout optimization
  - Low-level design
    - Optimization and control of processing steps and motion dynamics, logic control
    - Choice of sensors and actuators, communication system
  - Implementation
    - PLCs, embedded controllers, communication system

Challenges for Model-based Design (2)





- The control system spans the complete control hierarchy
  - Coordination control — **Timed or hybrid models**
    - Scheduling and performance optimization
  - Advanced control
    - Control of batch processes
    - AGV path planning — **Continuous models**
  - Regulatory control — **Discrete-event, hybrid, and continuous models**
    - AGV motion control
    - Docking control
    - Sequence control in the processing stations
    - Low-level continuous control
  - Low-level safety-related control

Discrete-event, timed, and hybrid models

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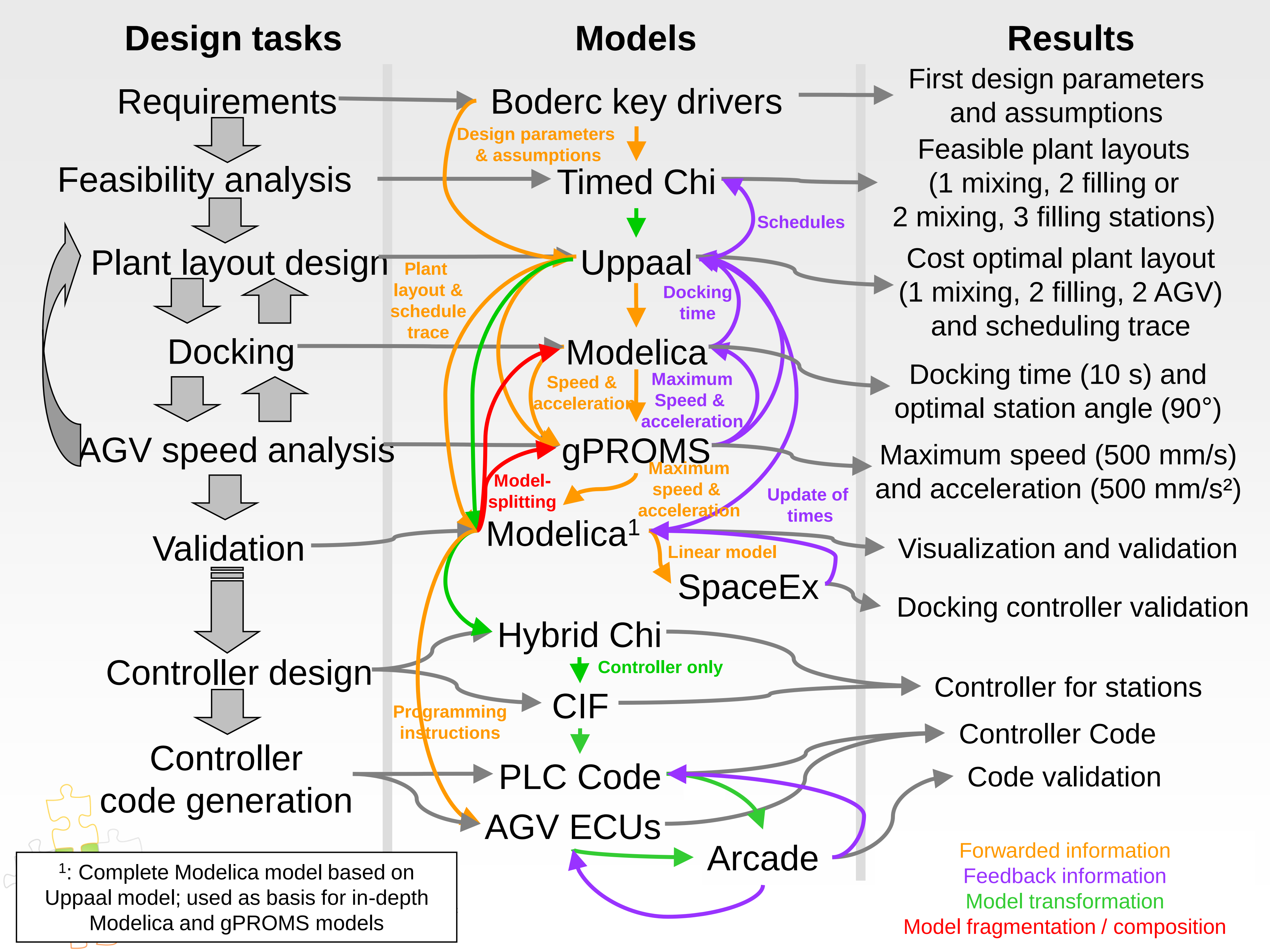


Design tasks
Models
Results
Requirements
Feasibility analysis
Plant layout design
Docking
AGV speed analysis
Validation
Controller design
Controller
code generation
Boderc key drivers
Design parameters
& assumptions
Timed Chi
Uppaal
Plant
layout &
schedule
trace
Schedules
Docking
time
Modelica
Speed &
acceleration
Maximum
Speed &
acceleration
gPROMS
Model-
splitting
Maximum
speed &
acceleration
Update of
times
Modelica¹
Linear model
SpaceEx
Hybrid Chi
Controller only
CIF
Programming
instructions
PLC Code
AGV ECUs
Arcade
First design parameters
and assumptions
Feasible plant layouts
(1 mixing, 2 filling or
2 mixing, 3 filling stations)
Cost optimal plant layout
(1 mixing, 2 filling, 2 AGV)
and scheduling trace
Docking time (10 s) and
optimal station angle (90°)
Maximum speed (500 mm/s)
and acceleration (500 mm/s²)
Visualization and validation
Docking controller validation
Controller for stations
Controller Code
Code validation
Forwarded information
Feedback information
Model transformation
Model fragmentation / composition
¹: Complete Modelica model based on
Uppaal model; used as basis for in-depth
Modelica and gPROMS models

Integrated Model-based Design

- Integrated modeling and design of the system itself and of the multi-layered and networked control system
  - Including a structured approach to the management of specifications, design decisions, models, and results
- Coverage of all layers of the automation and design hierarchy
  - Integrated tool support on all layers of the automation and design hierarchies
    - Current state: Islands of support for specific design and analysis tasks
- Trans-level integration of model-based design approaches
- Support of iterations in the design process
    - Propagation of faults and unexpected behaviors
    - Modifications over the life cycle without top-down redesign

→ Improvement of the ***tool support*** for the design steps

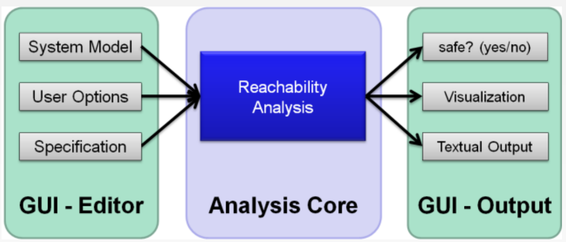
→ Tool integration and ***Design Framework***

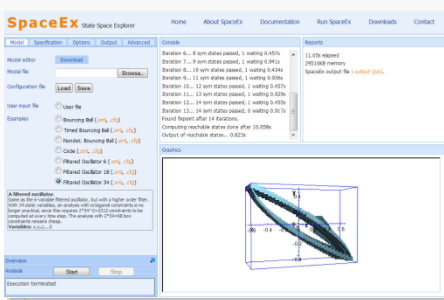
→ ***Exchange of models*** between tools via the CIF (Compositional Interchange Format)

MULTIFORM Tools and Tool Chains

Verification

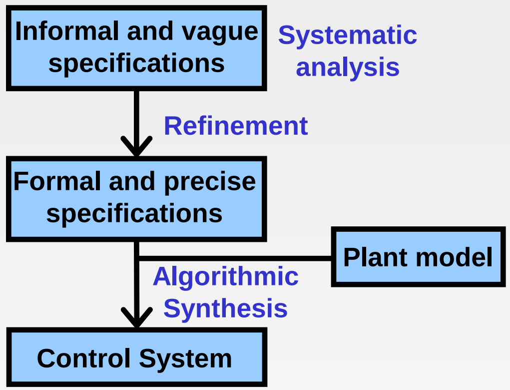
- Verification tool *SpaceEx* (successor of *PHAVer*)
- Consistency checking methods using *UPPAAL*
- Step-wise refinement based on *HCIF*



