TOWARDS AN INTEGRATED TOOL CHAIN FROM PHYSICAL MODELS TO DIAGNOSIS FUNCTIONS

MODPROD WORKSHOP

FEBRUARY 6TH-7TH, 2018, LINKÖPING, SWEDEN

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From Physical Models to Diagnosis Functions
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  - ITEA3 Project: EMPHYSIS
- Model-based Diagnosis
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- Conclusions & Outlook

CORPORATE SECTOR RESEARCH AND ADVANCE ENGINEERING

Organization
Bosch Corporate Research

Future Mobility Systems	Software-intensive Systems and Technologies: Enabling Open Context Systems	Future Systems for Industrial Technology, Consumer Goods and Building Technology	Metal and Plastics Technology, Production Automation	Advanced Functional Materials and Microsystems	Future Components and Simulation Methods
▶ Powertrain and eMobility Systems ▶ Connected Mobility Systems ▶ Computer Vision ▶ Vehicle Safety and Automated Driving	▶ Model-based Systems Engineering ▶ Dependable Connected Systems ▶ Human Machine Interaction	▶ Systems for Industrial Technology ▶ Robotic Systems and Power Tools ▶ Systems for Building Technology	▶ Laser material processing, electronic packaging and interconnection technology ▶ Materials- and Process Engineering Metals ▶ Production Automation ▶ Plastics Engineering	▶ Analytics ▶ Chemical Processes and Technology ▶ Functional Materials and Coating Technologies ▶ Microsystem Technologies	▶ Electrodynamics and Electric Drive Technology ▶ Future Mechanical and Fluid Components ▶ Integrated Component Design

Research and Technology Center North America
Circuit Design, Semiconductor- and Wireless Technology

Bosch – A Global Network
Four Business Sectors

Mobility Solutions	Industrial Technology	Energy and Building Technology	Consumer Goods
			

Bosch Mobility Solutions
Integrated System Solutions for Maximum Benefit

Connected mobility

Automated mobility

Powertrain systems and electrified mobility

fun and **fascinating**

safe and **comfortable**

efficient and **economical**

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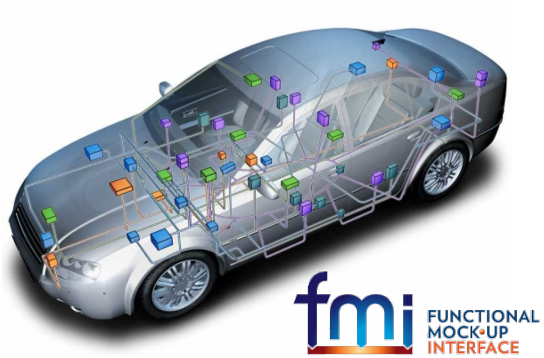
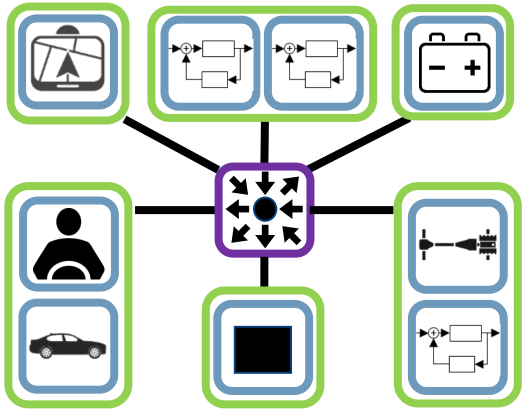
EMPHYSIS Embedded Systems with Physical Models in the Production Code Software

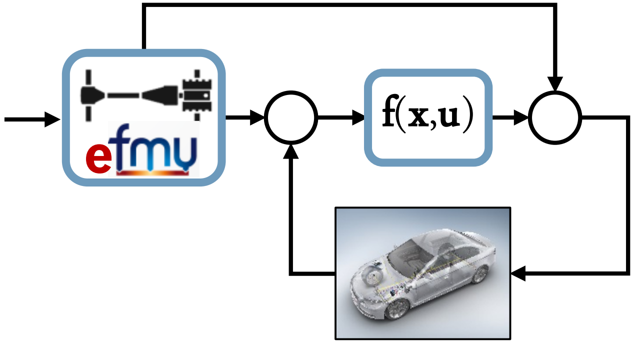
From System Design to ECU Software

- Model-based Systems Engineering

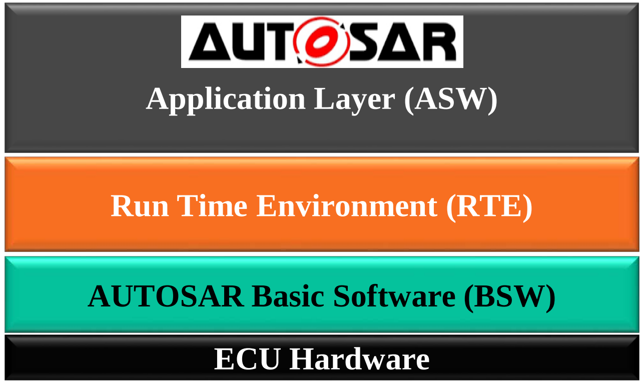


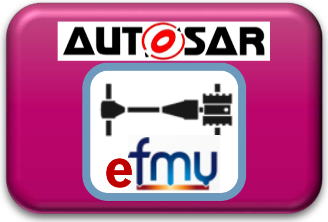


- Model-based Functions
  - Virtual Sensors
  - Feed-forward Control
  - Model-based Diagnosis
  - Model Predictive Control
  - Advanced operating strategies
  - …



- Software Engineering





FMU SWC

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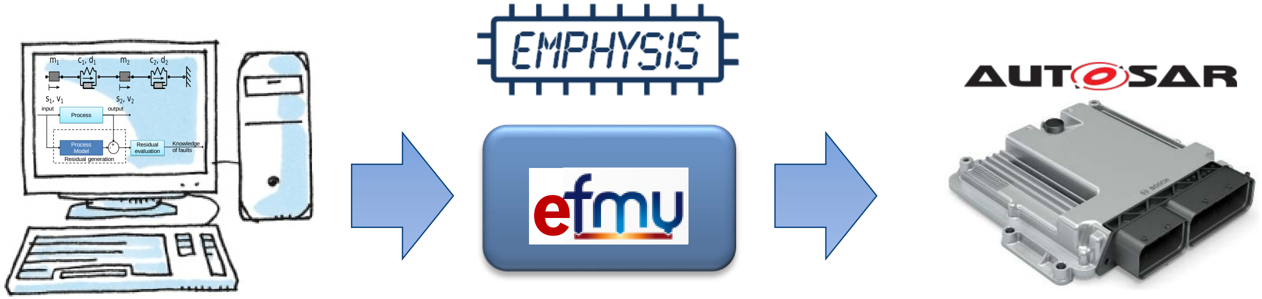
EMPHYSIS Embedded Systems with Physical Models in the Production Code Software

Project Goals

- Bridging the gap between modelling and simulation tools and embedded systems through a new interface definition (eFMI)
- Enabling the efficient implementation of advanced control and diagnosis functions with physical models on the ECU.
- Seamless and easy re-use of physical models both for offline simulation and on the ECU

- Reduce software complexity.
- Improve software development productivity.
- Enable software innovations through advanced functions for smarter products
  - Automotive
  - Robotics
  - Buildings
  - Industrial Applications

