A Foundation for Inconsistency Management in Model-Based Systems Engineering

Istvan David

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PhD Defense – Antwerp, Belgium – July 1, 2019.

Supervisor: Prof. Dr. Hans Vangheluwe

MSDL
Modelling, Simulation and Design Lab

FLANDERS MAKE
MANUFACTURING INNOVATION NETWORK

Ansymo
Antwerp Systems & Software Modelling
University of Antwerp

CORRECTNESS

Correctness: satisfies the required properties.

CORRECTNESS

Correctness: satisfies the required properties.

COMPLEXITY

CORRECTNESS

Correctness: satisfies the required properties.

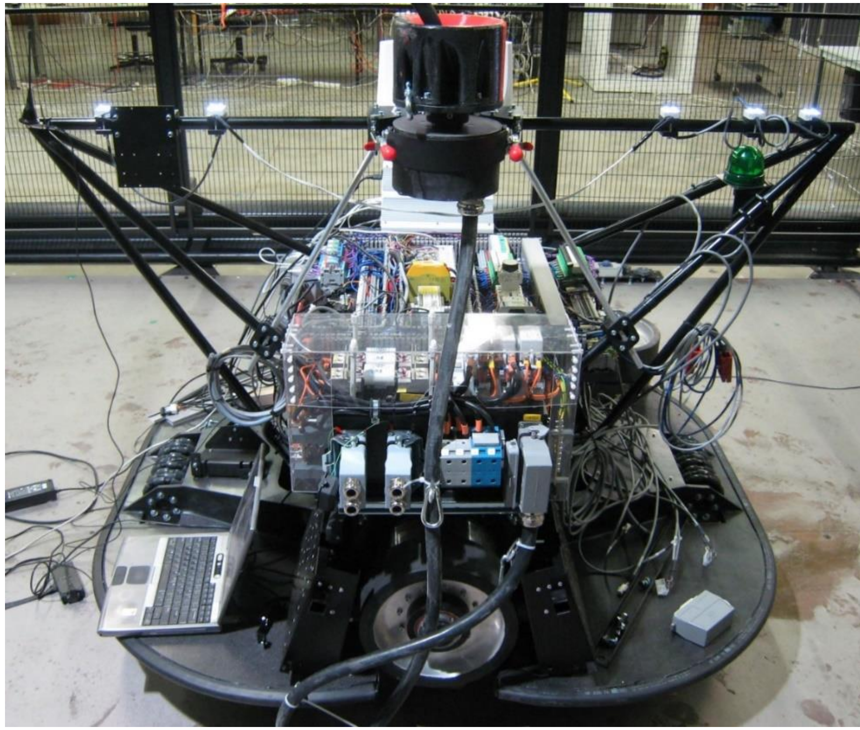
Steam engine

COMPLEXITY

CORRECTNESS

Correctness: satisfies the required properties.

Steam engine



Automated Guided Vehicle (AGV)

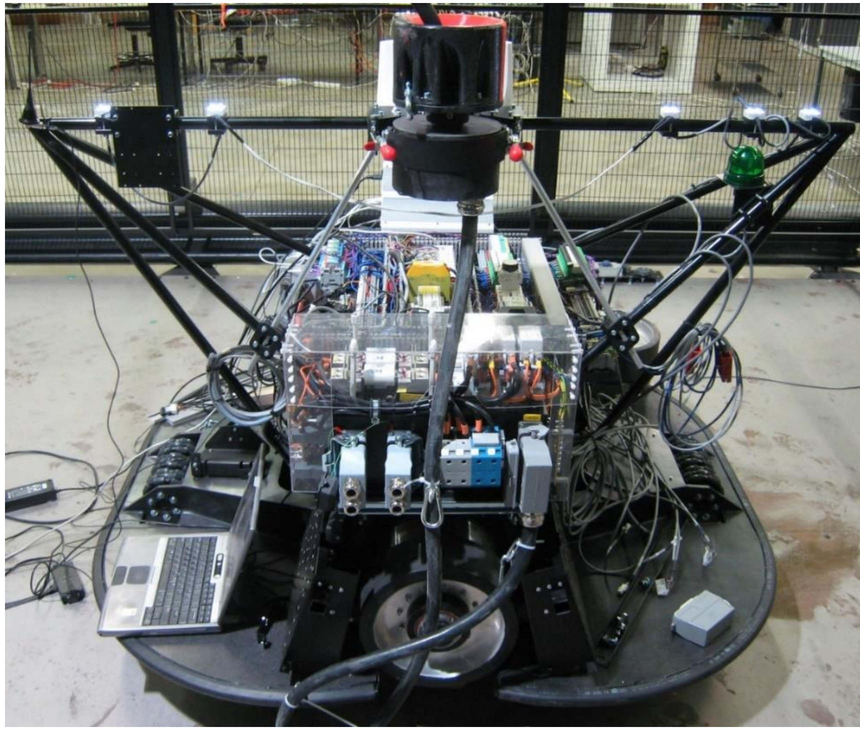
COMPLEXITY

CORRECTNESS

Correctness: satisfies the required properties.

Steam engine

	Number
Components	<
Concerns	<



Automated Guided Vehicle (AGV)

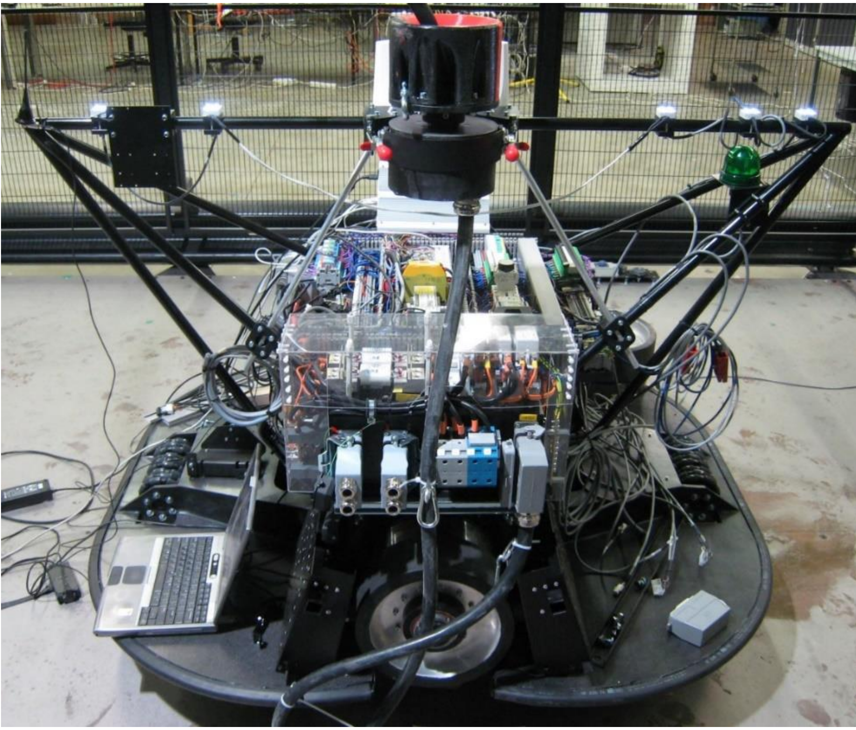
COMPLEXITY

CORRECTNESS

Correctness: satisfies the required properties.

Steam engine

	Number	Heterogeneity
Components	<	≪
Concerns	<	≪



Automated Guided Vehicle (AGV)

COMPLEXITY

Tackling complexity: Multi-paradigm modeling

MODEL
EVERYTHING!

…explicitly
at the most appropriate level(s) of abstraction
using the most appropriate formalism(s),
with processes modelled explicitly.

Tackling complexity: Multi-paradigm modeling

MODEL EVERYTHING!

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at the most appropriate level(s) of abstraction
using the most appropriate formalism(s),
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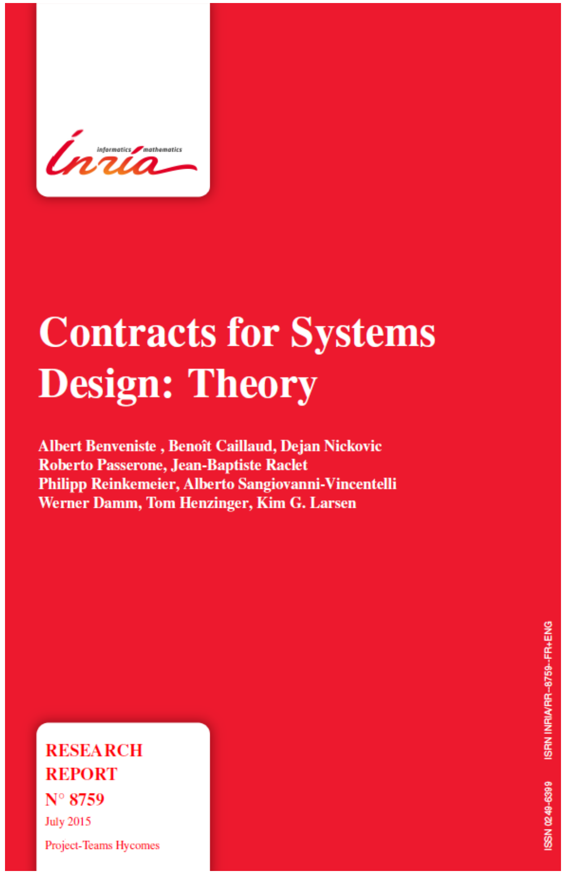
Tackle complexity by

- architectural decomposition
  - ...and designing individual components
- view decomposition
  - ...and work in individual views
- abstraction/refinement