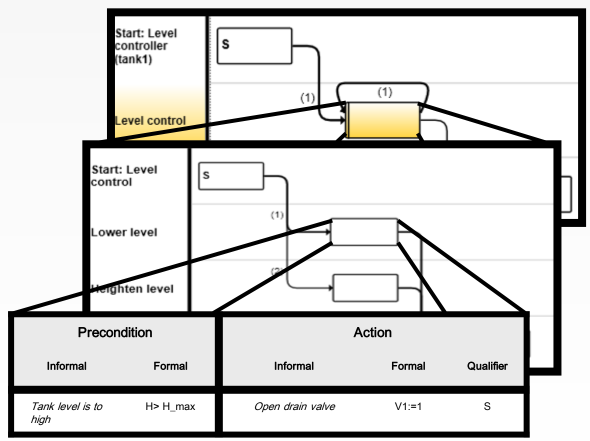


Logic Controller Design

Integrated controller design and analysis

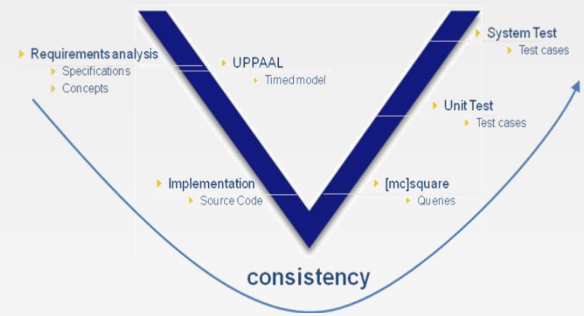


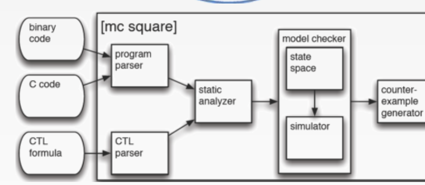
Specification using *DC/FT*

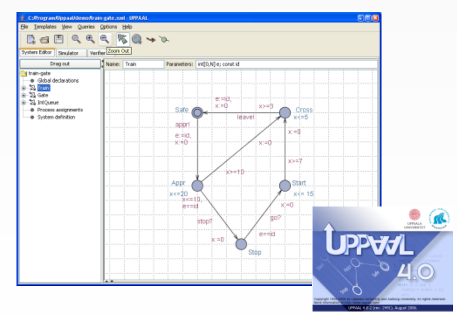


Code Analysis

Code and requirements analysis for ECUs using *Arcade* and *UPPAAL*







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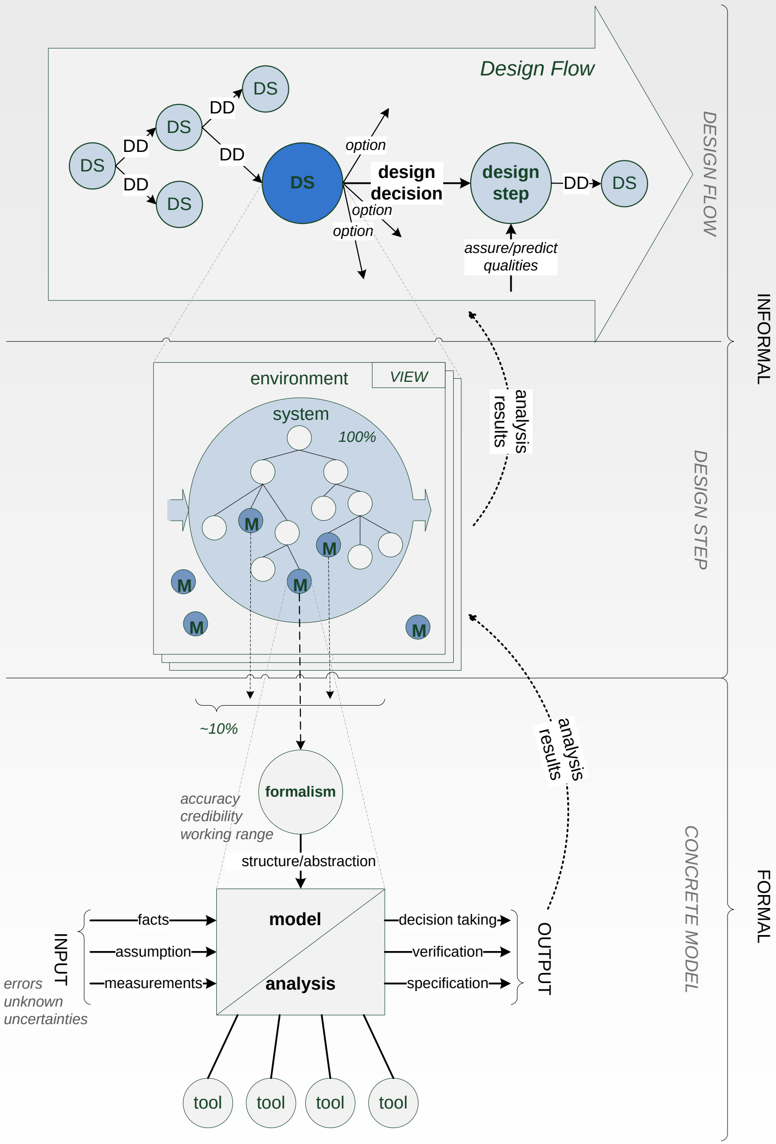
The MULTIFORM *Design Framework* [ESI]

- Consistent integration of design models into a common software framework
- Support of a generic design flow model
  - Design decisions
  - System design
- Consistency management
  - Communication of design parameters
  - Conflict detection
  - Models and results management