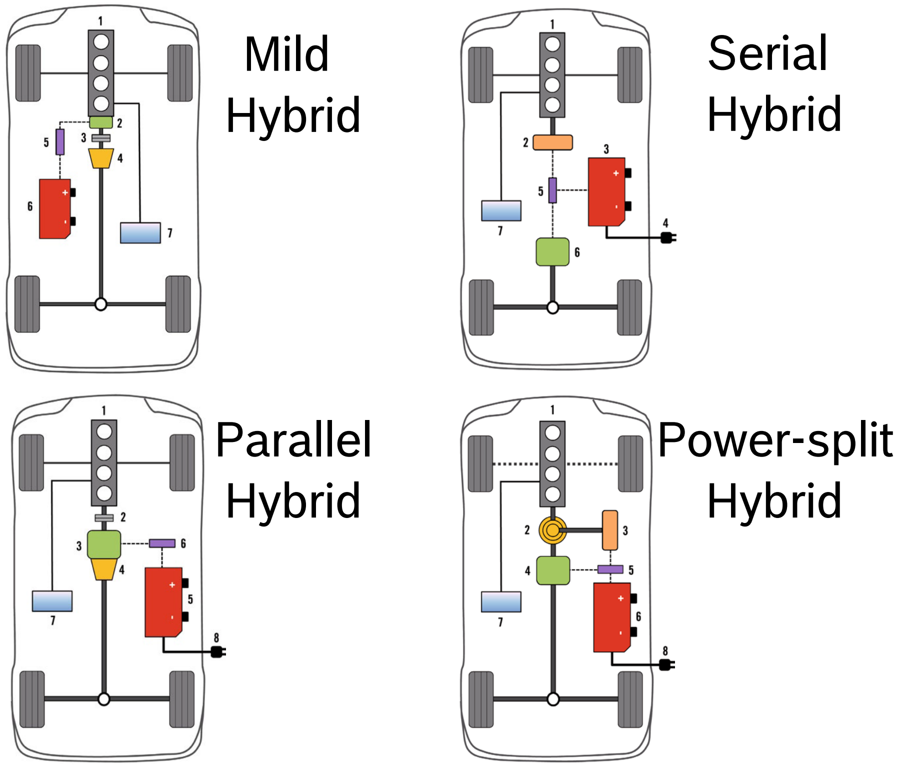


Model-based Diagnosis

From Physical Models to Diagnosis Functions
Model-based Diagnosis – Motivation

- Growing Variability of Drive Train Topologies
  - Electrification of the drive train (esp. hybrid vehicles) largely increases the design choices.
  - Design choices have a strong impact on the topology of the thermal system.
  - Topologies of the thermal system differ by OEM and by vehicle class (low-cost to luxury).

- Topology Variability:
  - 3 OEMs
  - 3 Vehicle Categories (small, medium, premium)
  - Assuming 30% similarity → ~6 Topologies

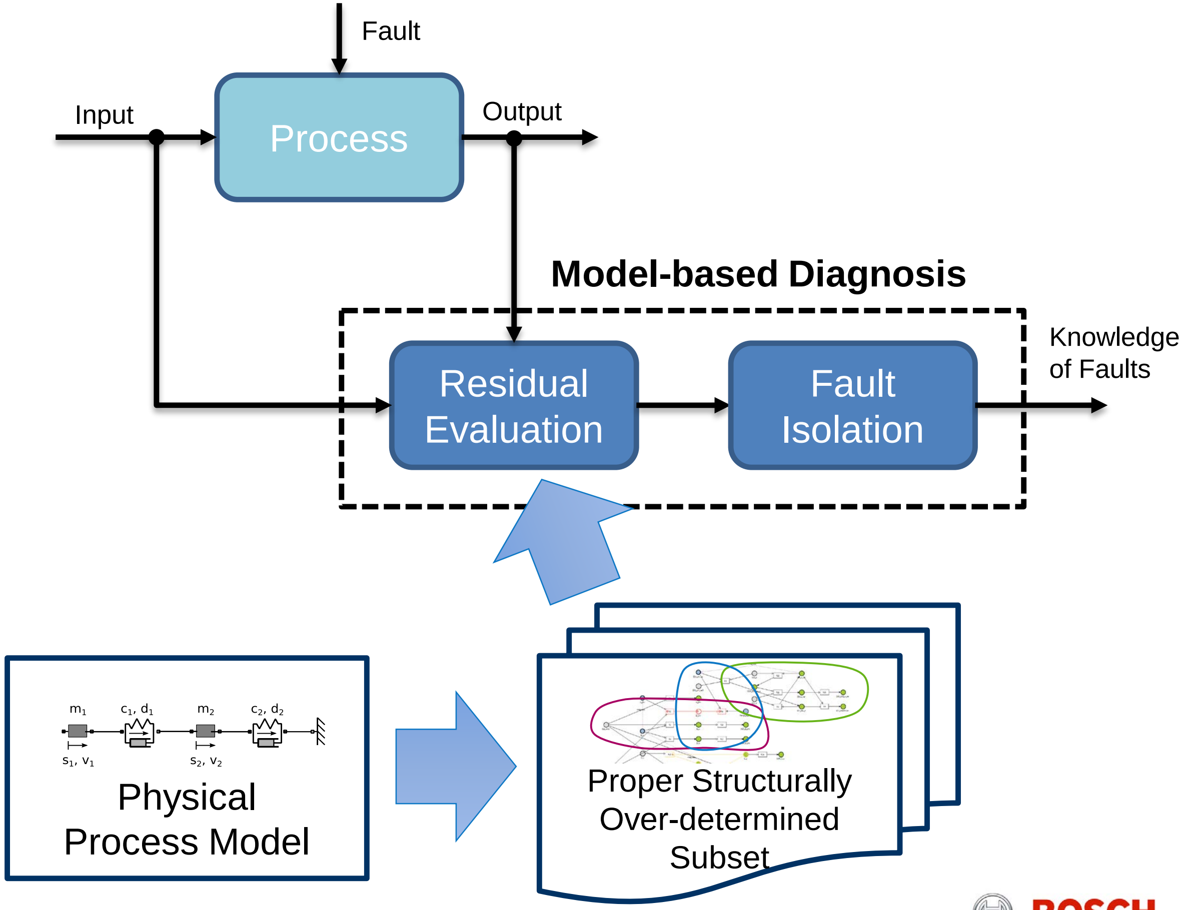


Source: Tschöke, Helmut, ed. 2015. *Die Elektrifizierung des Antriebsstrangs*. Wiesbaden: Springer Fachmedien Wiesbaden. doi:10.1007/978-3-658-04644-6.

Mastering software complexity is a success factor for future automotive applications.

From Physical Models to Diagnosis Functions
Model-based Diagnosis – Workflow

- Describe a physical model of the process to be diagnosed as DAE in equation-based form.
- Analyze the structure of the DAE system to determine the detectable and isolable faults.
- Derive residual functions from the DAE system.
- Calculate residuals considering the actual inputs and outputs of the on-going process.
- Evaluate the calculated residuals to detect faults.
- Use the fault signature matrix to isolate the active fault class.



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From Physical Models to Diagnosis Functions
Benefits of Model-based Diagnosis

- Holistic approach to systematically exploit side effects on a system level.
- Early evidence about fault detectability and isolability.
- Dependencies between individual faults become explicit and manageable.
- More reliable and robust diagnosis allows better utilization of the full component capacity.
- Adjustment to other topologies is achieved in a comprehensible way by reusing component models.
- Calibration effort is reduced by using physical parameters instead of heuristics and maps.

Structural Analysis

From Physical Models to Diagnosis Functions
Structural Analysis – Basic Representation

Behavioral model

- Differential algebraic equations, algebraic equations

$$c\colon\ y = 2z + 3u + f$$

- Used for simulation, sensitivity analysis, controller design, etc.

Structural model

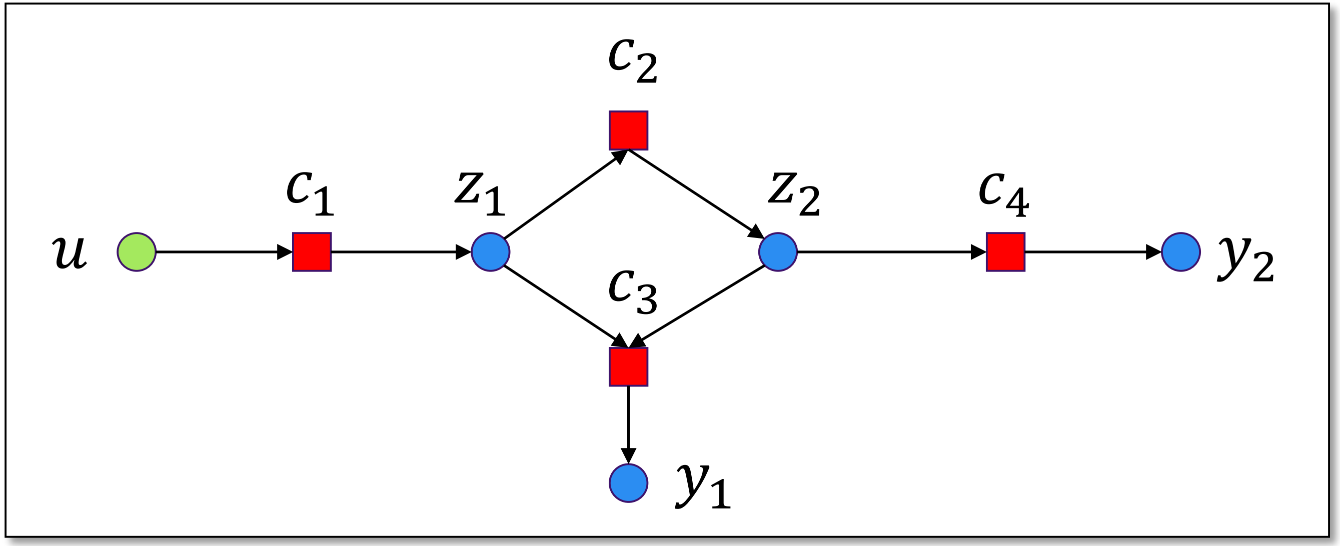
- Structure graph (bipartite graph)

- Used for equation solving (preprocessing) and diagnosis

Structural information is sufficient for general conclusions.