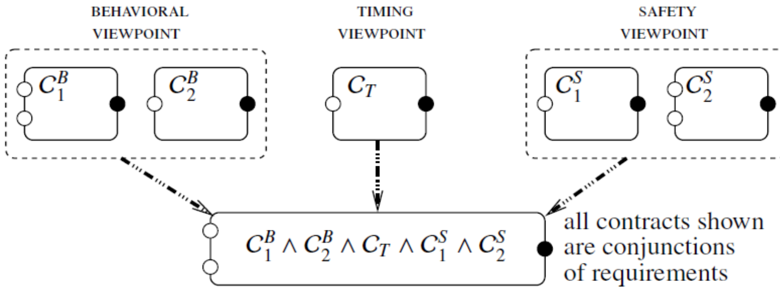
Inria informatics mathematics

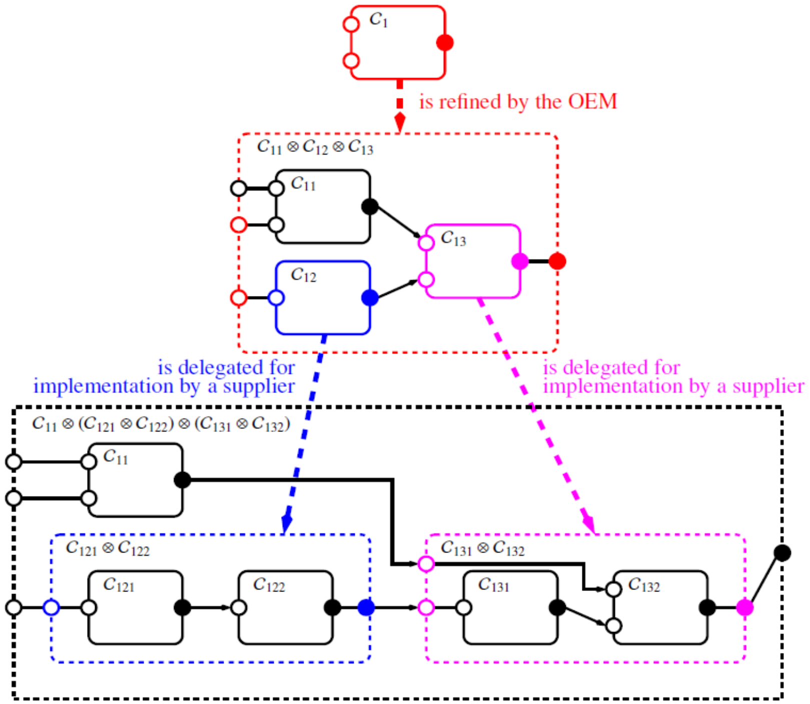
Contracts for Systems Design: Theory

Albert Benveniste , Benoît Caillaud, Dejan Nickovic
Roberto Passerone, Jean-Baptiste Raclet
Philipp Reinkemeier, Alberto Sangiovanni-Vincentelli
Werner Damm, Tom Henzinger, Kim G. Larsen

RESEARCH REPORT
N° 8759
July 2015
Project-Teams Hycomes

ISSN 0249-6399 ISRN INRIA/RR--8759--FR+ENG


BEHAVIORAL VIEWPOINT
TIMING VIEWPOINT
SAFETY VIEWPOINT
C_1^B
C_2^B
C_T
C_1^S
C_2^S
$C_1^B \wedge C_2^B \wedge C_T \wedge C_1^S \wedge C_2^S$
all contracts shown are conjunctions of requirements


C_1
is refined by the OEM
$C_{11} \otimes C_{12} \otimes C_{13}$
C_{11}
C_{13}
C_{12}
is delegated for implementation by a supplier
is delegated for implementation by a supplier
$C_{11} \otimes (C_{121} \otimes C_{122}) \otimes (C_{131} \otimes C_{132})$
C_{11}
$C_{121} \otimes C_{122}$
C_{121}
C_{122}
$C_{131} \otimes C_{132}$
C_{131}
C_{132}

Tackling complexity: Multi-paradigm modeling

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  - ...and designing individual components
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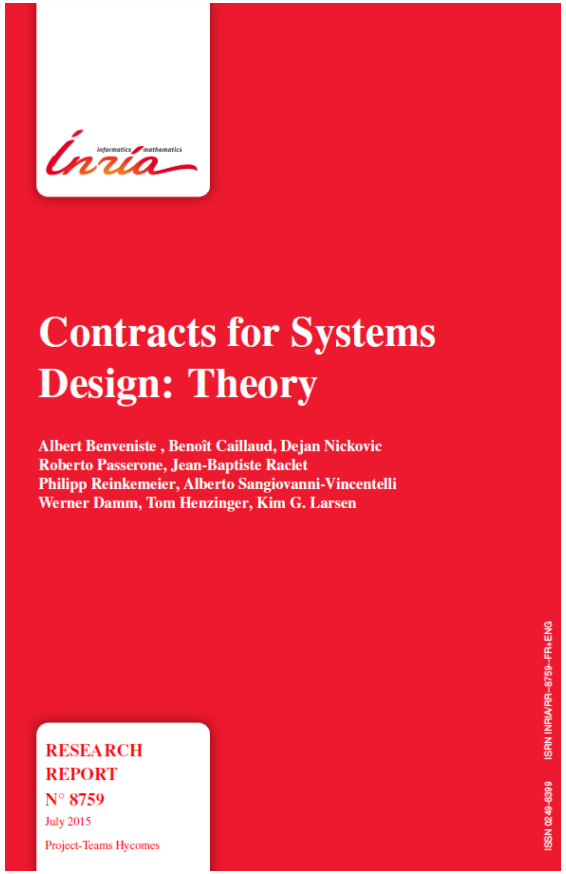

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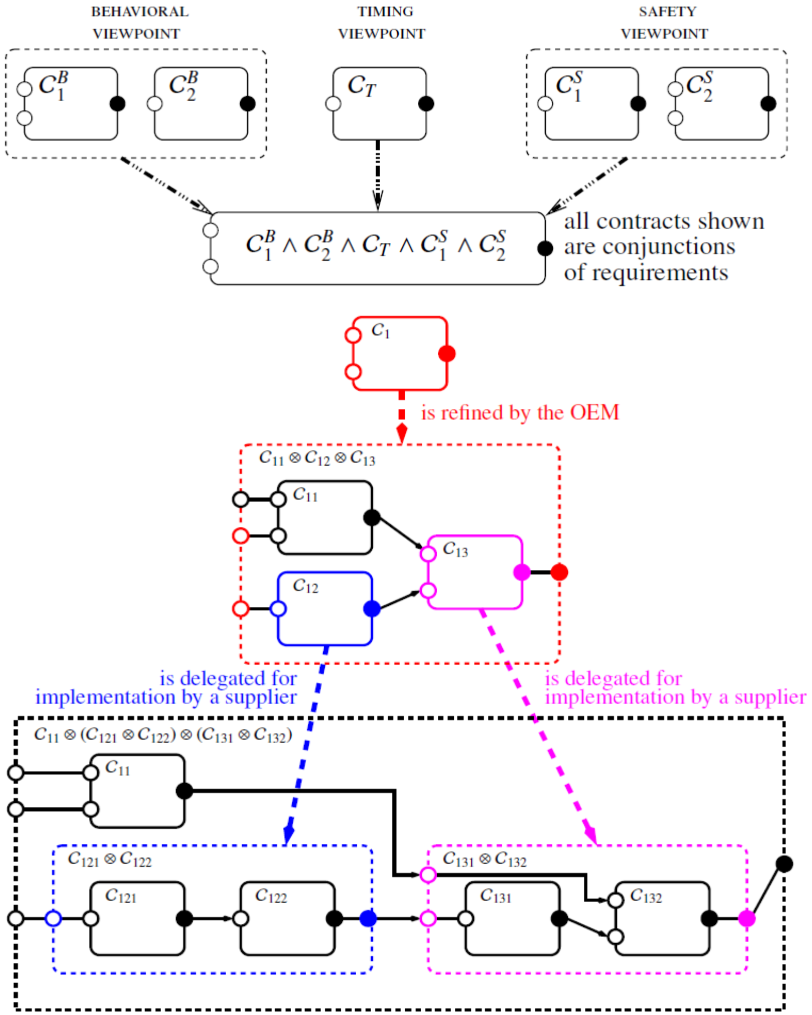
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Parallel branches give rise to inconsistencies!

(In?)consistency

An inconsistency is present if two or more statements are made that are not jointly satisfiable [such as a] *failure of an equivalence test, non-conformance to a standard or constraint and the violation of physical or mathematical principles.*

S. Herzig, C. Paredis: „A conceptual basis for inconsistency management in model-based systems engineering.” *Procedia CIRP* 21 (2014): 52-57.

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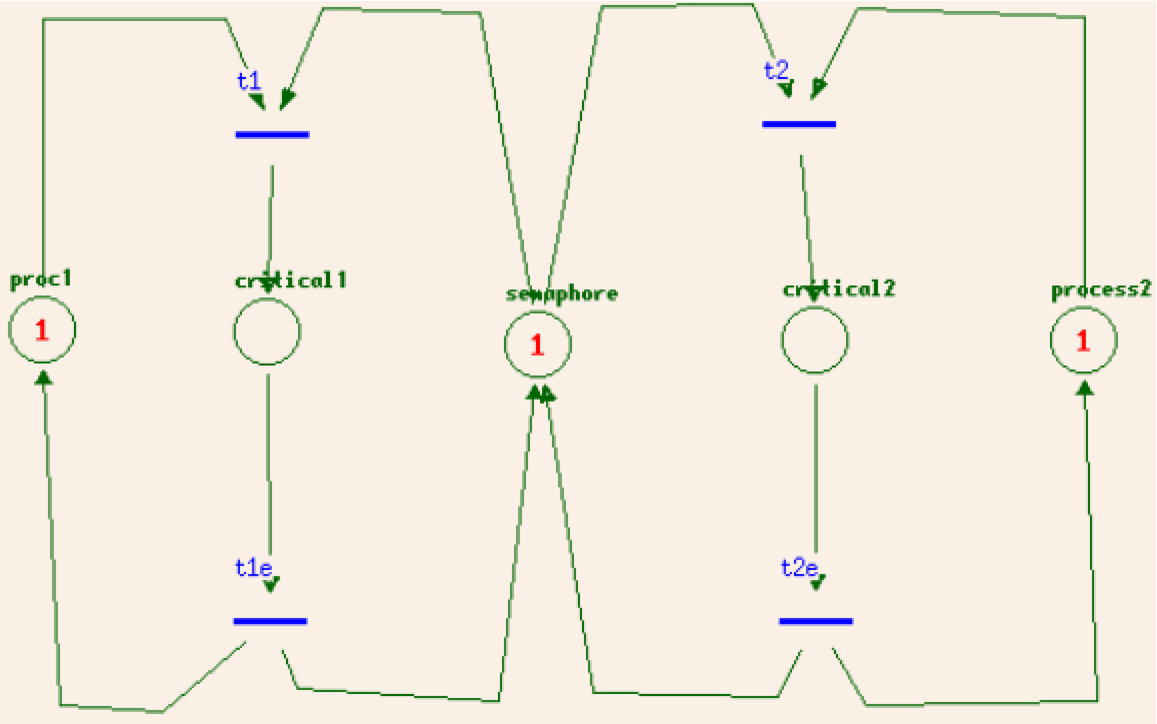
Problem: (un)satisfiability often remains hidden in the semantic domain.