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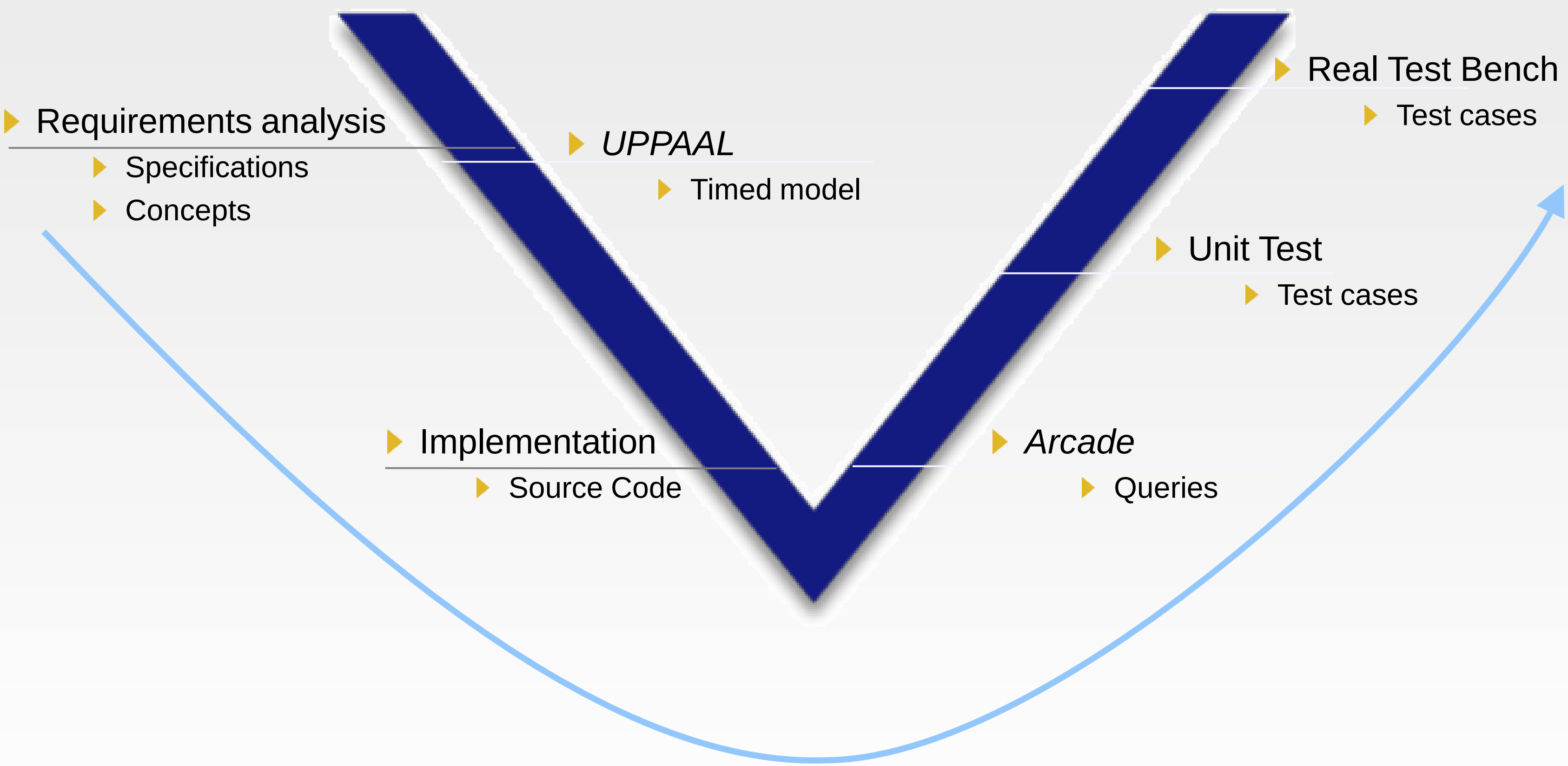
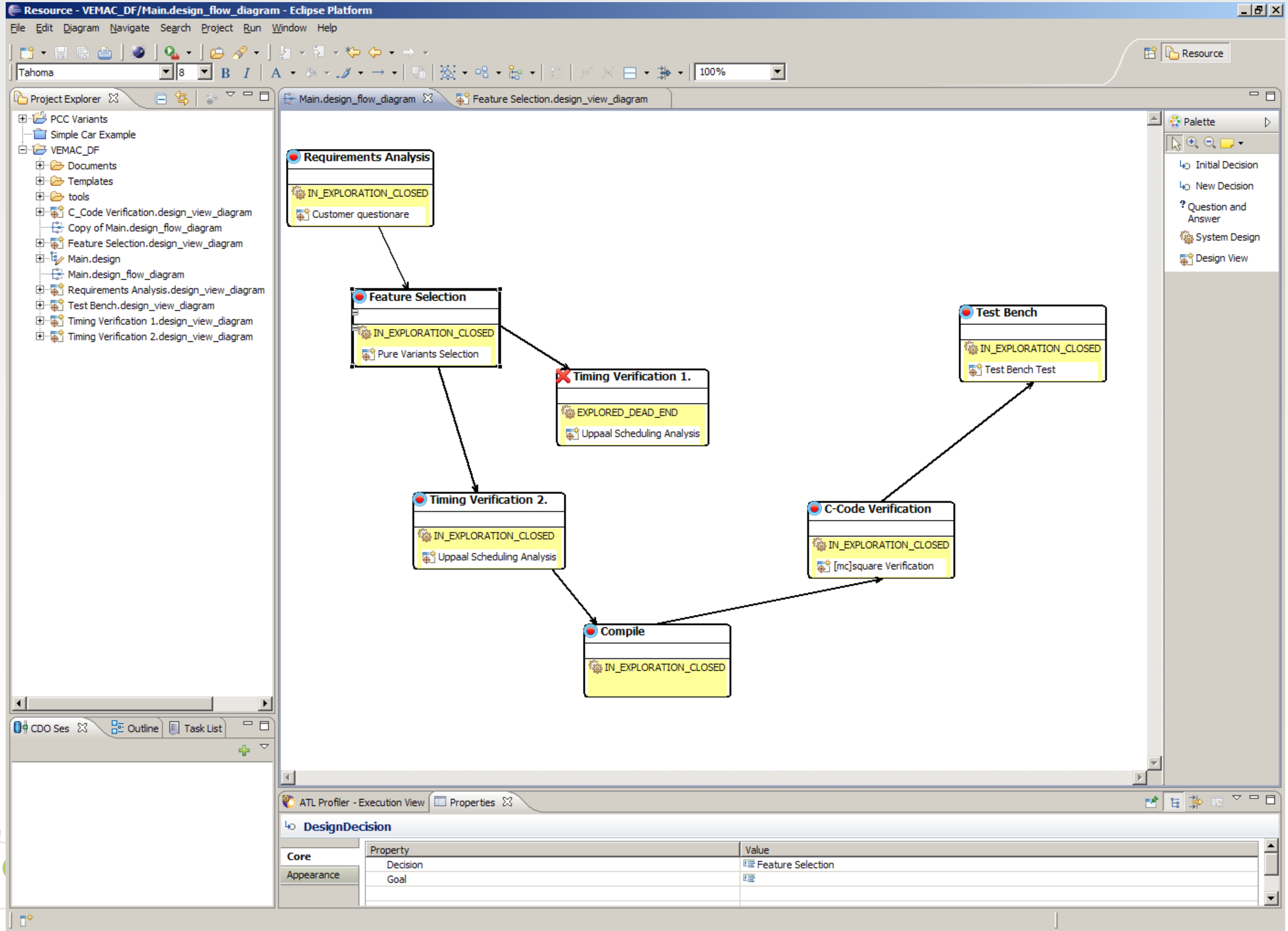
VEMAC Development Process

V-Model



Customized Design Framework Prototype

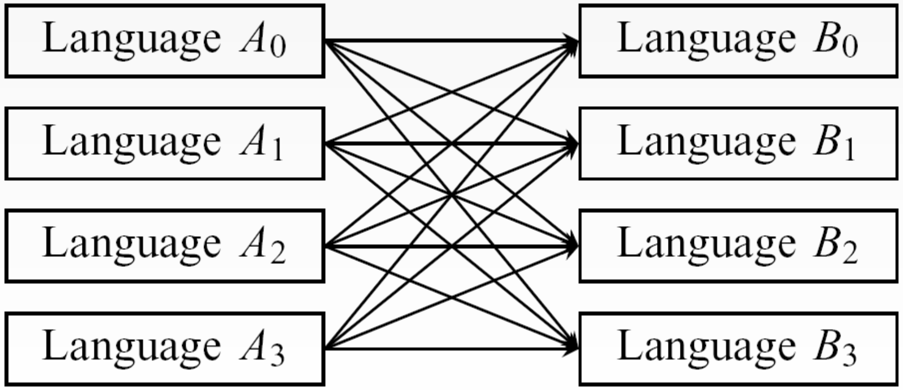


Model Exchange Using the Compositional Interchange Format (CIF)

- Incompatibility of tools is one of the major obstacles for a broader acceptance of model-based design in industry

→ Achieve inter-operability by (algorithmic) model transformations

- One possibility: Bi-lateral transformations
  - Problems
    - Many transformations may be needed
    - The developer of a transformation must be familiar with many different formalisms



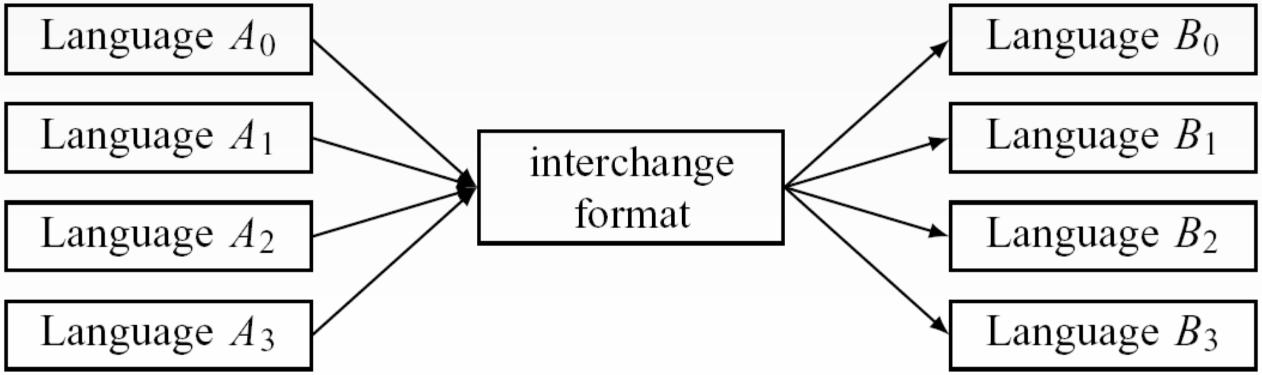
Model Exchange with the Compositional Interchange Format (CIF)

- Incompatibility of tools is one of the major obstacles for a broader acceptance of model-based design in industry

→ Achieve inter-operability by (algorithmic) model transformations

- One possibility: Bi-lateral transformations
- Interchange format
  - Generic and sufficiently rich modelling formalism
  - Only transformations from/to the interchange format are necessary