From Physical Models to Diagnosis Functions
Structural Analysis –Determined System

- **Determined** system (same number of equations and unknowns) $|\mathrm{C}^0| - |\mathrm{Z}^0| = 4 - 4 = 0$
- Outputs are considered as unknown, system can be solved for the unknowns (forward simulation)



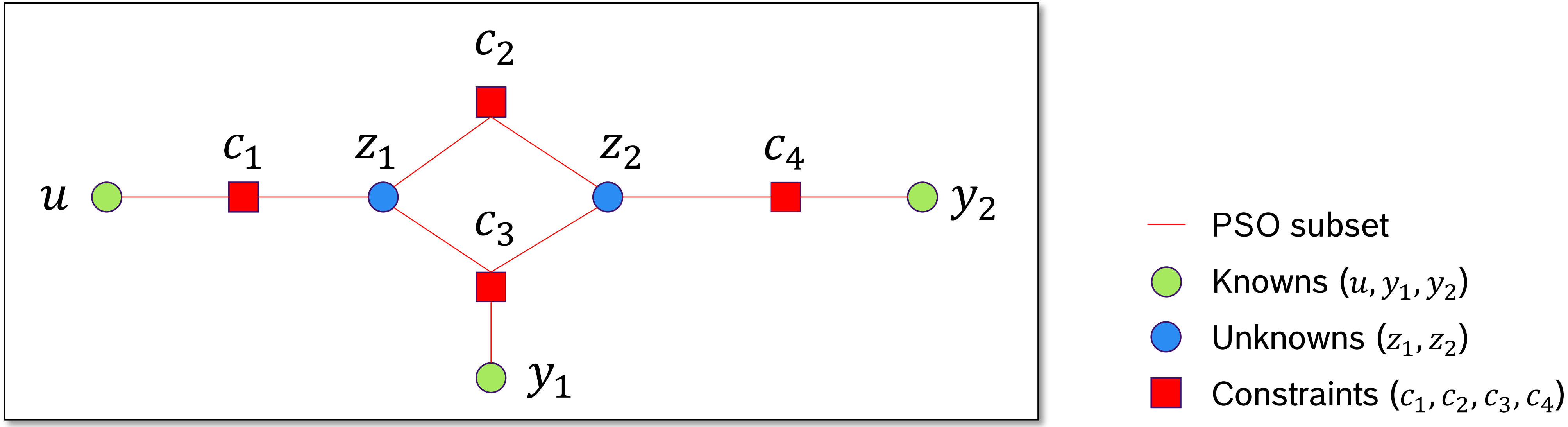
Knowns (u)

Unknowns (y_1, y_2, z_1, z_2)

Constraints (c_1, c_2, c_3, c_4)

From Physical Models to Diagnosis Functions
Structural Analysis – Over-Determined System

- **Over-determined** system (2 more equations than unknowns) $|\mathrm{C}^{+}| - |\mathrm{Z}^{+}| = 4 - 2 = 2$
- Outputs are considered as known (senor signals set as input)



Krysander, Mattias, Jan Aslund, and Mattias Nyberg. 2005. *An Efficient Algorithm for Finding Over-Constrained Sub-Systems for Construction of Diagnostic Tests*.

PSO: Proper structurally over-determined

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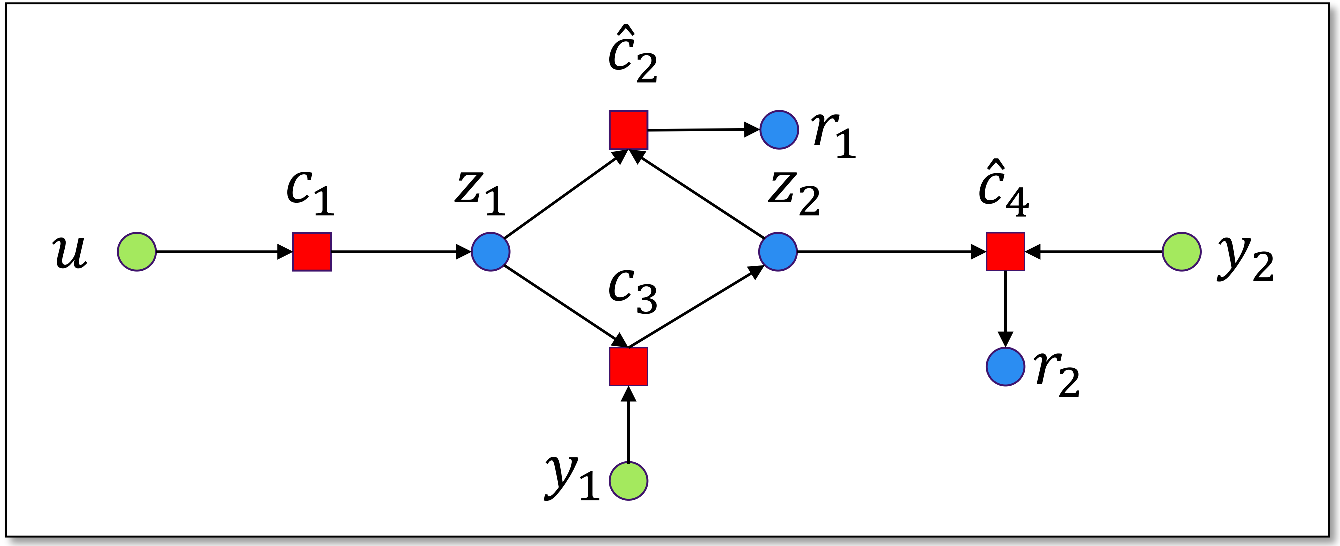
Structural Analysis – PSO with Residuals

- **Over-determined** system is **balanced** by 2 more unknowns $|C^0| - |Z^0| - |R^0| = 4 - 2 - 2 = 0$
- Redundant information (PSO) is used to calculate additional residuals (e.g. for diagnosis)



PSO subset

Knowns (u, y_1, y_2)

Unknowns (z_1, z_2, r_1, r_2)

Constraints $(c_1, \hat{c}_2, c_3, \hat{c}_4)$

PSO: Proper structurally over-determined

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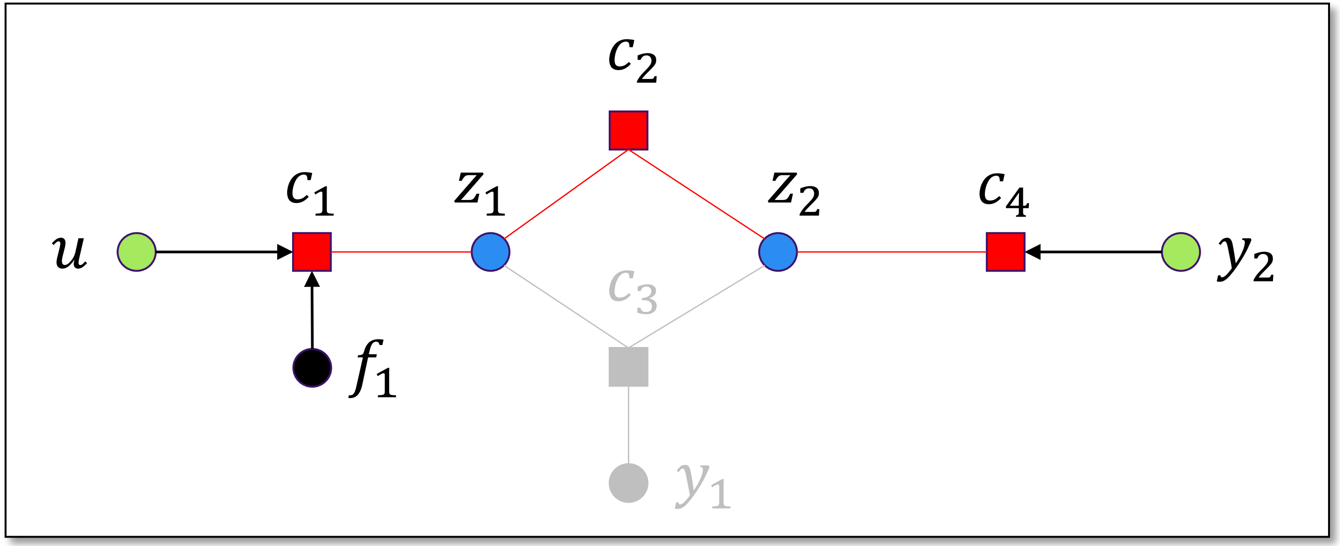
Structural Analysis – Structural Fault Detection