Properties in the semantic domain

Property: ***„The system is safe”.***

Petri net

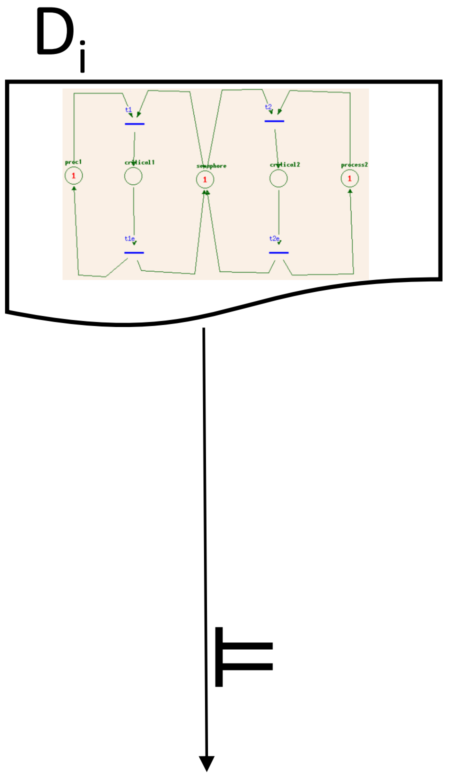


The two processes are never simultaneously situated in their respective critical sections.

Properties in the semantic domain

Property: ***„The system is safe”***.

Petri net



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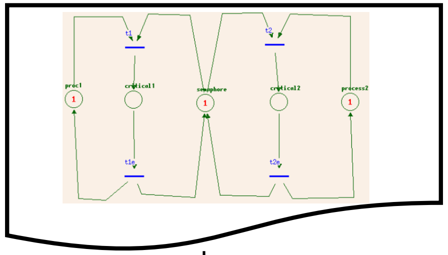
Properties in the semantic domain

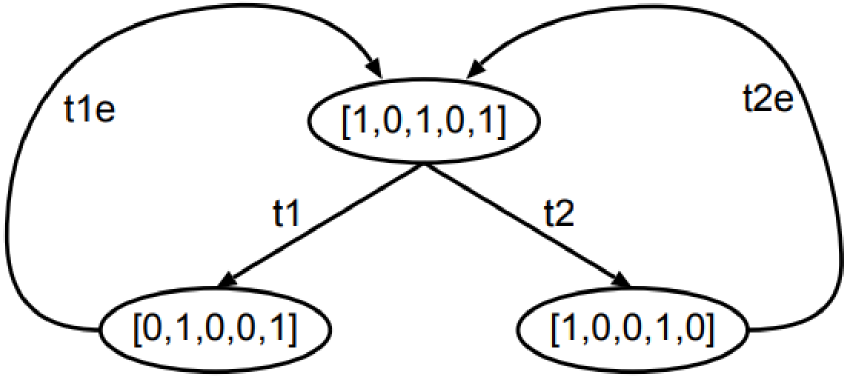
Property: ***„The system is safe”.***

D_i



[[.]]

Semantic domain



True/False

$\models$

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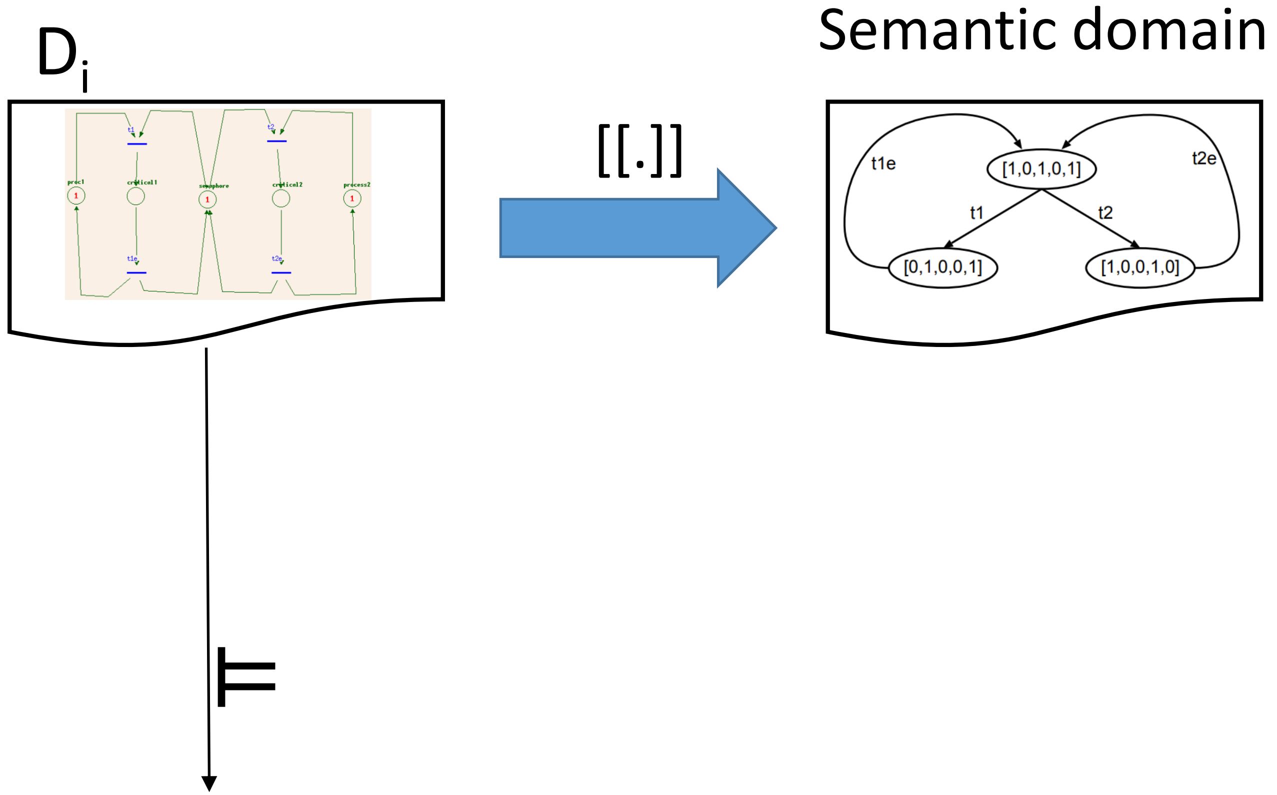
Properties in the semantic domain

Property: ***„The system is safe”***.



D_i

Semantic domain

[[.]]

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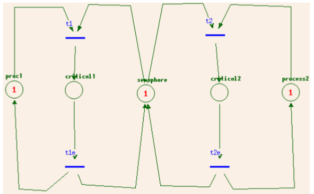
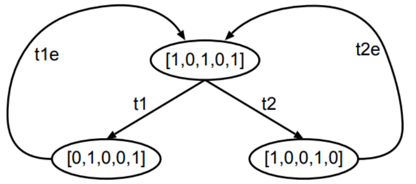


[[.]]

Semantic domain



$\models$

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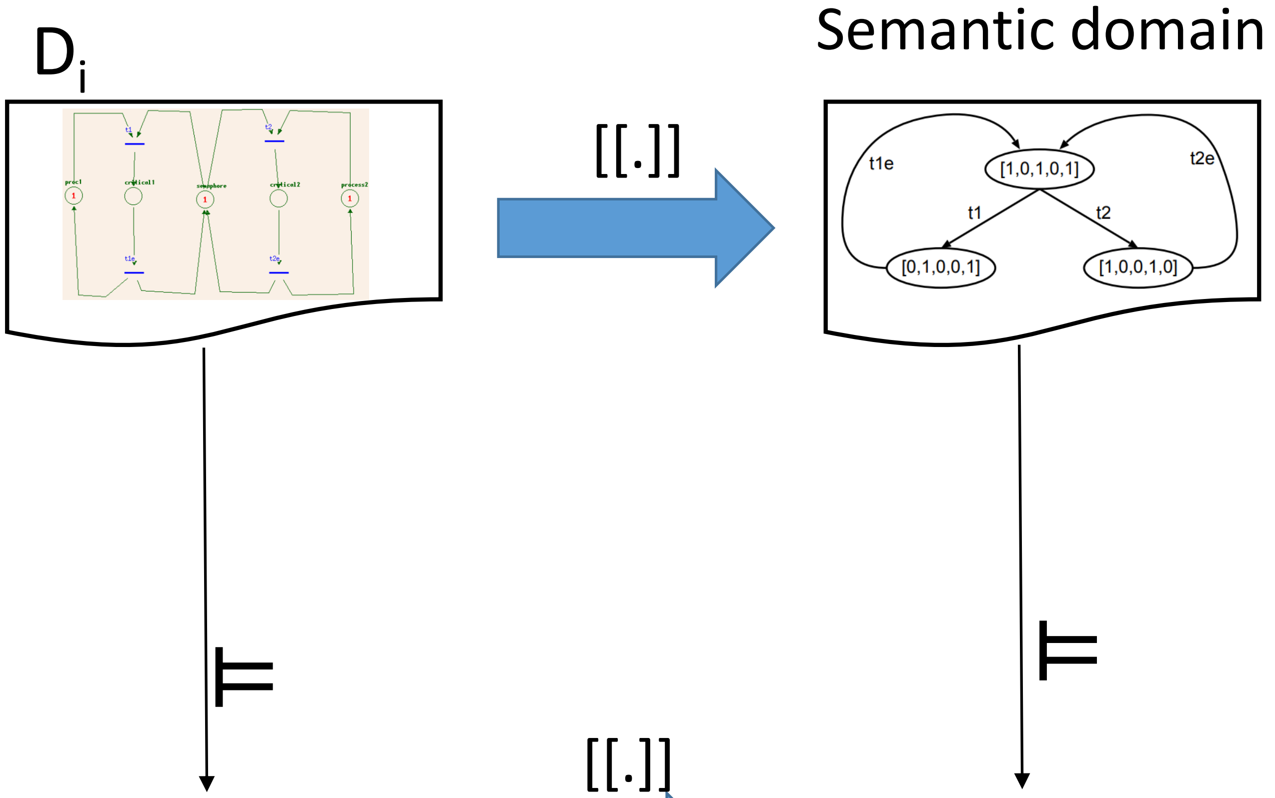
[[.]]