  → Reduction of the implementation effort



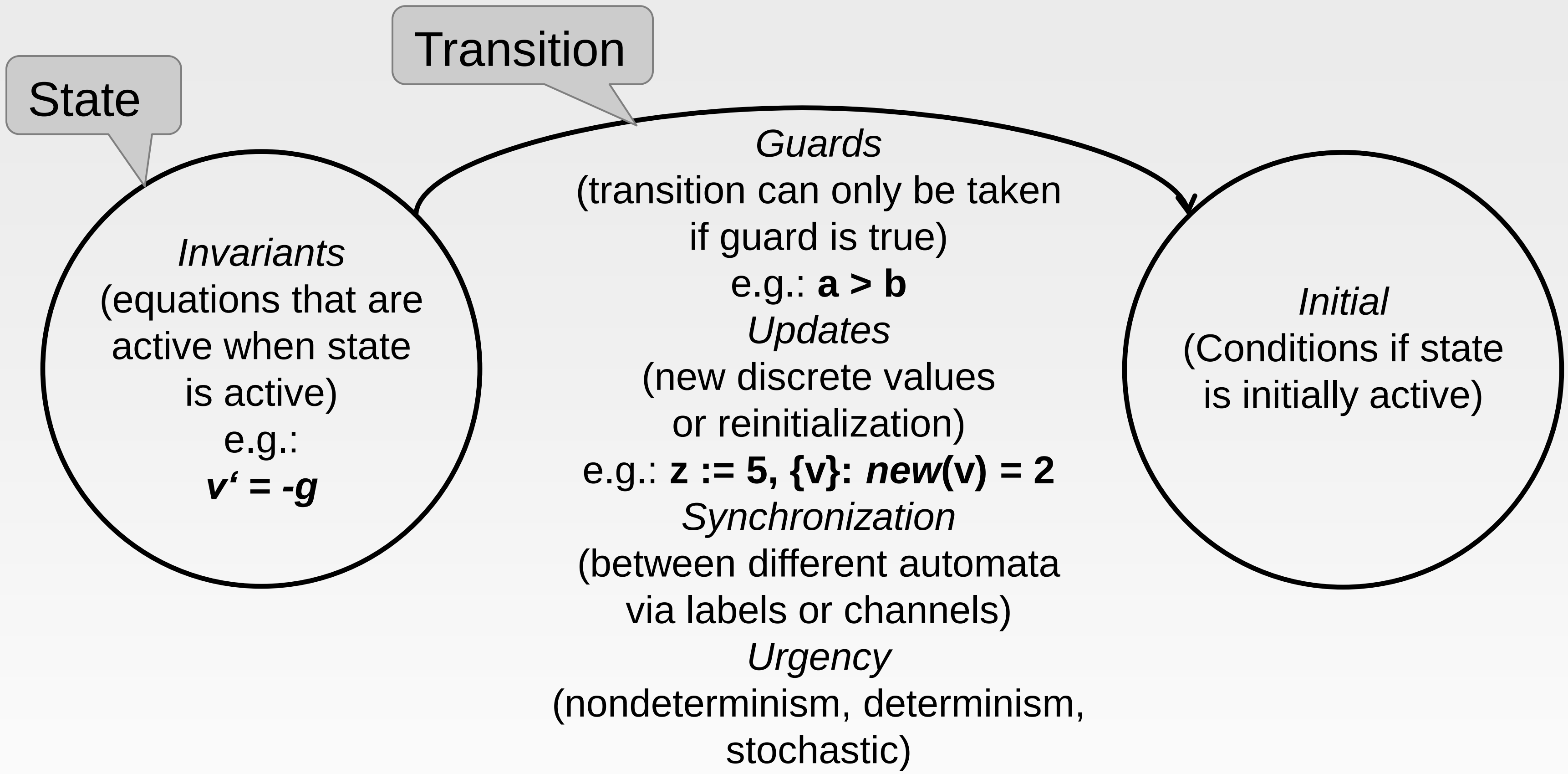
The Compositional Interchange Format (CIF) [Bert van Beek et al., TUE]

- Purposes
  - Establish inter-operability of a wide range of tools
  - Provide a generic formalism for general hybrid systems
- Major features
  - Formal and compositional semantics
    - Independent of implementation aspects
    - Mathematical correctness proofs of translations

    → Property-preserving model transformations possible
  - Fully implicit DAE dynamics (possibly discontinuous)
  - Hierarchy and re-usability
    - Parallel composition with different communication concepts
  - Model component interaction
    - Point to point communication, multi-component synchronization, broadcast communication, shared variables
  - Different urgency concepts

http://devel.se.wtb.tue.nl/trac/cif/

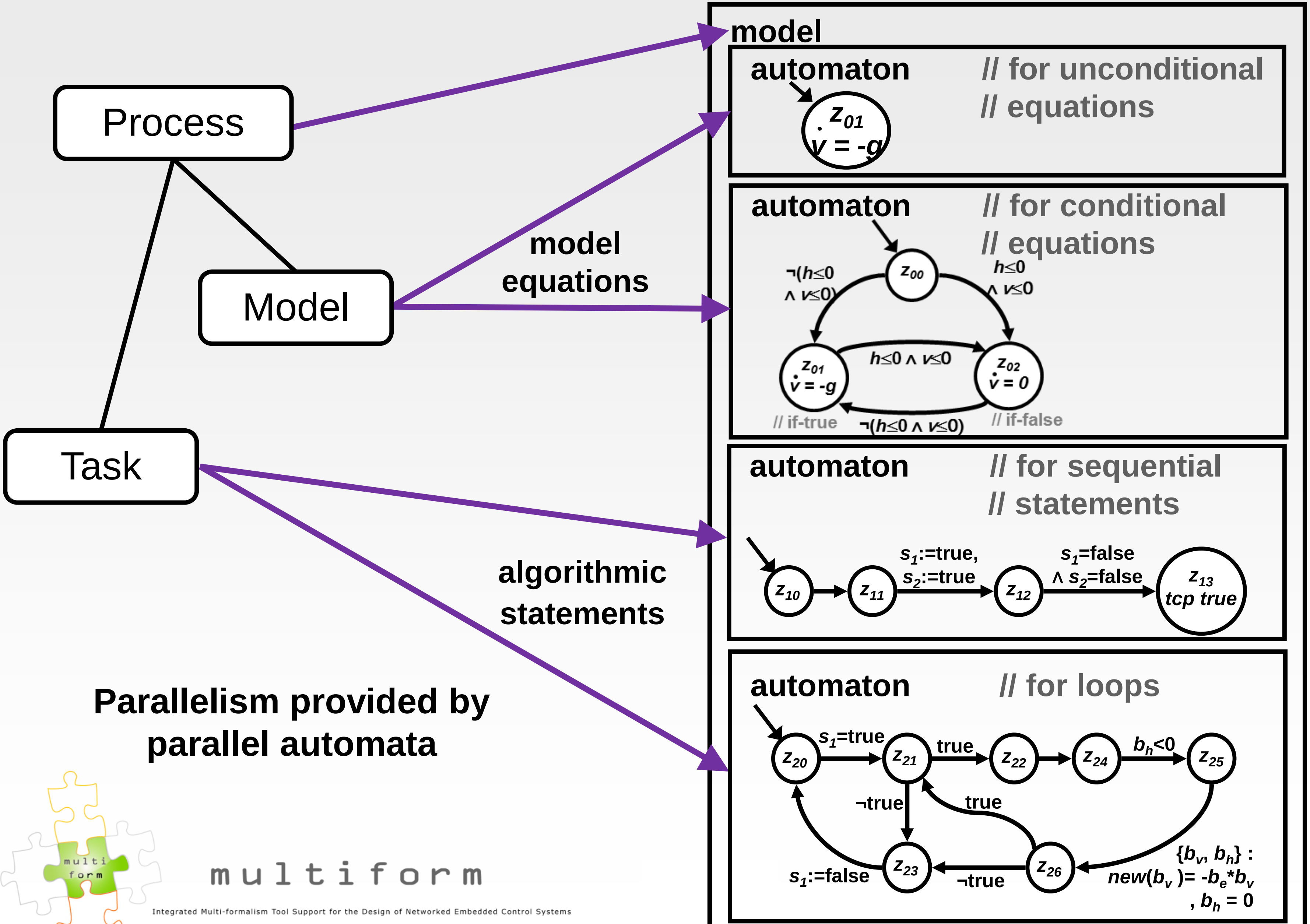
The Compositional Interchange Format (CIF) [Bert van Beek et al., TUE]