- Faults are associated with constraints (f_1 with c_1)
- System is considered as fault free ($f_1 = 0$)
- Fault (deviation from nominal behavior) is detectable, if C^+depends on fault ($PSO\{c_1, c_2, c_4\} = f(f_1)$)

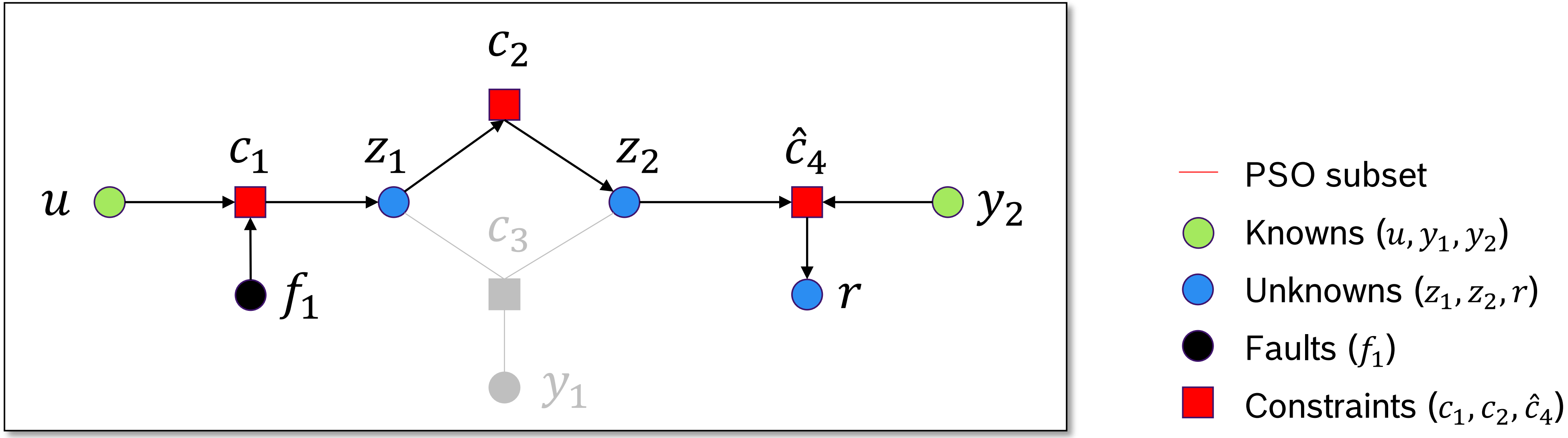


PSO: Proper structurally over-determined

From Physical Models to Diagnosis Functions

Structural Analysis – Structural Fault Detection

- Faults are associated with constraints (f_1 with c_1)
- Fault is detectable, if C^+ depends on fault ($PSO\{c_1, c_2, \hat{c}_4\} = f(f_1)$) and can be solved for an additional residual ($r = y_2 - f_{PSO}(u, f_1)$)



PSO: Proper structurally over-determined

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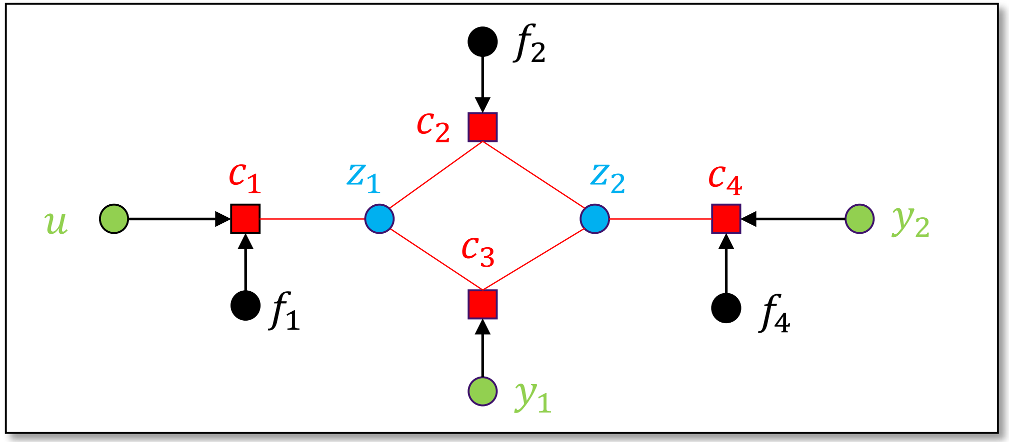
Structural Analysis – Structural Fault Detection

- Sensor signals are considered as known
- Multiple faults are added to the model
- All faults are considered as known



	f_1	f_2	f_4
$PSO_0\{c_1, c_2, c_3, c_4\}$	1	1	1

All faults are detectable through PSO_0, but not distinguishable.

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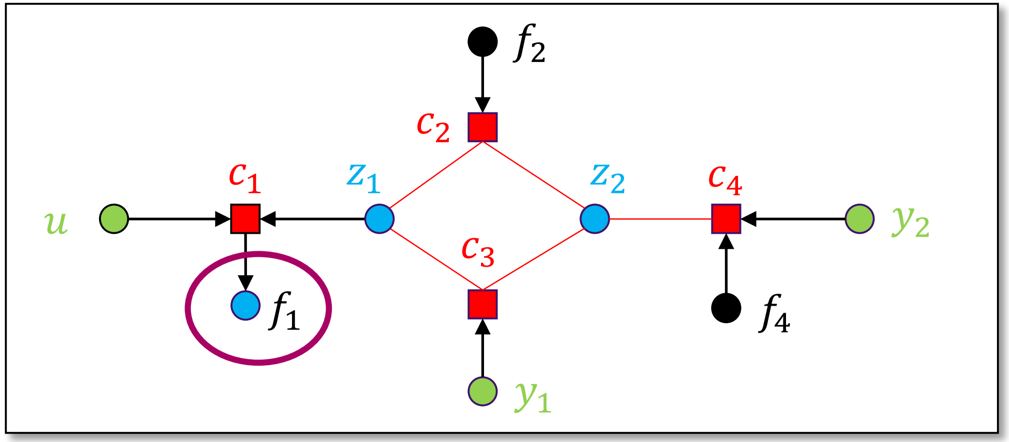
Structural Analysis – Structural Fault Isolation

- Consider one fault as unknown
- Determine PSO
- Mark all faults with impact on PSO in Fault Signature Matrix as one others zero