∄[_, 1, _, 1, _]

Properties in the semantic domain

Property: ***„The system is safe”***.



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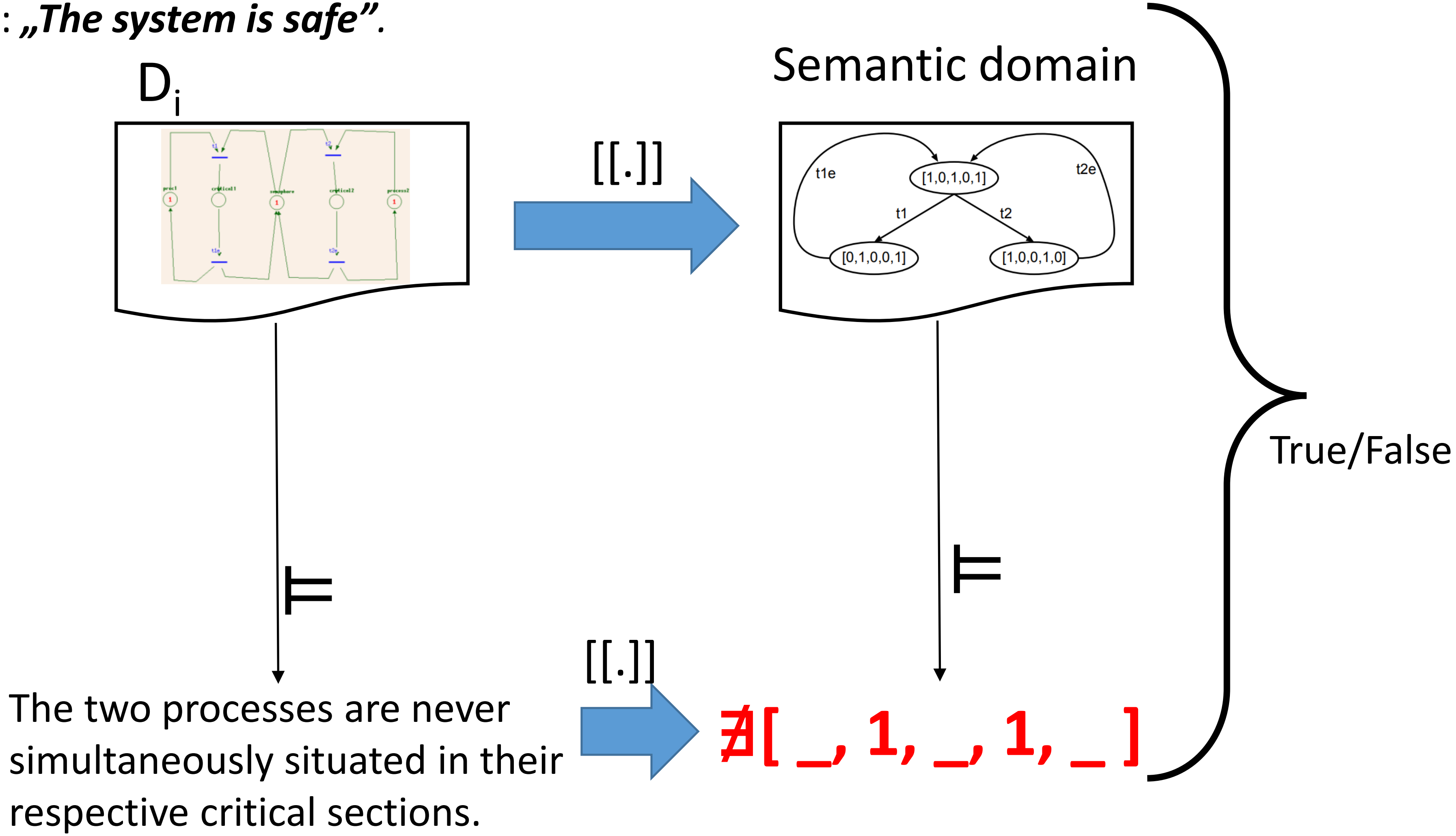
[[.]]

$\nexists [\ \_, 1, \_, 1, \_\ ]$

Properties in the semantic domain

Property: ***„The system is safe”***.



D_i

Semantic domain

[[.]]

⊨

⊨

True/False

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Properties in the semantic domain

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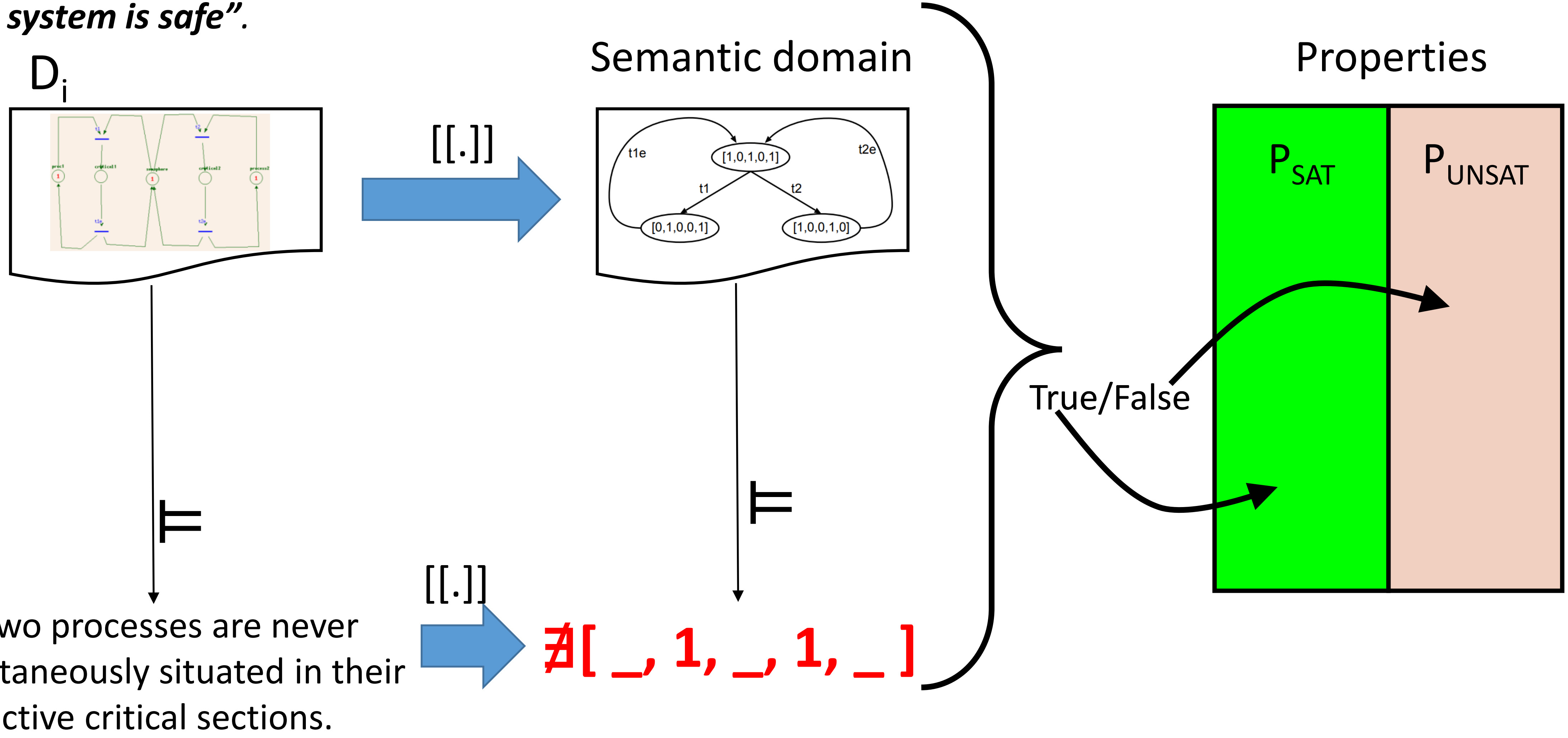
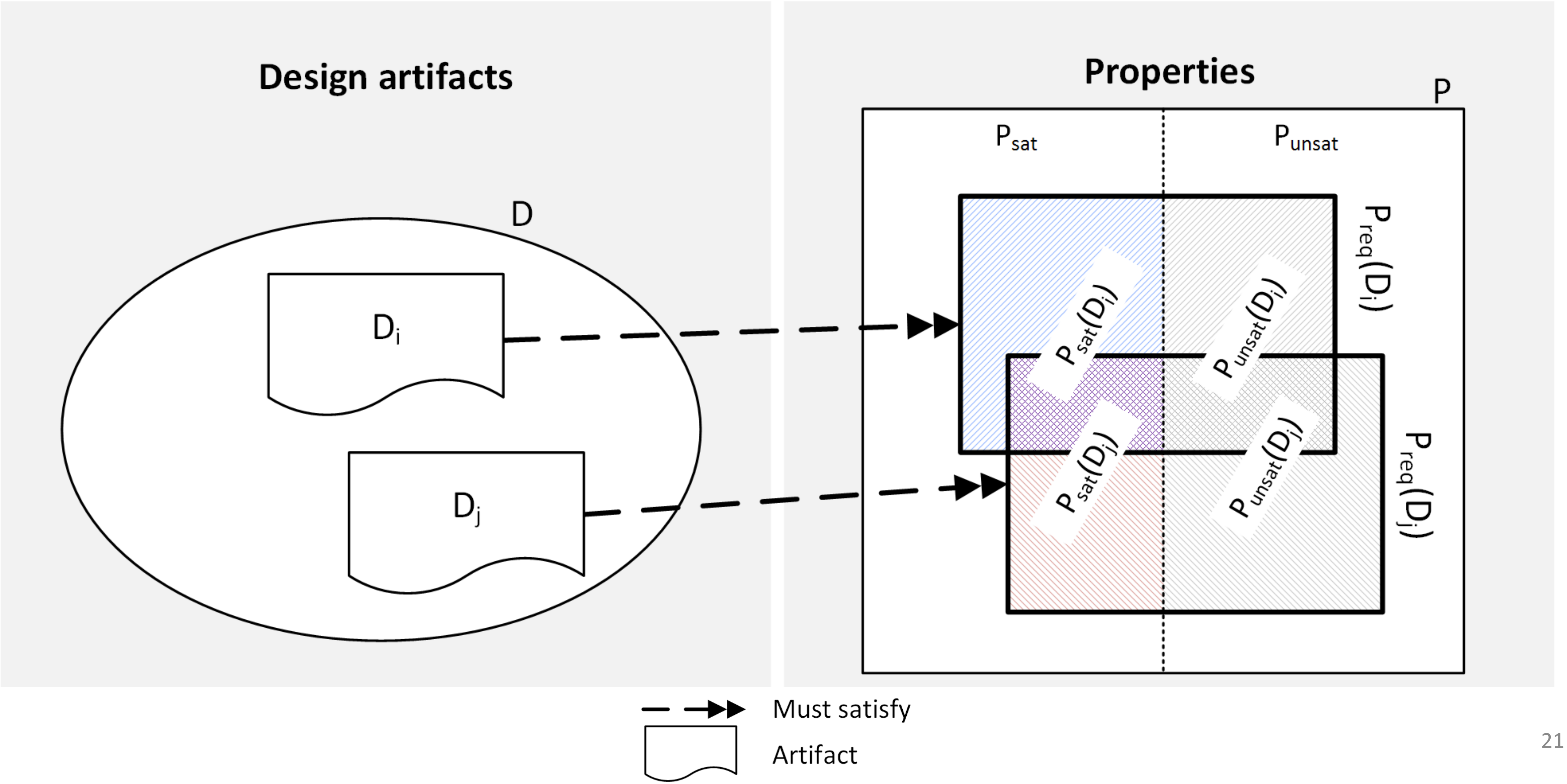