Formal definition by *Structural Operational Semantics* (SOS) rules, e.g.:

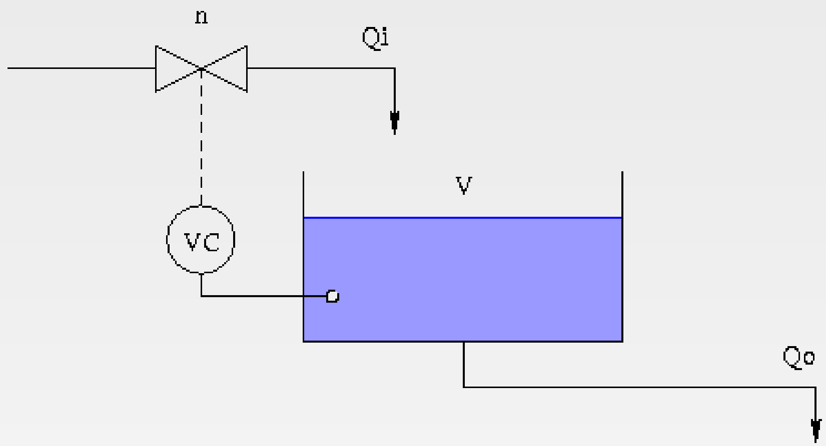
$$\frac{(\alpha_0, \sigma) \xrightarrow{a,\mathrm{true},X} (\alpha_0', \sigma'),\ (\alpha_1, \sigma) \xrightarrow{a,\mathrm{true},X} (\alpha_1', \sigma')}{(\alpha_0 \parallel \alpha_1, \sigma) \xrightarrow{a,\mathrm{true},X} (\alpha_0' \parallel \alpha_1', \sigma')}$$

Transformations – gPROMS ➔ CIF (Excerpt)



Parallelism provided by parallel automata

Simple Example: tank.cif



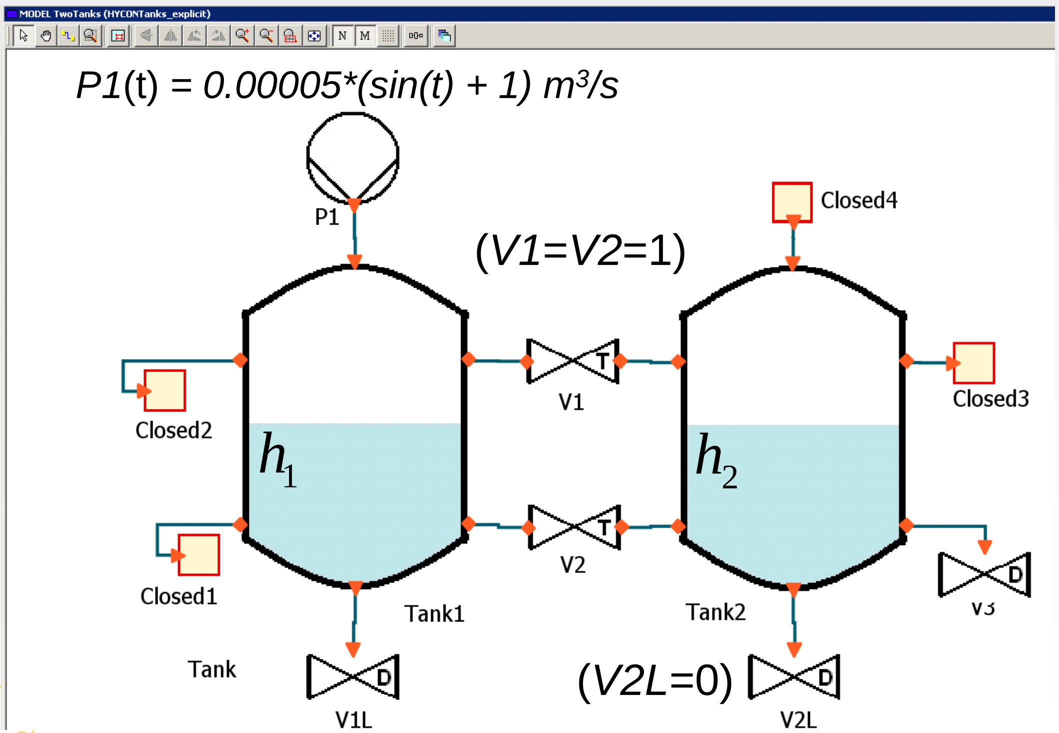

```
model TankController()=
|[ cont control real V = 10.0
 ; var          real Qi, Qo
 ; disc control nat n = 0
:: Tank : |( mode physics = initial
                  inv V' = Qi - Qo
                    , Qi = n * 5.0
                    , Qo = sqrt(V)
        )|
||
   Controller : |( mode closed = initial
                            (when V <= 2  now do n := 1) goto opened
                   , opened = (when V >= 10 now do n := 0) goto closed
             )|
]|
```

Flattened Example: tank_flat.cif

```
model TankController() =
|[ var real V = 10.0  ; var real Qi  ; var real Qo  ; var nat n = 0
:: Tank_Controller:
 |(
     var string Controller_LP ; var string Tank_LP
   ; controlset Controller_LP, Tank_LP, V, n
   ; dyntypemap disc Controller_LP; disc Tank_LP; disc n; cont V;
    mode X =
      initial  (((Tank_LP) = ("physics")) and (true))
                    and (((Controller_LP) = ("closed")) and (true))
      inv ((Tank_LP) = ("physics")) => ((((V)') = ((Qi) - (Qo)))
                    and (((Qi) = ((n) * (5.0))) and ((Qo) = (sqrt(V)))))
      tcp ((Controller_LP) = ("closed")) => (not ((V) <= (2)))
      tcp ((Controller_LP) = ("opened")) => (not ((V) >= (10)))
       ( when (V) <= (2), (Controller_LP) = ("closed") do
           {Controller_LP, n} : (new(n)) = (1), (new(Controller_LP)) = ("opened") )
       ( when (V) >= (10), (Controller_LP) = ("opened") do
           {Controller_LP, n} : (new(n)) = (0), (new(Controller_LP)) = ("closed") ) goto
      X
 )|
]|
```

A Two-tank System under Discrete Control

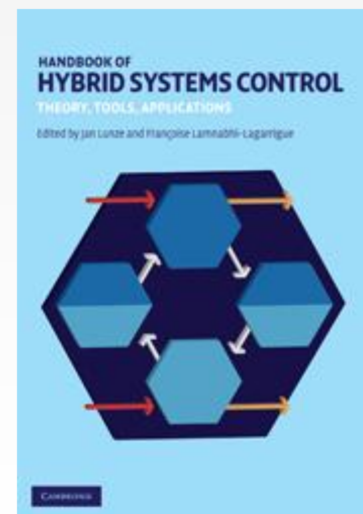
- Hybrid non-linear model of a two-tank system, modeled in *gPROMS*
  - Designed to contain many constructs of the *gPROMS* language