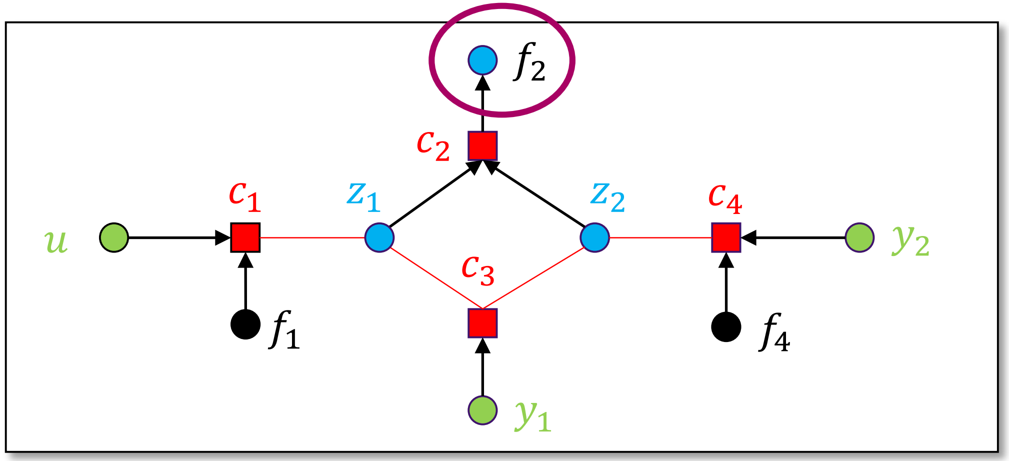


	f_1	f_2	f_4
$PSO_0\{c_1, c_2, c_3, c_4\}$	1	1	1
$PSO_1\{c_2, c_3, c_4\}$	0	1	1

From Physical Models to Diagnosis Functions
Structural Analysis – Structural Fault Isolation

- Consider next fault as unknown
- Determine PSO
- Mark all faults with impact on PSO in Fault Signature Matrix as one

	f_1	f_2	f_4
$PSO_0\{c_1, c_2, c_3, c_4\}$	1	1	1
$PSO_1\{c_2, c_3, c_4\}$	0	1	1
$PSO_2\{c_1, c_3, c_4\}$	1	0	1



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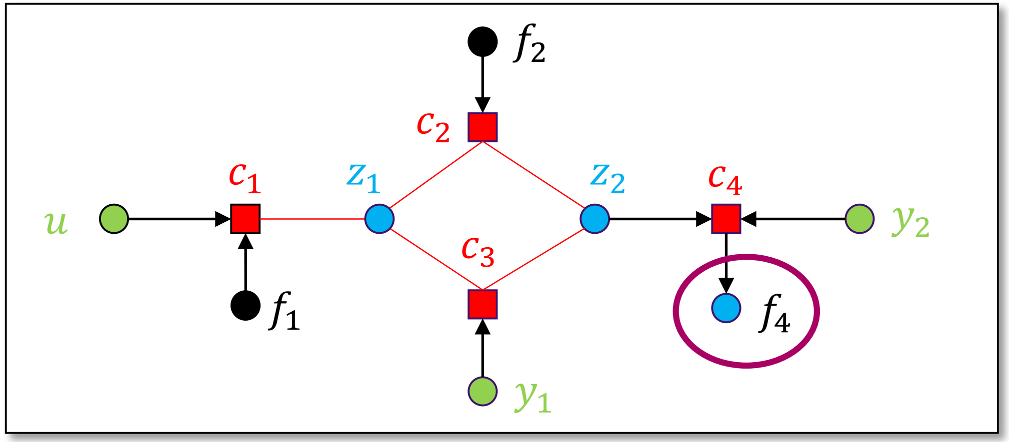
From Physical Models to Diagnosis Functions
Structural Analysis – Fault Isolation

- Consider next fault as unknown
- Determine PSO
- Mark all faults with impact on PSO in Fault Signature Matrix as one

	f_1	f_2	f_4
$PSO_0\{c_1, c_2, c_3, c_4\}$	1	1	1
$PSO_1\{c_2, c_3, c_4\}$	0	1	1
$PSO_2\{c_1, c_3, c_4\}$	1	0	1
$PSO_4\{c_1, c_2, c_3\}$	1	1	0



Different faults are isolable if columns in signature matrix are mutually distinguishable*.

*under single fault assumption

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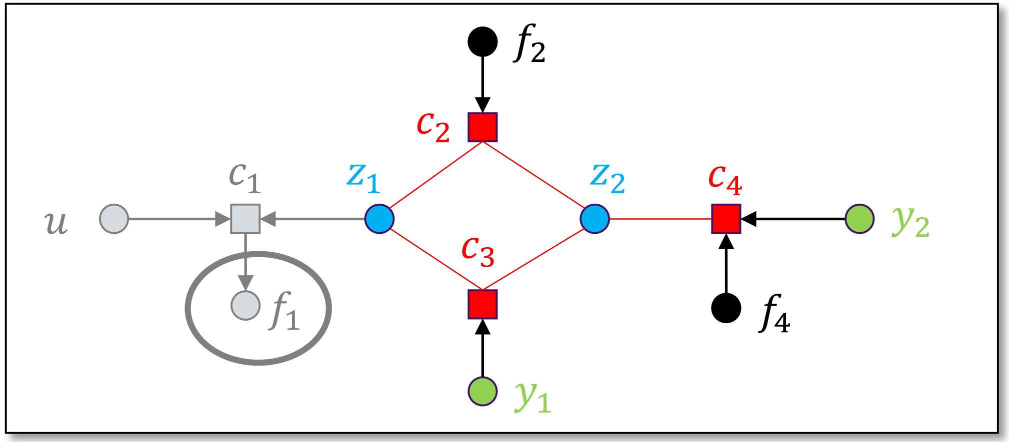
From Physical Models to Diagnosis Functions

Structural Analysis – Residual Generation

- Focus on one PSO subset



	f_1	f_2	f_4
$PSO_0\{c_1, c_2, c_3, c_4\}$	1	1	1
$\boldsymbol{PSO_1\{c_2, c_3, c_4\}}$	0	1	1
$PSO_2\{c_1, c_3, c_4\}$	1	0	1
$PSO_4\{c_1, c_2, c_3\}$	1	1	0

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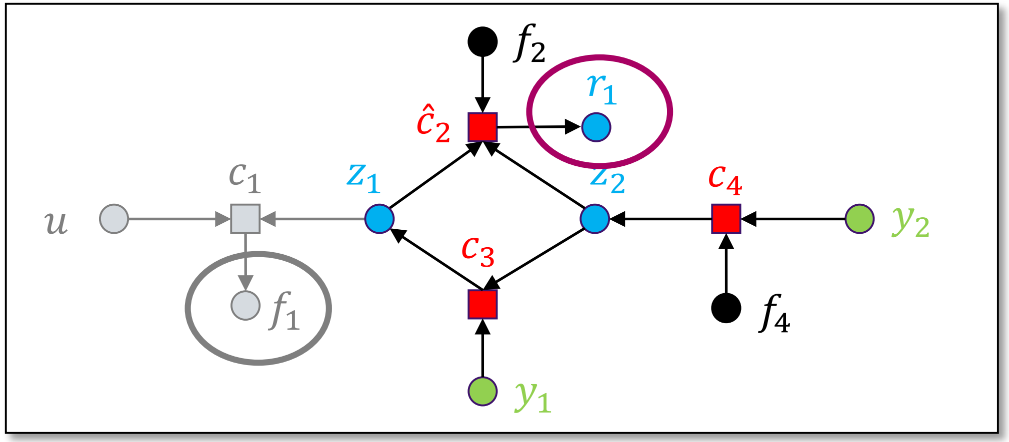
From Physical Models to Diagnosis Functions
Structural Analysis – Residual Generation

- Focus on one PSO subset
- Balance the PSO by additional residual(s)
- Solve the PSO for the residual(s)
  ($r_1 = f_2 - f_{PSO(y_1,y_2)}$)



	f_1	f_2	f_4
$PSO_0\{c_1, c_2, c_3, c_4\}$	1	1	1
$\boldsymbol{PSO_1\{c_2, c_3, c_4\}}$	0	1	1
$PSO_2\{c_1, c_3, c_4\}$	1	0	1
$PSO_4\{c_1, c_2, c_3\}$	1	1	0

Selection of the Residual depends on quantitative properties such as fault to noise ratio.