The two processes are never simultaneously situated in their respective critical sections.

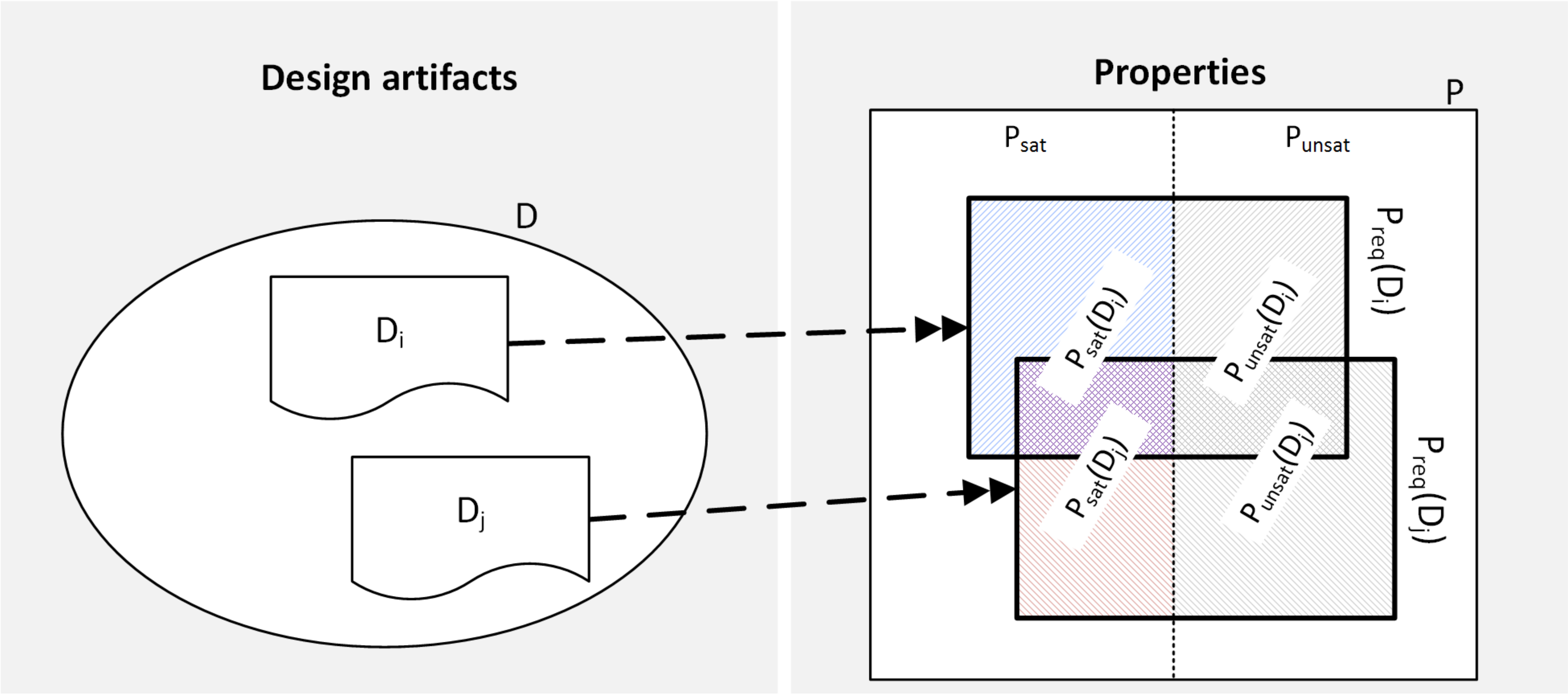
$\nexists$[_, 1, _, 1, _]

Consistency



The design artifacts D_i and D_j are said to be consistent w.r.t. the set of properties $P' \subseteq P \equiv P_{req}(D_i) \bigcap P_{req}(D_j)$ iff $\forall p \in P' : D_i \vDash p \Leftrightarrow D_j \vDash p$.

Consistency



– –▶▶ Must satisfy

Artifact

Consistency

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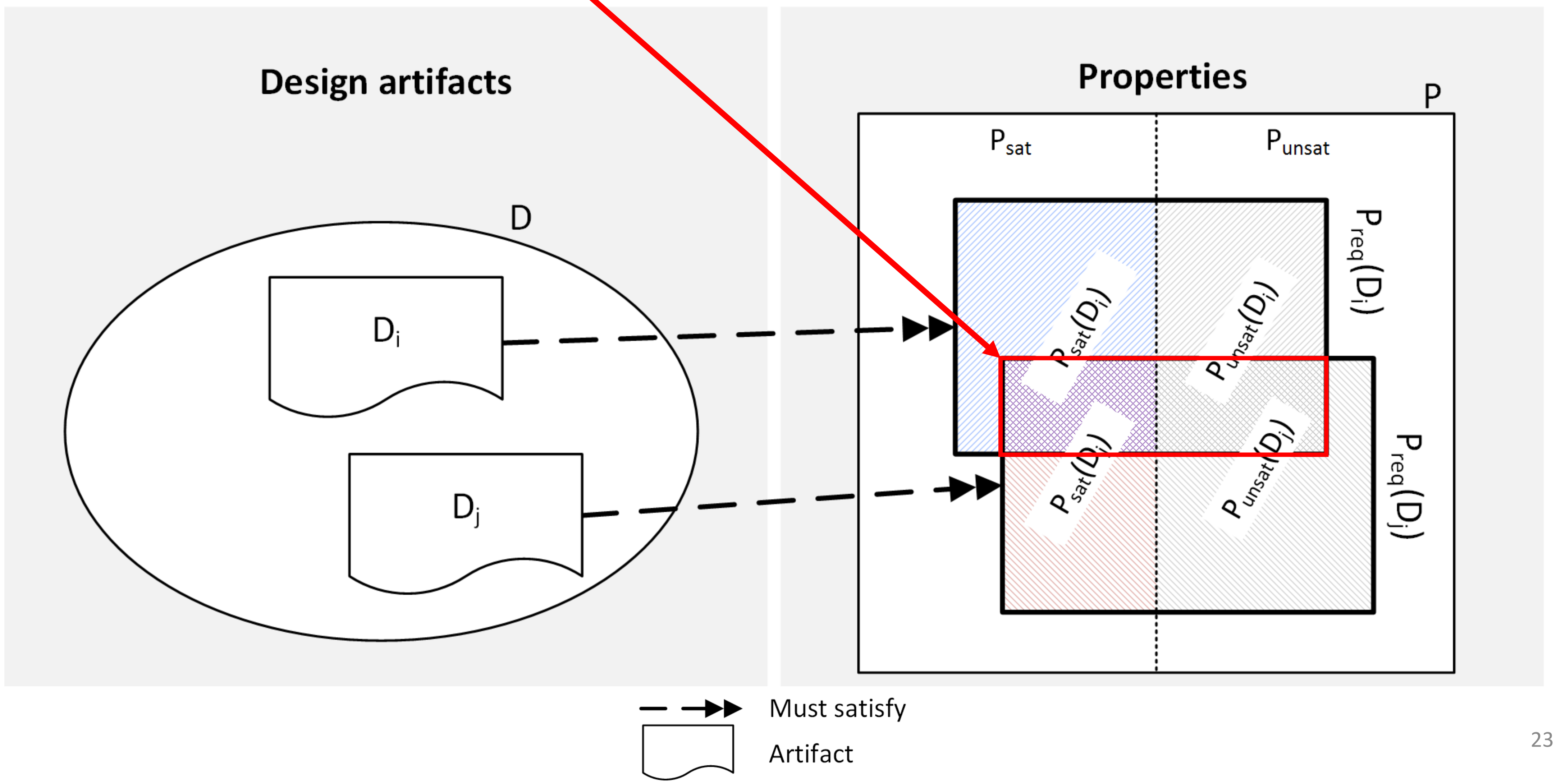
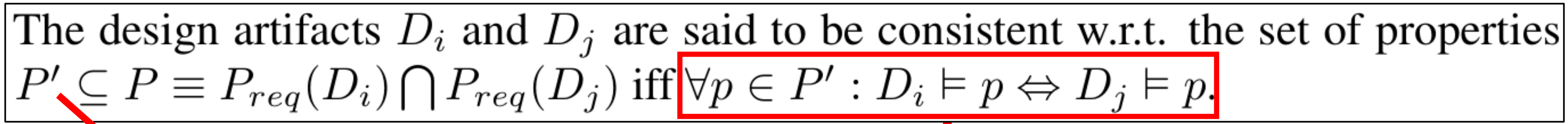