Two-tank system in the graphical *gPROMS* model editor

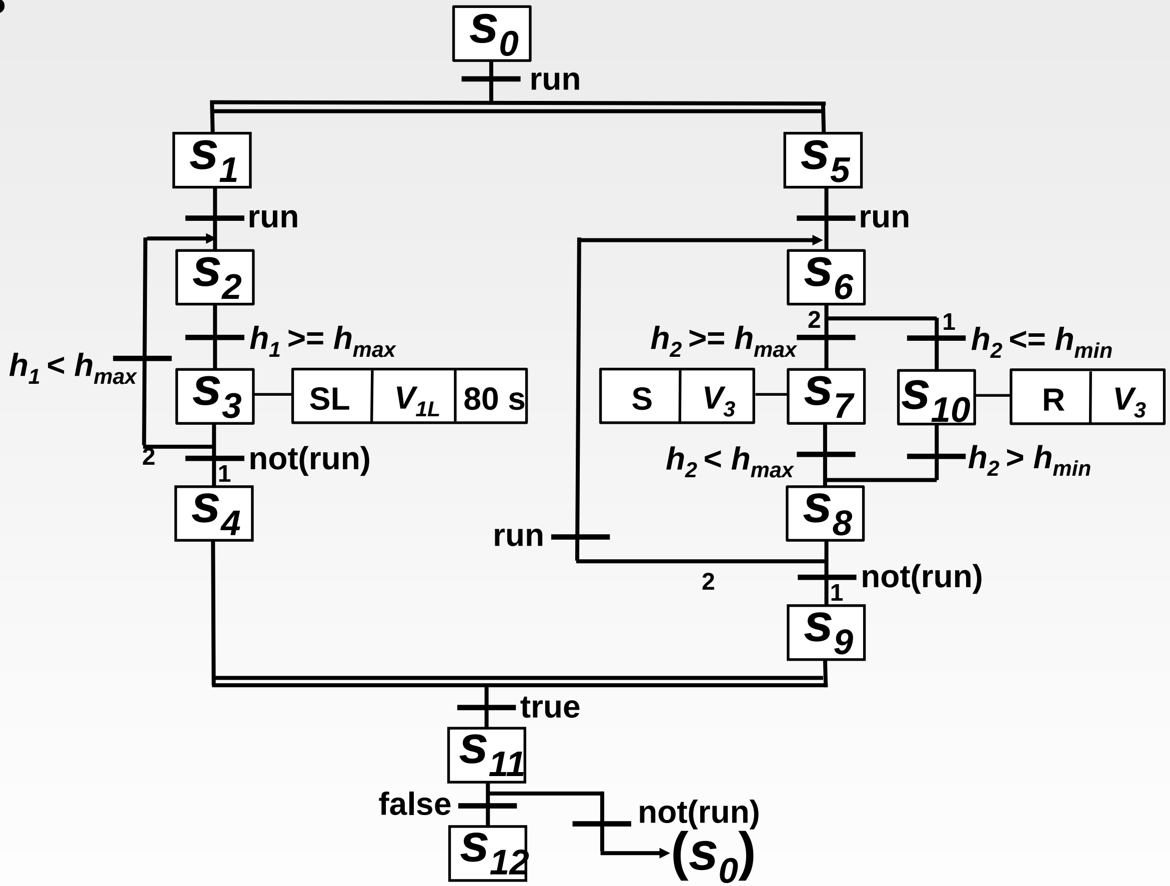
- Controlled variables: h_1, h_2
- Manipulated (discrete) variables: *V1L, V3*

Taken from:

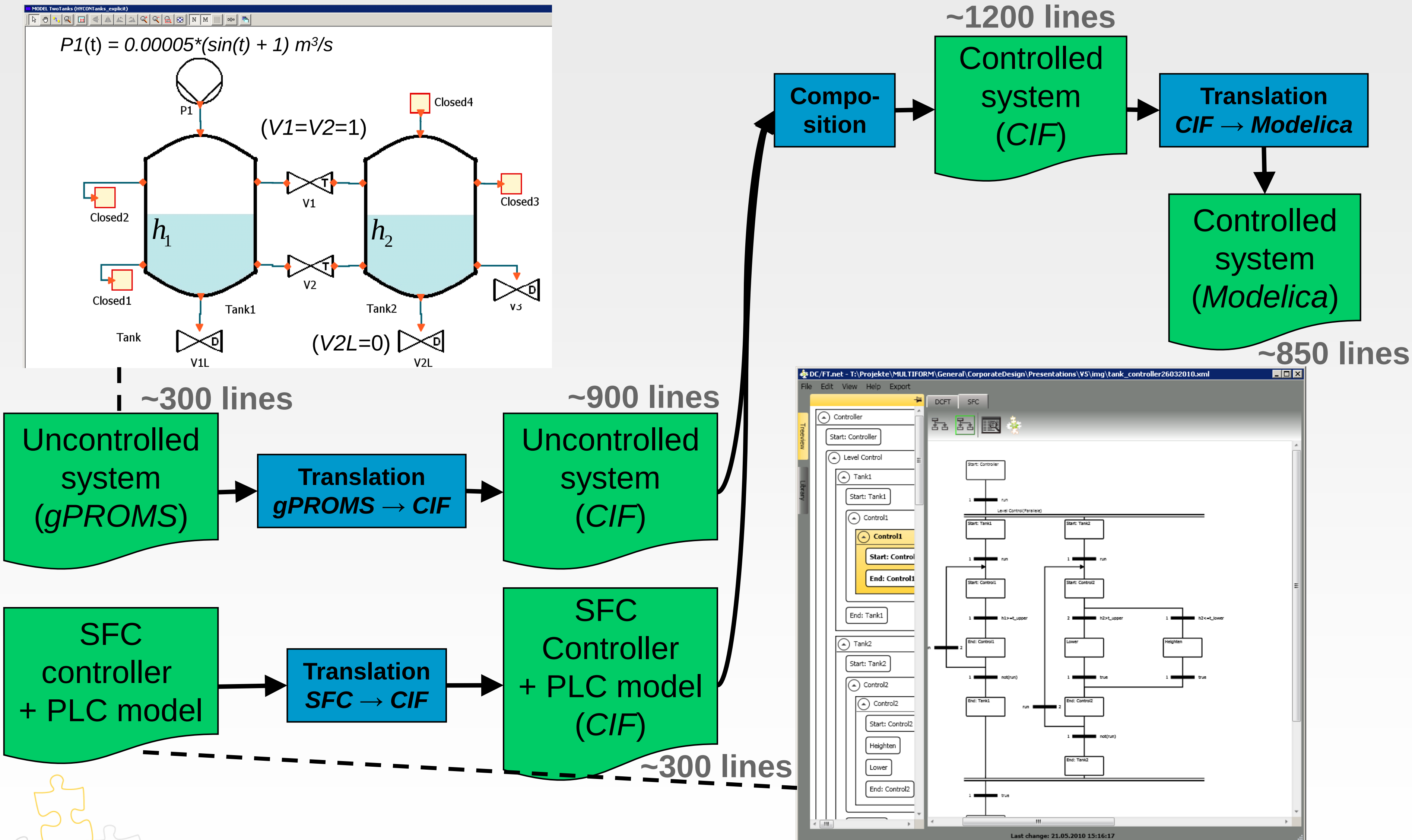


Two-tank Example: *SFC* Controller

- The SFC controller keeps the filling levels h_1 and h_2 between h_{min}=0.2 m and h_{max}=0.5 m
- If h_1 exceeds h_{max}, valve *V1L* is opened for 80s
- If h_2 exceeds h_{max}, valve *V3* is opened until h_2 falls below h_{min}



Two-tank Example: Transformation Tool Chain



DC/FT*: Software tool for the systematic refinement of informal specifications into *SFCs

```
model TwoTanks_SFC () =
|[
extern var Tanks_DOT_Tank1_DOT_h: cont real
```

```
::
|(
 mode v_tr1 = when l_u now do (c_c,t_rem) := (0, t_c - (time mod t_c)) goto v_tr2
, v_tr2 = when c_c >= t_rem now do (opt_V1,opt_V2,R_V1,R_V2,l_R_V2,l_u,c_c) := (0,0,false,false,true,false,0) goto v_tr3
```

```
|( //action "SL V1 End1"
```