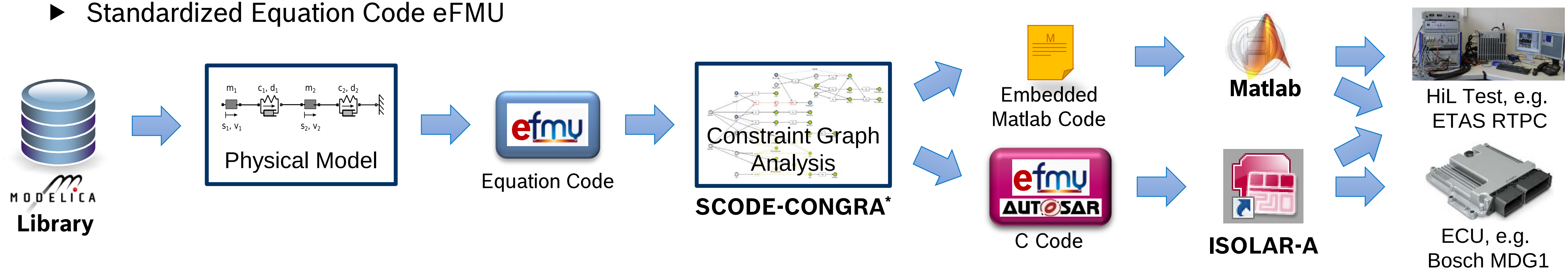
Tool Chain for Model-based Diagnosis

From Physical Models to Diagnosis Functions
Tool Chain – Requirements

- Physical Modeling
  - The physical system model must reflect all physical couplings and functional dependencies including environment, controls and faults.
  - Physical System Model must be validated against real system behavior.
  - The physical system model must be in a component-oriented structure for readability and maintainability.
- Structural Analysis:
  - Over-determined subsets of the DAE (PSO) have to be determined and visualized.
- Residual Generation
  - Numerically stable and fault sensitive residuals have to be derived from the PSOs.
- Target Code Generation
  - The functions generated from the selected residuals must satisfy real time requirements.

From Physical Models to Diagnosis Functions
Tool Chain – Solution Approach

- Reuse of physical component models
  - Object-oriented physical model library with models of multiple levels of detail derived from common interface
- Model the Physical System
  - Physical modeling tool to build system model from component models derived from system topology
  - Strong simulation capabilities to validate dynamic system behavior
- Exchange the equation-based models
  - Standardized Equation Code eFMU
- Select the Residuals
  - Structural and quantitative analysis on signal level
- Generate ECU compliant Code
  - Generate C Code eFMU wrapped into AUTOSAR Software Component
    Or generate embedded Matlab code
- Integrate in ECU software architecture
  - AUTOSAR or Matlab integration with other ECU software



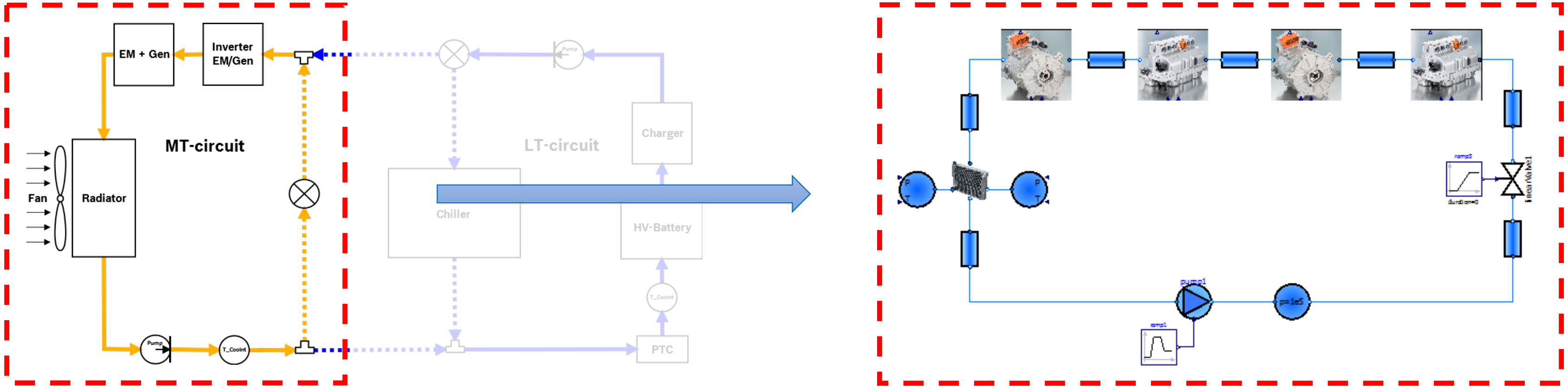
*www.etas.com/congra

Model-based Diagnosis at Bosch

From Physical Models to Diagnosis Functions
Model-based Diagnosis of Thermal System – Physical Modeling

- Physical component models are specified (heat sources, sinks, actuators).
- Standardized model interface definitions based on an object-oriented language enable fast assembly and modification of system simulations derived from system topology specifications.

  ➔ Handling of variability is expected to be simplified*.
- Component models are extended with error terms to include failure modes in the system simulation.

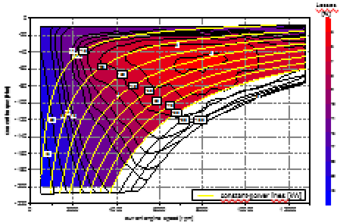


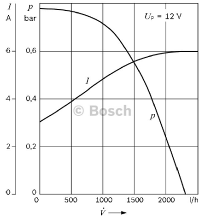
*Only one operation mode of a comparatively simple coolant circuit is considered in this example.
Benefits are expected to grow with increasing complexity i.e. of HEV topologies.

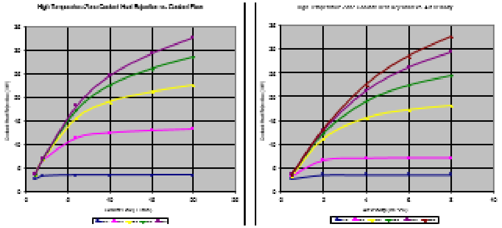
From Physical Models to Diagnosis Functions

Model-based Diagnosis of Thermal System – Physical Modeling

- **Component models** are based on physical first principles (i.e. thermodynamics, hydraulics).
- Allows to use component specifications and standard measurements for calibration, e.g.:
  - ➔ Flow characteristics for pumps, fans, radiator, cooling channels (EM, inverter, Battery)
  - ➔ Heat rejections for radiator
  - ➔ Power loss measurements (EM, inverter, battery)
- Complexity is shifted to its origin:
  - ➔ Reduction of heuristic calibration maps and enable/reset conditions.

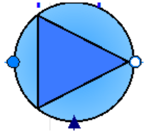






length, diameter
(laminar flow)

EM, Inverter



Pump, Fan

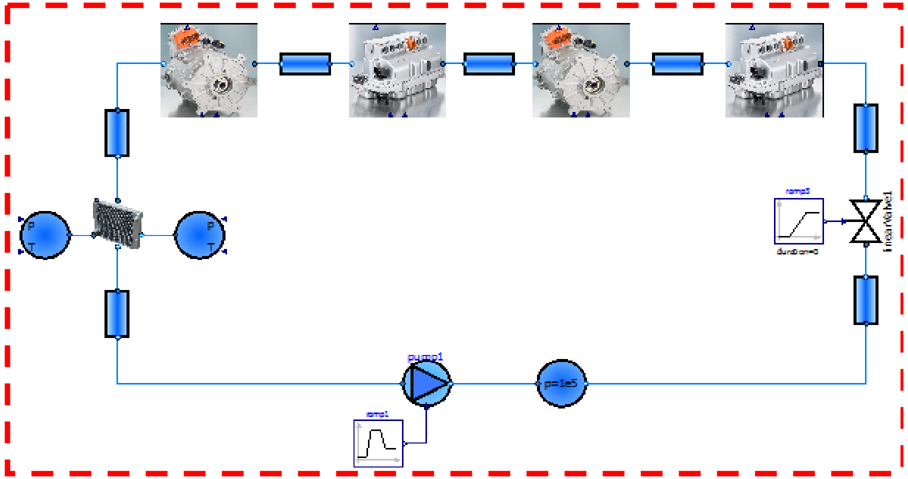
Radiator

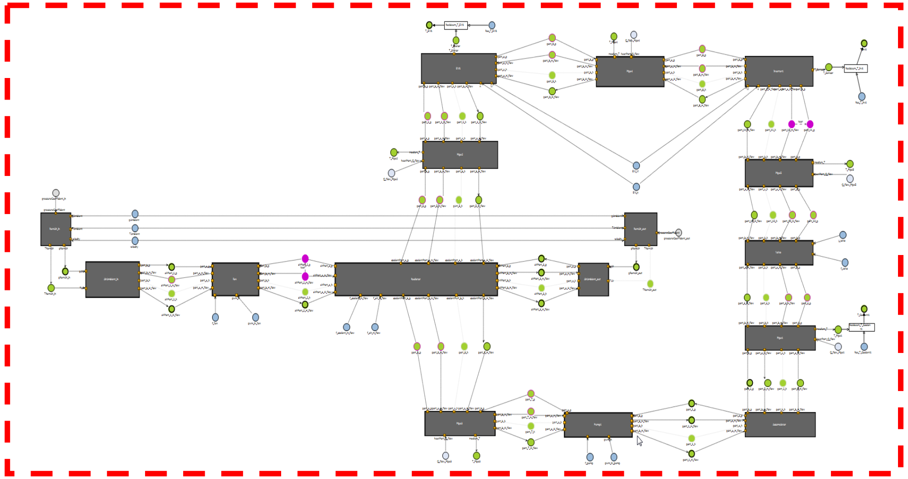
Pipe

From Physical Models to Diagnosis Functions

Model-based Diagnosis of Thermal System – Physical Modeling

- Component models are combined to system model.
- System simulations of realistic drive cycles are used for plausibility checks.
- Final set of equations is implemented in SCODE-CONGRA (ETAS).