Consistency



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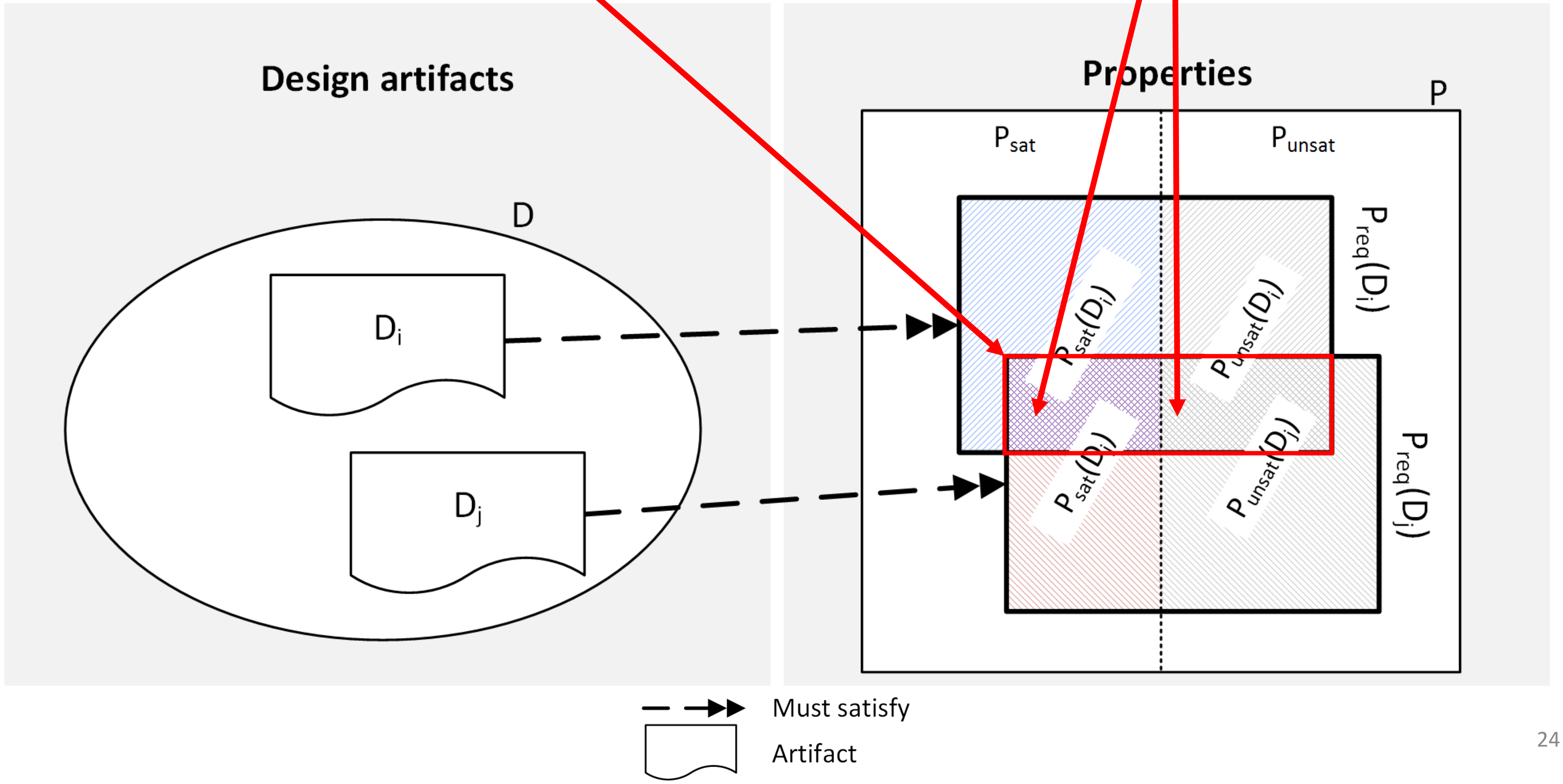
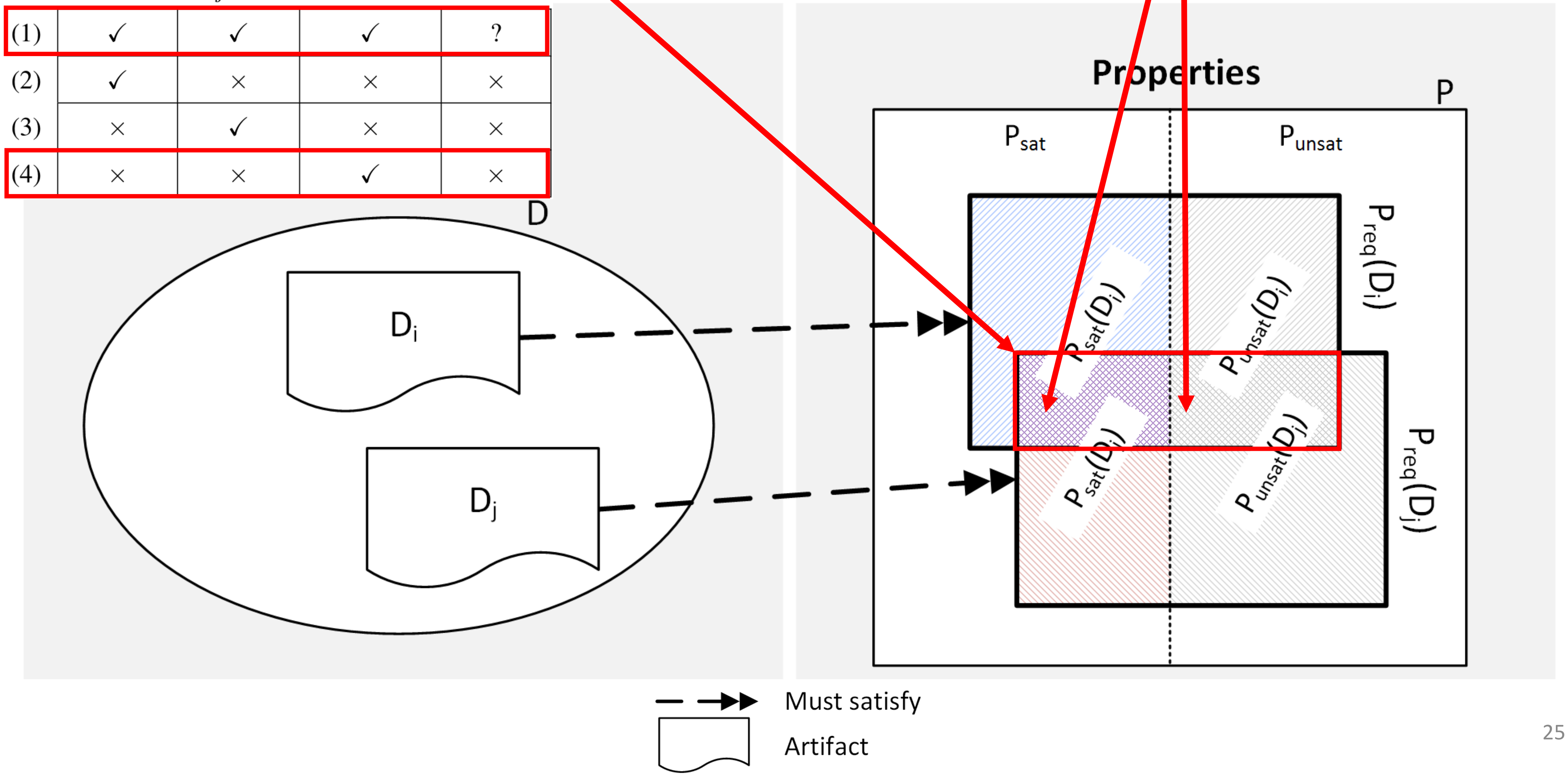


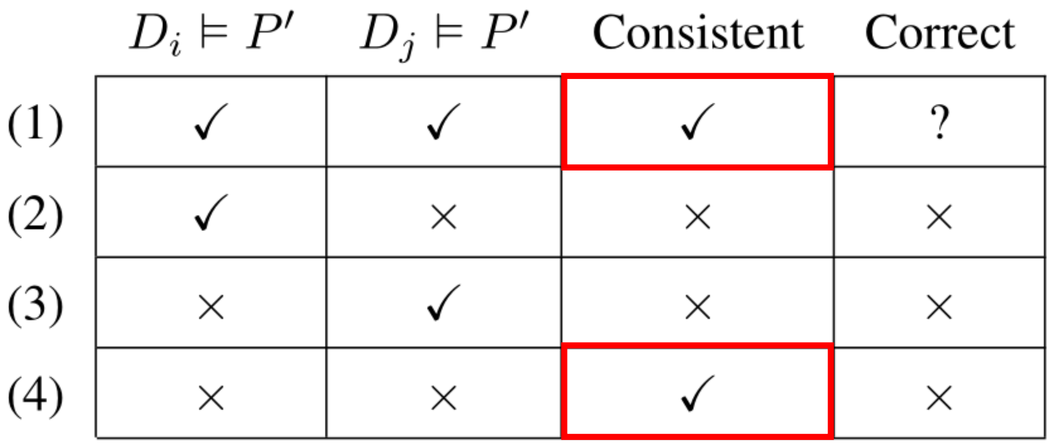
The design artifacts D_i and D_j are said to be consistent w.r.t. the set of properties $P' \subseteq P \equiv P_{req}(D_i) \bigcap P_{req}(D_j)$ iff $\forall p \in P' : D_i \models p \Leftrightarrow D_j \models p$.