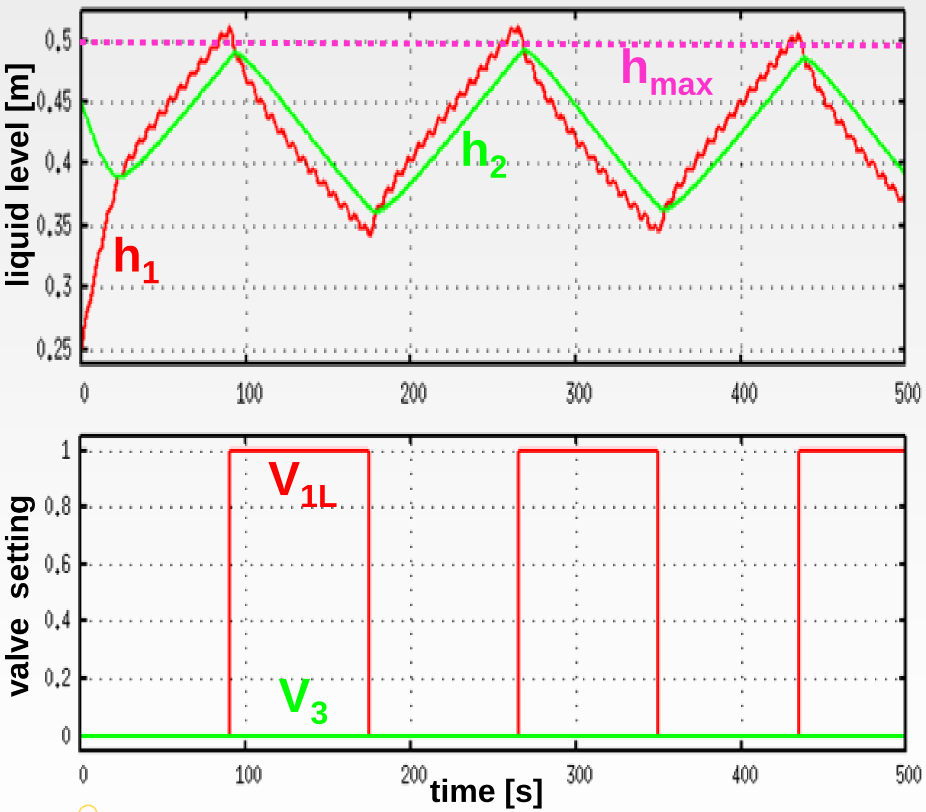
```
// Main structure automaton a_str,m
|(
```

```
||
 |(
 mode
vi_2= when l_par2 and l_str2 and not(l_strm) now do (s_S2,l_str2,not_finished2):=(true,false,true) goto v_s_S2
 when not(l_par2) and l_str2 and not(l_strm) now do (l_str2,not_finished2):=(false,false) goto vi_2
, v_s_S2= when (run) and l_str2 now do (s_Start2,s_S2,l_str2,not_finished2):=(true,false,false,true) goto v_s_Start2
 when not(run) and l_str2 now do (l_str2,not_finished2):=(false,false) goto v_s_S2
, v_s_Start2= when (Tanks_DOT_Tank2_DOT_h<=t_lower) and l_str2 now do (s_Hei2,s_Start2,l_str2,not_finished2):=(true,false,false,true)
goto v_s_Hei2
 when (Tanks_DOT_Tank2_DOT_h>t_upper) and not(Tanks_DOT_Tank2_DOT_h<=t_lower)  and l_str2 now do
(s_Low2,s_Start2,l_str2,not_finished2):=(true,false,false,true) goto v_s_Low2
 when not(Tanks_DOT_Tank2_DOT_h<=t_lower or Tanks_DOT_Tank2_DOT_h>t_upper) and l_str2 now do
(not_finished2,l_str2):=(false,false) goto v_s_Start2
, v_s_Hei2= when (Tanks_DOT_Tank2_DOT_h>t_lower) and l_str2 now do (s_End2,s_Hei2,l_str2,not_finished2):=(true,false,false,true)
goto v_s_End2
 when not(Tanks_DOT_Tank2_DOT_h>t_lower) and l_str2 now do (not_finished2,l_str2):=(false,false) goto v_s_Hei2
, v_s_Low2= when (Tanks_DOT_Tank2_DOT_h<=t_upper) and l_str2 now do (s_End2,s_Low2,l_str2,not_finished2):=(true,false,false,true)
goto v_s_End2
 when not(Tanks_DOT_Tank2_DOT_h<=t_upper) and l_str2 now do (not_finished2,l_str2):=(false,false) goto v_s_Low2
, v_s_End2 = when (not(run)) and l_str2 now do (s_FEnd_1,s_End2,l_par2,l_str2,not_finished2):=(true,false,false,false,false) goto vi_2 //
last step
 when (run) and not(not(run))  and l_str2 now do (s_Start2,s_End2,l_str2,not_finished2):=(true,false,false,true) goto v_s_Start2
 when not(not(run) or run) and l_str2 now do (not_finished2,l_str2):=(false,false) goto v_s_End2
// last step, return to start (step variable is deactivated by main automaton)
:: vi_2
)|
//SFC end
```

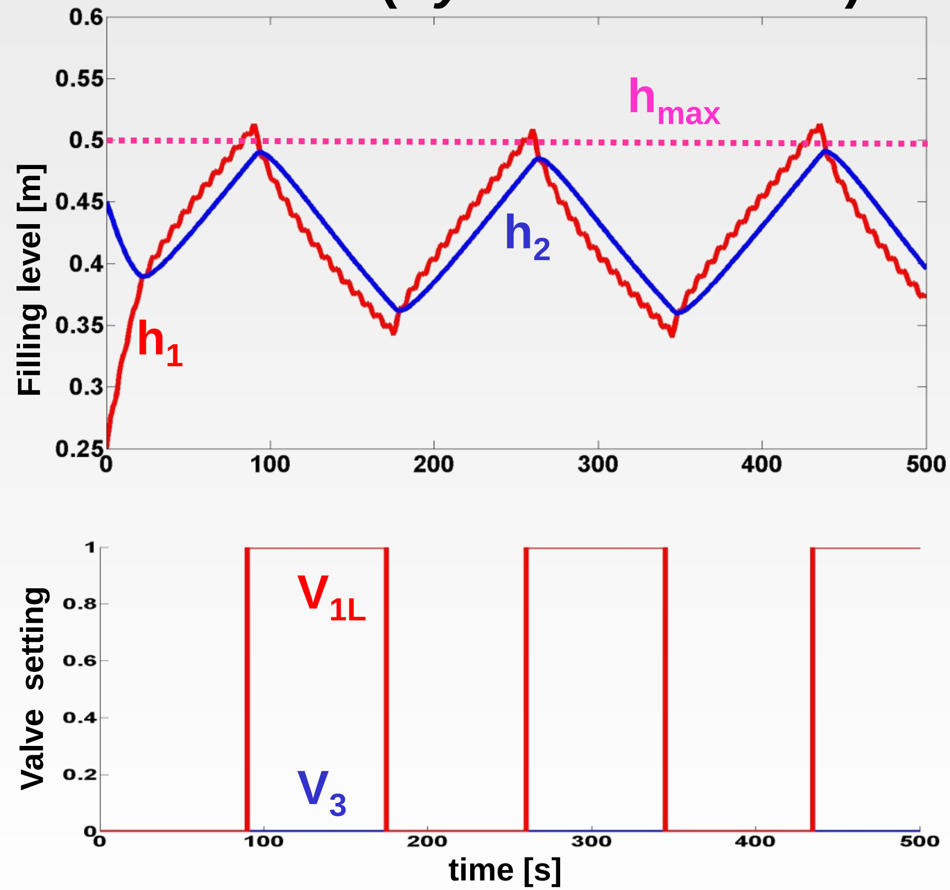
```
:: vi_1
)| // structure automaton
```

Two-tank Example: Simulation Results

CIF simulator



Modelica (*Dymola simulator*)