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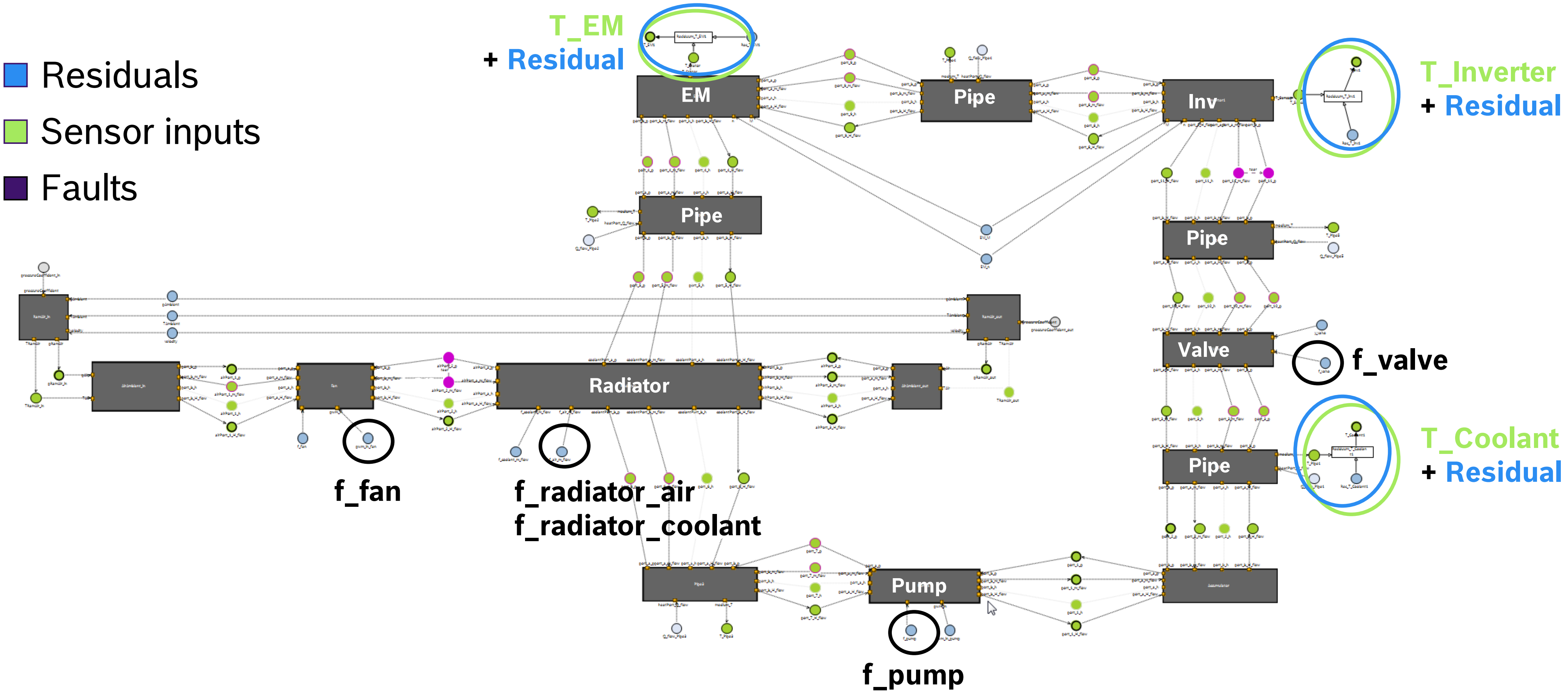
Model-based Diagnosis of Thermal System – Structural Analysis

- Residuals
- Sensor inputs
- Faults



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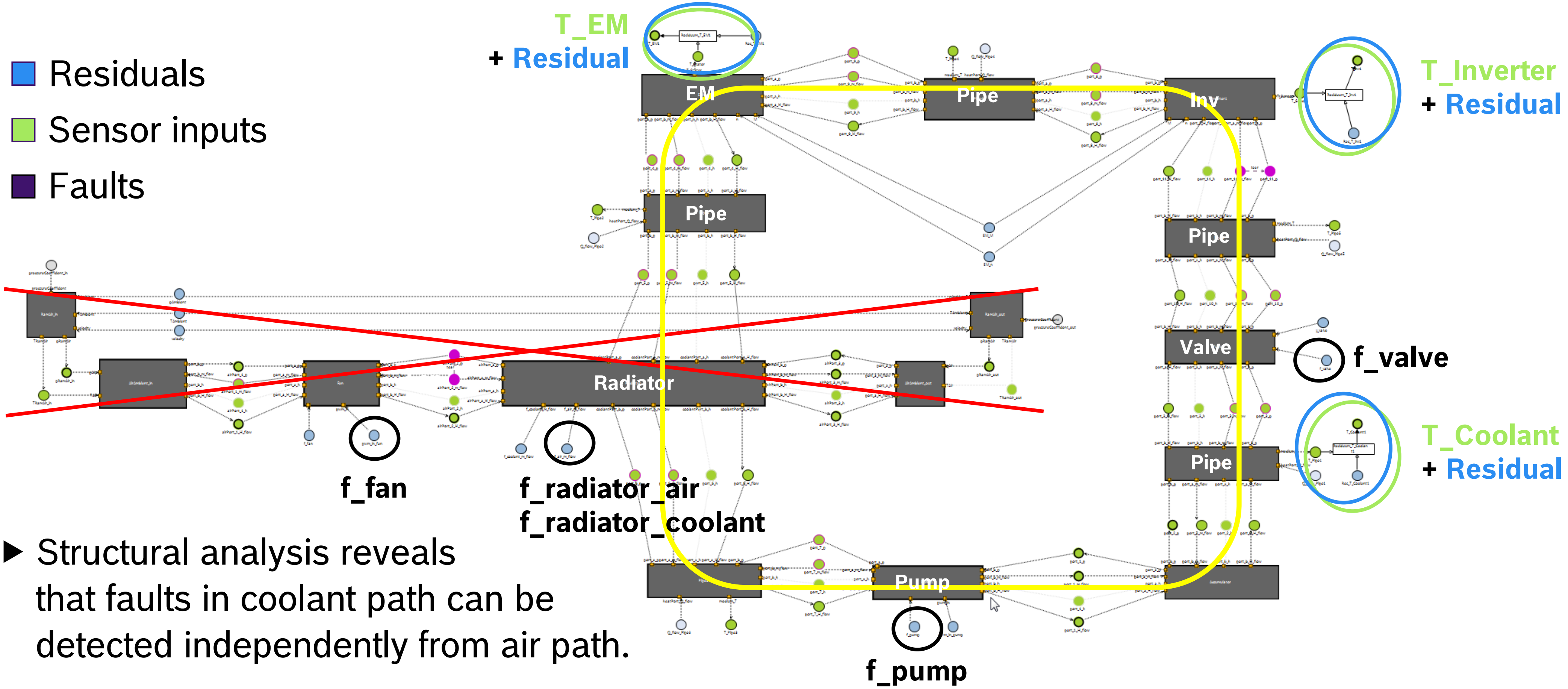
From Physical Models to Diagnosis Functions