Consistency

	$D_i \models P'$	$D_j \models P'$	Consistent	Correct
(1)	✓	✓	✓	?
(2)	✓	×	×	×
(3)	×	✓	×	×
(4)	×	×	✓	×

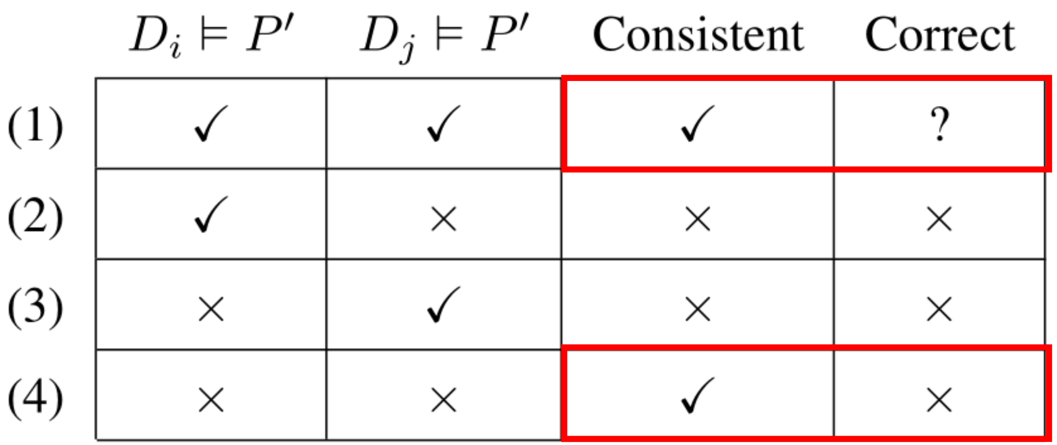


(In)correctness and (in)consistency



	$D_i \vDash P'$	$D_j \vDash P'$	Consistent	Correct
(1)	✓	✓	✓	?
(2)	✓	×	×	×
(3)	×	✓	×	×
(4)	×	×	✓	×

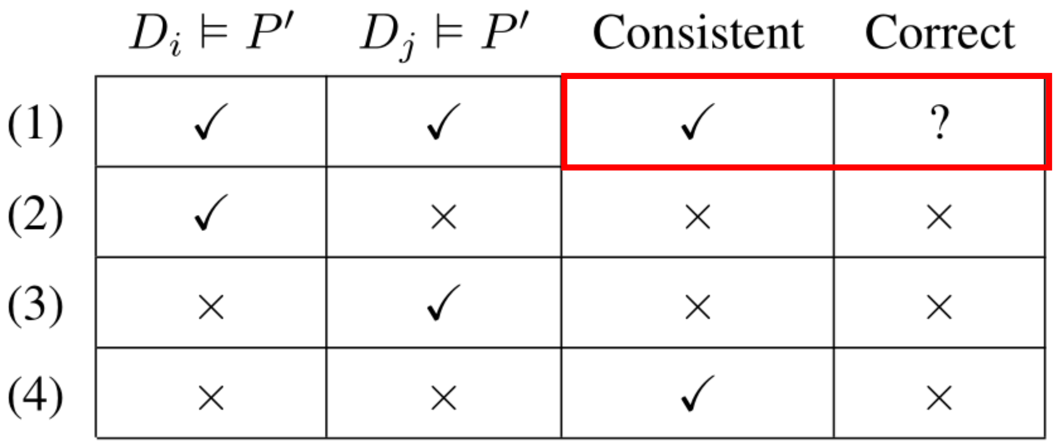
(In)correctness and (in)consistency



	$D_i \models P'$	$D_j \models P'$	Consistent	Correct
(1)	✓	✓	✓	?
(2)	✓	×	×	×
(3)	×	✓	×	×
(4)	×	×	✓	×

$$consistent(D_i, D_j) \not\Rightarrow correct(D)$$

(In)correctness and (in)consistency



	$D_i \vDash P'$	$D_j \vDash P'$	Consistent	Correct
(1)	✓	✓	✓	?
(2)	✓	×	×	×
(3)	×	✓	×	×
(4)	×	×	✓	×

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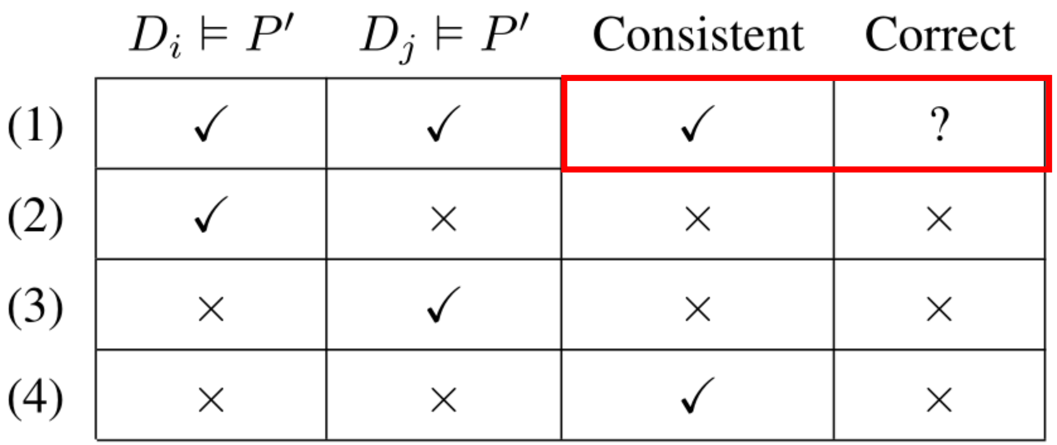
(In)correctness and (in)consistency



	$D_i \models P'$	$D_j \models P'$	Consistent	Correct
(1)	✓	✓	✓	?
(2)	✓	×	×	×
(3)	×	✓	×	×
(4)	×	×	✓	×

$$consistent(D_i, D_j) \nRightarrow correct(D)$$

$$correct(D) \Rightarrow consistent(D_i, D_j)$$

(In)correctness and (in)consistency

	$D_i \models P'$	$D_j \models P'$	Consistent	Correct
(1)	✓	✓	✓	?
(2)	✓	×	×	×
(3)	×	✓	×	×
(4)	×	×	✓	×

$$consistent(D_i, D_j) \nRightarrow correct(D)$$

$$correct(D) \Rightarrow consistent(D_i, D_j)$$

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$$incorrect(D) \nRightarrow inconsistent(D_i, D_j)$$

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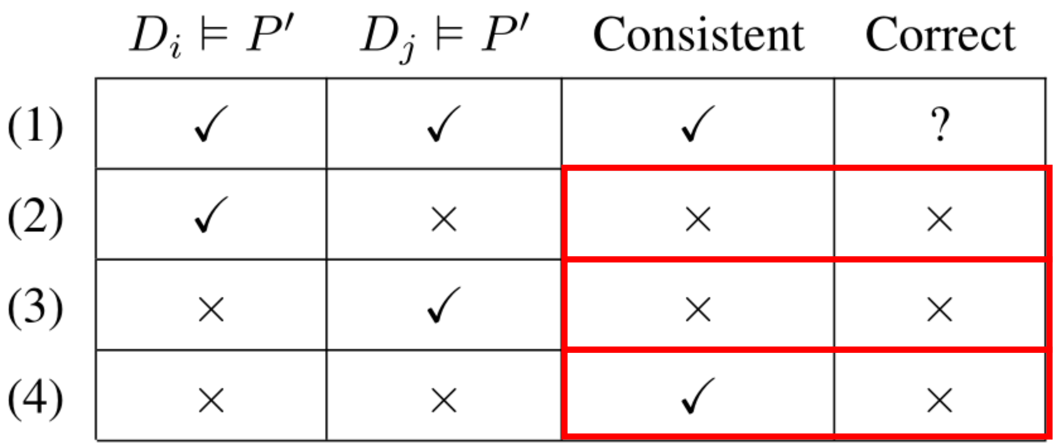

	$D_i \vDash P'$	$D_j \vDash P'$	Consistent	Correct
(1)	✓	✓	✓	?
(2)	✓	×	×	×
(3)	×	✓	×	×
(4)	×	×	✓	×

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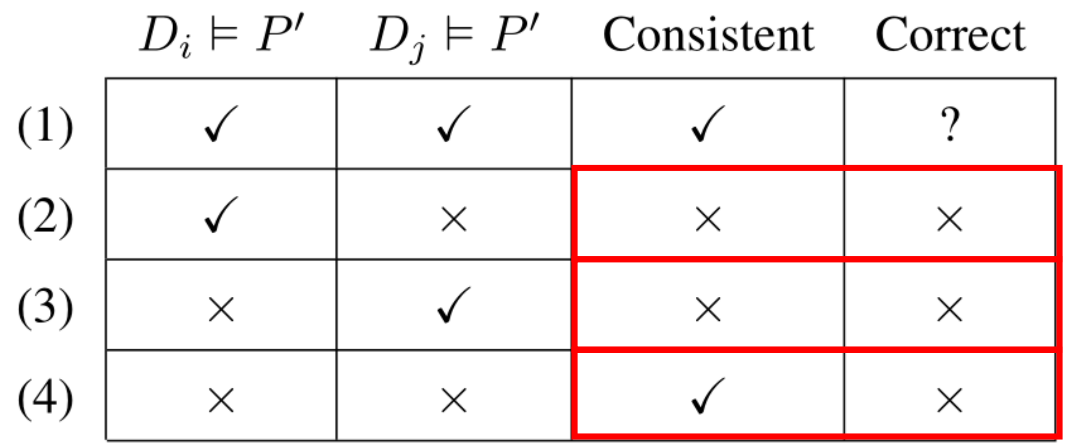

	$D_i \vDash P'$	$D_j \vDash P'$	Consistent	Correct
(1)	✓	✓	✓	?
(2)	✓	×	×	×
(3)	×	✓	×	×
(4)	×	×	✓	×

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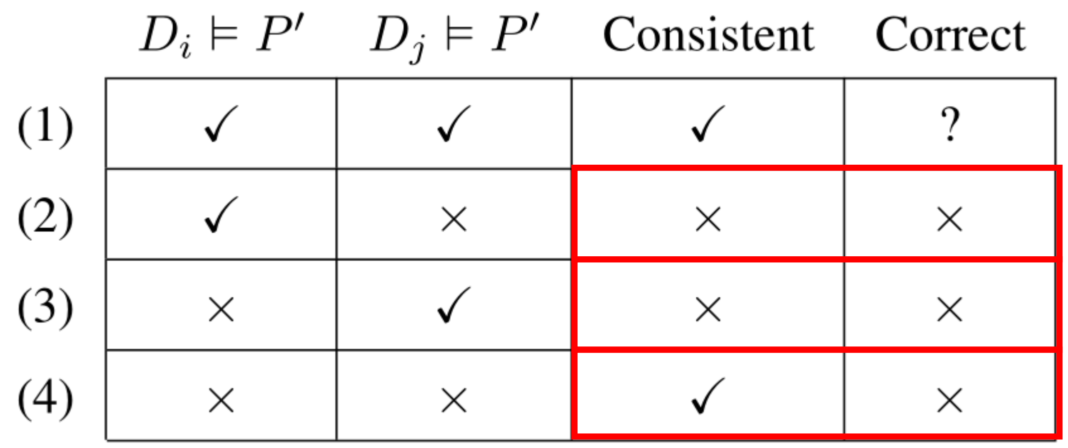