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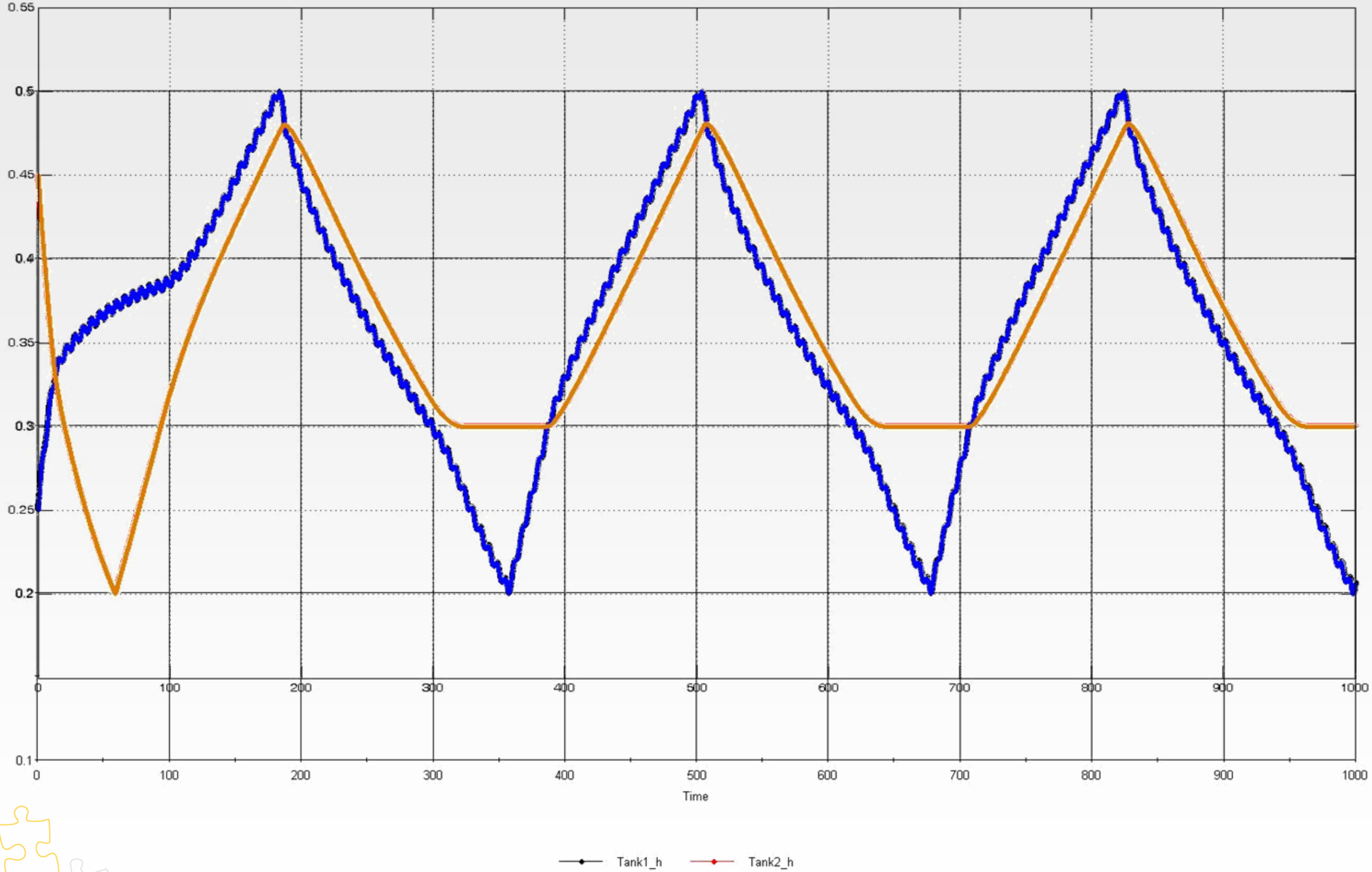
Output Identical



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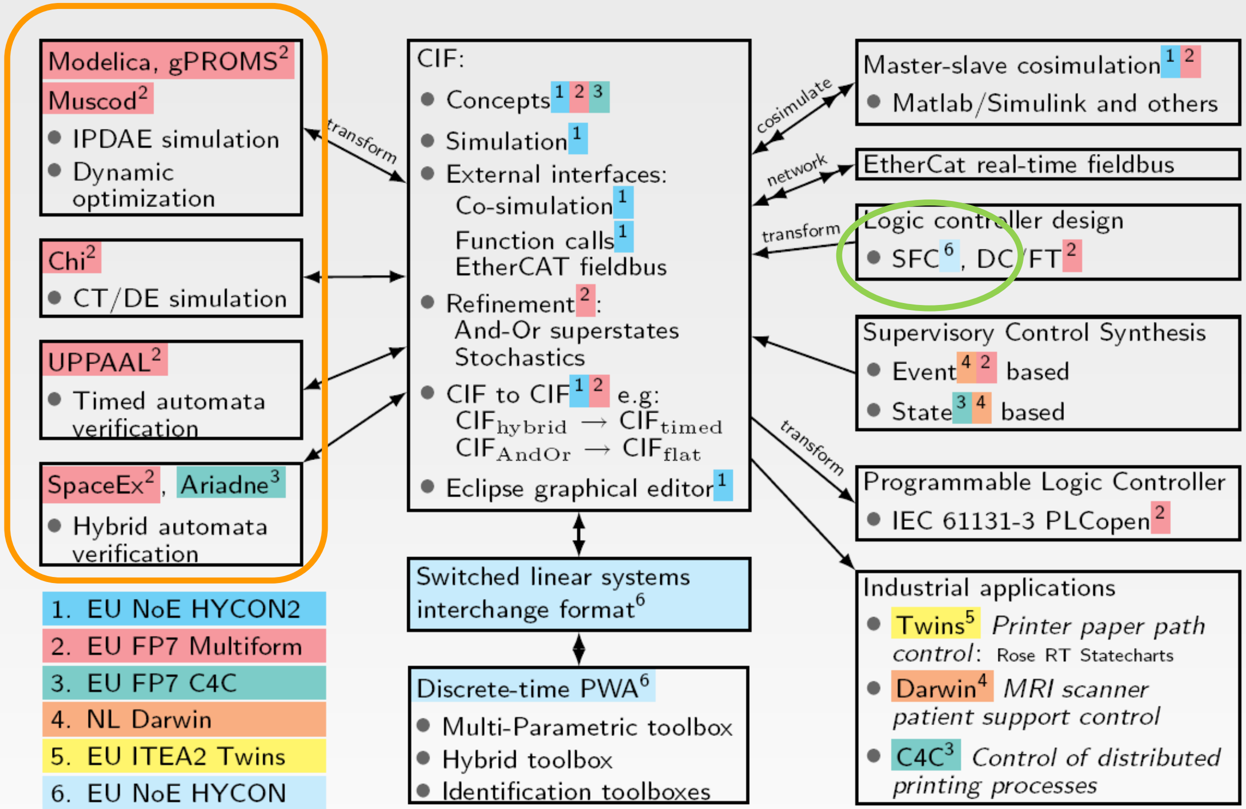
Compositional Interchange Format (CIF)



http://se.wtb.tue.nl/sewiki/cif/start

References:

Fischer, S.; Hüfner, M.; Sonntag, C.; Engell, S.: Systematic Generation of Logic Controllers in a Model-based Multi-formalism Design Environment. Proc. 18th IFAC World Congress, 28.08.-02.09.2011, 12490-12495.

Hendriks, D.; Schiffelers, R.; Hüfner, M.; Sonntag, C.: A Transformation Framework for the Compositional Interchange Format for Hybrid Systems. Proc. 18th IFAC World Congress, 28.08.-02.09.2011, 12509-12514.

Sonntag, C.; Hüfner, M.: On the Connection of Equation- and Automata-based Languages: Transforming the Compositional Interchange Format to Modelica. Proc. 18th IFAC World Congress, 28.08.-02.09.2011, 12515-12520.

Equation-based vs. Automaton-based Formalisms

- Simulation/Solver/Tool options encoded in model code (e.g. *EcosimPro*, *gPROMS*)
  - Tool specific options cannot be transformed
    ➔ Other tools might not find a solution for a difficult initialization problem

- Formal semantics not available ➔ Transformation not provably correct

- Equation-based models can be more restrictive than automata models
  - E.g. *Modelica* enforces globally and locally balanced models
    ➔ Automata models need to be preprocessed
    - Either by flattening of the model
    - Or by rebuilding the automata structure in an equation-based formalism

Summary

- There is a need for efficient model-based support of the design of complex automated systems with trans-level propagation and iteration, and re-use of models
- An all-encompassing mega-tool for the design of complex automated systems is not realistic, so several tools and modeling formalisms must be used in the design process.
- Three different routes to tool and model integration and design support were pursued in MULTIFORM:
  - Model exchange and tool chains via the *CIF*
  - Direct coupling of tools for testing of specifications
  - Propagation of parameters via the Design Framework

Lessons and Challenges from MULTIFORM

- The *CIF* and its tool set are stable and relatively mature
- Available under open source licence
- The effort for developing model transformations is high
- Transformations from the CIF in most cases can only be performed for subsets of the models which can be represented in the formalism.
  - A **formal** specification of the the supported *CIF* subset of a tool is needed
- It should be possible to trace elements of a model after the transformation
- Model blow-up is not as bad as could be expected

Lessons and Challenges from MULTIFORM (2)

- The *CIF* is very expressive and well suited for model exchange between automata-based formalisms, but conceptually different from equation-oriented languages (e.g. *Modelica*, *gPROMS*, *EcosimPro*)
  - **Possible solution:** Use a *Modelica* subset as an exchange formalism for equation-oriented languages, bridge equation- and automata-oriented formalisms via the *CIF* ↔ *Modelica* transformation
- Often only some elements of a system are modeled precisely, and these models are formulated in different formalisms (*fragmented modeling*)
  - How can the interdependencies between model fragments be **formally** described and exploited?
- **Model ontology needed**
  - Specification of model formalism expressivity using a common formal vocabulary
  - Equipping model artifacts with meta data on their origin(s) → traceability
  - Description of relations of partial models to an overall model