Model-based Diagnosis of Thermal System – Structural Analysis

- Residuals
- Sensor inputs
- Faults

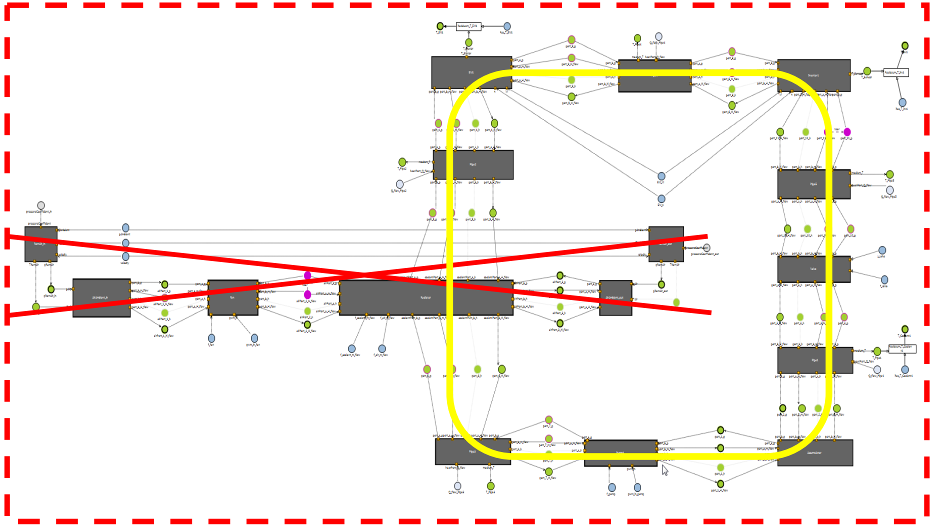


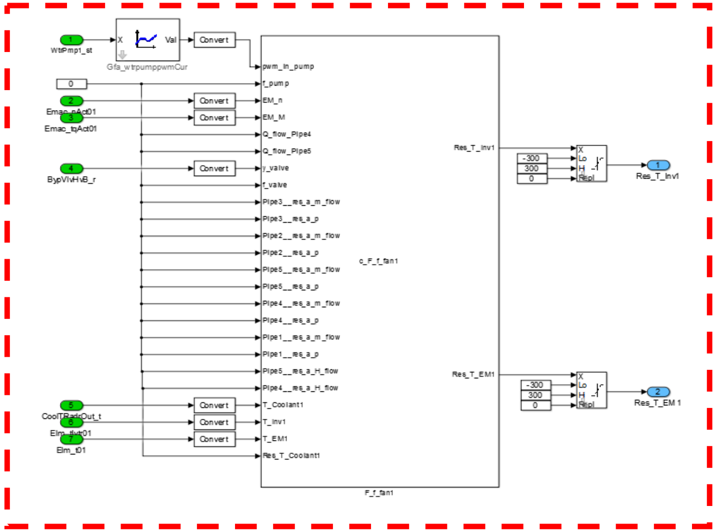
- Structural analysis reveals that faults in coolant path can be detected independently from air path.

From Physical Models to Diagnosis Functions

Model-based Diagnosis of Thermal System – Code Generation

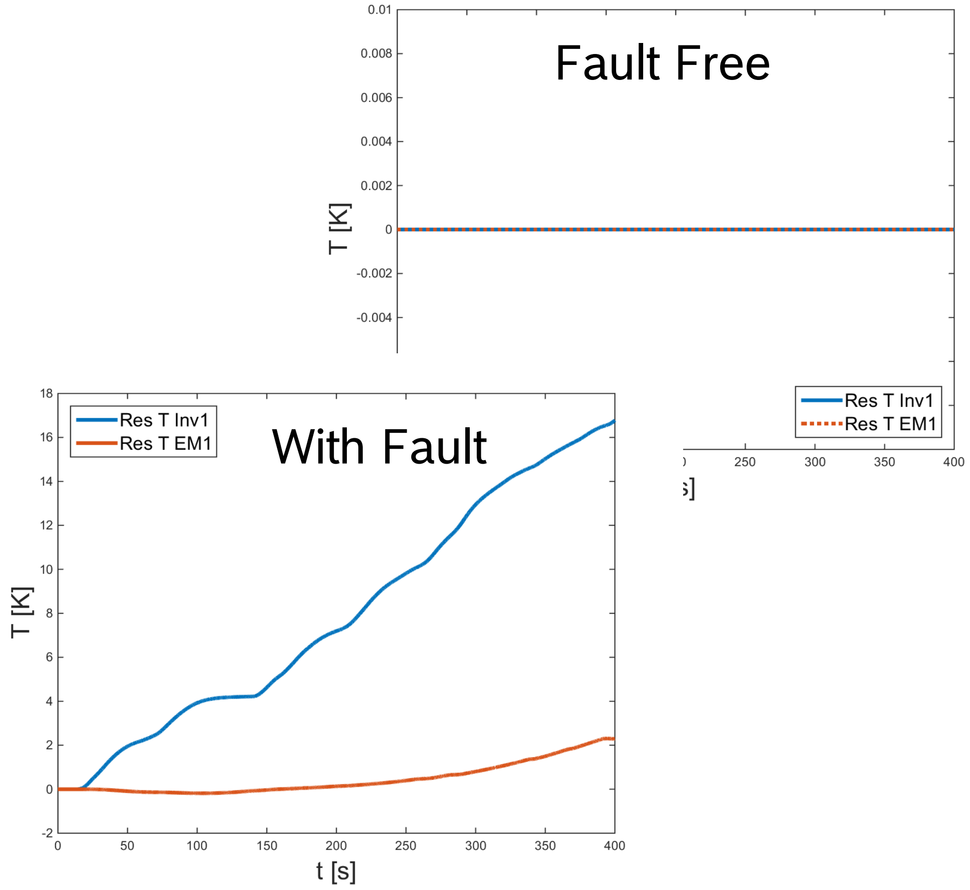
- Simulink blocks for residuals are generated for relevant subsystem (PSO) via SCODE-CONGRA.
- Residual function blocks are directly integrated in Simulink models to generate Bosch compliant target code executable on HiL, ECU and VCU.





From Physical Models to Diagnosis Functions
Model-based Diagnosis of Thermal System – Residual Evaluation

- Residuals of PSO for pump and valve diagnosis are evaluated.
- Fault free case:
  - Residuals remain zero:
    → No deviation from nominal behavior
    → No fault.
- Fault case:
  - Residuals increase:
    → Deviation from nominal behavior.
    → Fault Detection.
  - Residuals behave differently:
    → Fault Signature Matrix
    → Fault Isolation



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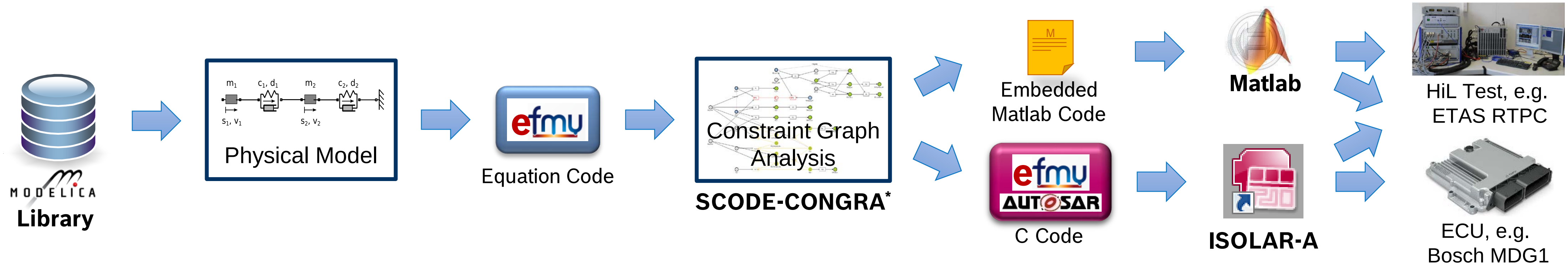
From Physical Models to Diagnosis Functions
Conclusions and Outlook

Conclusions

- Model-based diagnosis approach has been proven to be applicable and beneficial especially for thermal systems.
- Structural analysis with SCODE-CONGRA* is a crucial step in the workflow from physical models to ECU SW.
- Better tool support with standardized interfaces for acausal and causal models is required.

Outlook

- Approach shall be applied to more complex HEV topologies. Benefits are expected to be even more obvious.
- ITEA3 EMPHYSIS project is aiming to standardize the exchange of physical models:
  - Equation Code eFMU: Including equation based description of acausal/causal physical models.
  - C Code eFMU: Including target ready C code with meta information for reproducible target code generation.



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Thank you for your attention.

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