	$D_i \models P'$	$D_j \models P'$	Consistent	Correct
(1)	✓	✓	✓	?
(2)	✓	×	×	×
(3)	×	✓	×	×
(4)	×	×	✓	×

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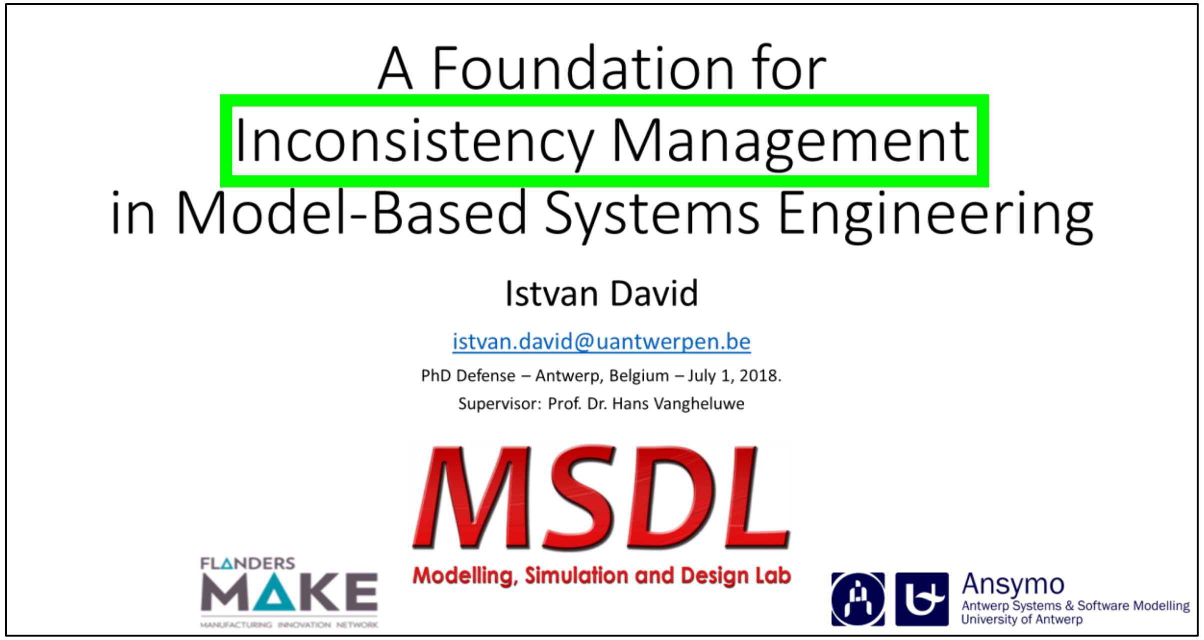

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$$incorrect(D) \not\Rightarrow inconsistent(D_i, D_j)$$

Managing inconsistencies

Rather than thinking about removing inconsistency, we need to think about ***managing consistency****. – Finkelstein, 2000*

$$consistent(D_i, D_j) \nRightarrow correct(D)$$
$$inconsistent(D_i, D_j) \Rightarrow incorrect(D)$$

A. Finkelstein: „*A foolish consistency: Technical challenges in consistency management*“. In *International Conference on Database and Expert Systems Applications*, pp. 1-5. Springer, Berlin, Heidelberg, 2000.

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Rather than thinking about removing inconsistency, we need to think about ***managing*** ~~***consistency**. – Finkelstein, 2000*~~ ***inconsistency**.* (Vangheluwe, Denil, Vanherpen, David, et.al., 2013-2019)

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- K. Vanherpen: „*A contract-based approach for multi-viewpoint consistency in the concurrent design of cyber-physical systems*”, PhD Thesis, 2018.
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A. Finkelstein: „*A foolish consistency: Technical challenges in consistency management*“. In *International Conference on Database and Expert Systems Applications*, pp. 1-5. Springer, Berlin, Heidelberg, 2000.

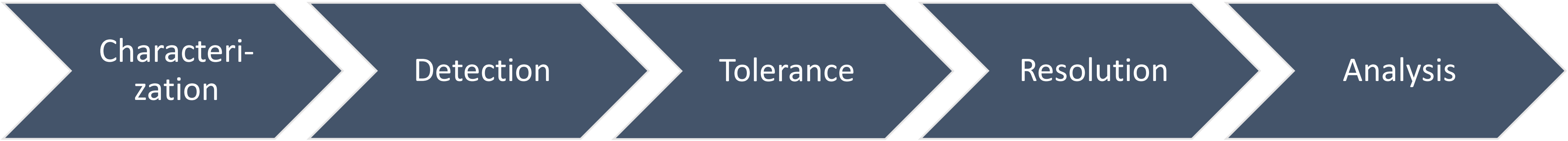
Managing inconsistencies

*Rather than thinking about removing inconsistency, we need to think about **managing** ~~**consistency**. – Finkelstein, 2000~~* ***inconsistency***. (Vangheluwe, Denil, Vanherpen, David, et.al., 2013-2019)

- Prevention (e.g. contract-based design)
- Detect-and-Resolve

VANHERPEN, 2018

DAVID, 2019



K. Vanherpen: „*A contract-based approach for multi-viewpoint consistency in the concurrent design of cyber-physical systems*”. PhD Thesis, 2018.

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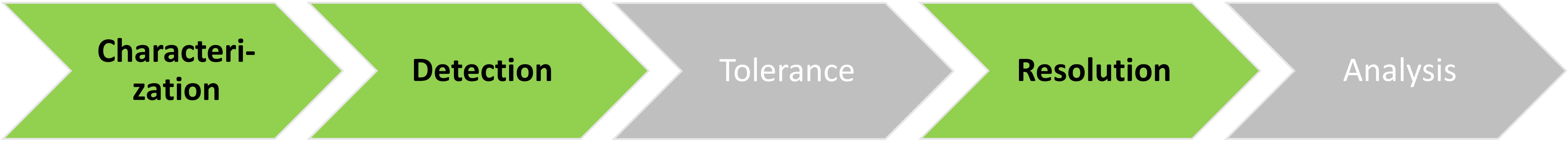

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Managing inconsistencies

Rather than thinking about removing inconsistency, we ne *to thin* *out* ***aging*** ~~***consistency.***~~ ~~*– Finkelstein, 2000*~~ ***inconsistency***. (Va avid et.al., 2013-2019)

- Prevention (e.g. contract-based design)
- Detect-and-Resolve

VANHE

DAVID,

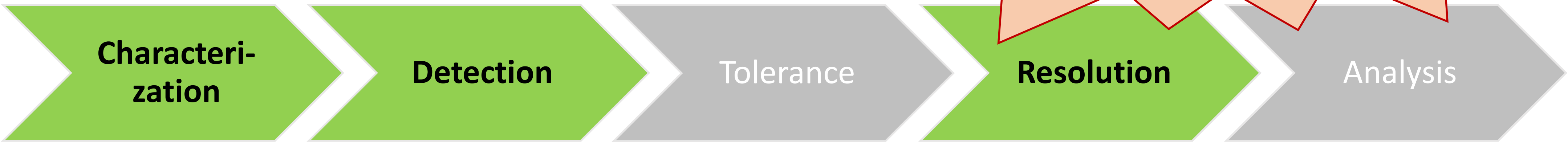
Which one to employ?

When to initiate?

What scope?

....

?



Managing inconsistencies

Rather than thinking about removing inconsistency, we ne[...] *to thin*[...] *out* [...]***aging*** ~~***consistency****. – Finkelstein, 2000*~~ ***inconsistency****.* (Va [...] David et.al., 2013-2019)

- Prevention (e.g. contract-based design)
- Detect-and-Resolve

VANHE

DAVID,

EFFICIENCY!

…of the overall engineering endeavor.

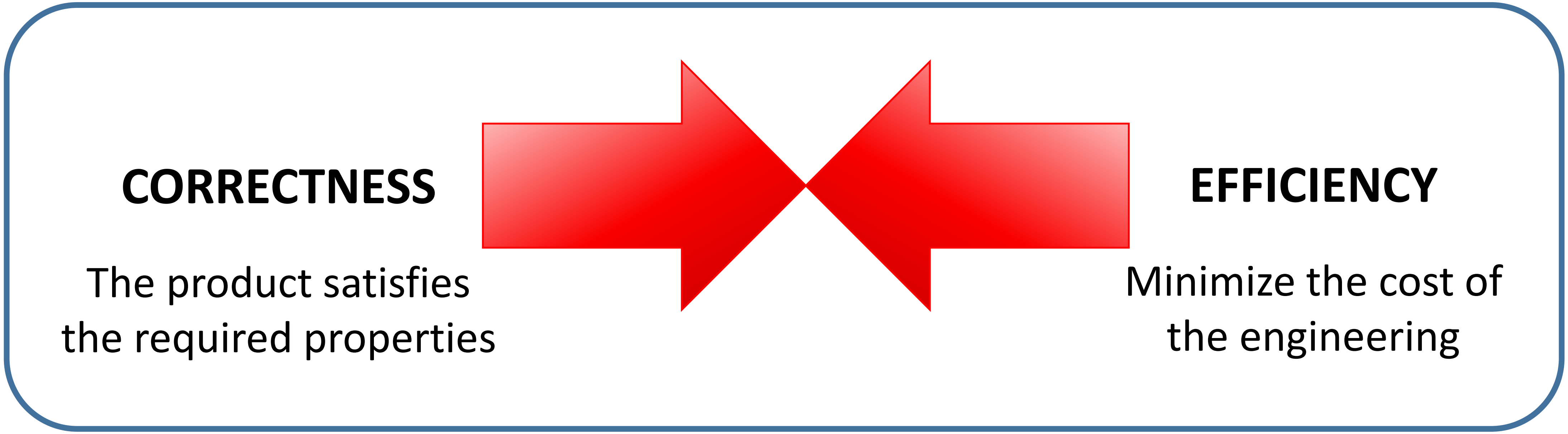
Characteri-zation

De

Resolution

Analysis

„...of the overall engineering endeavor”



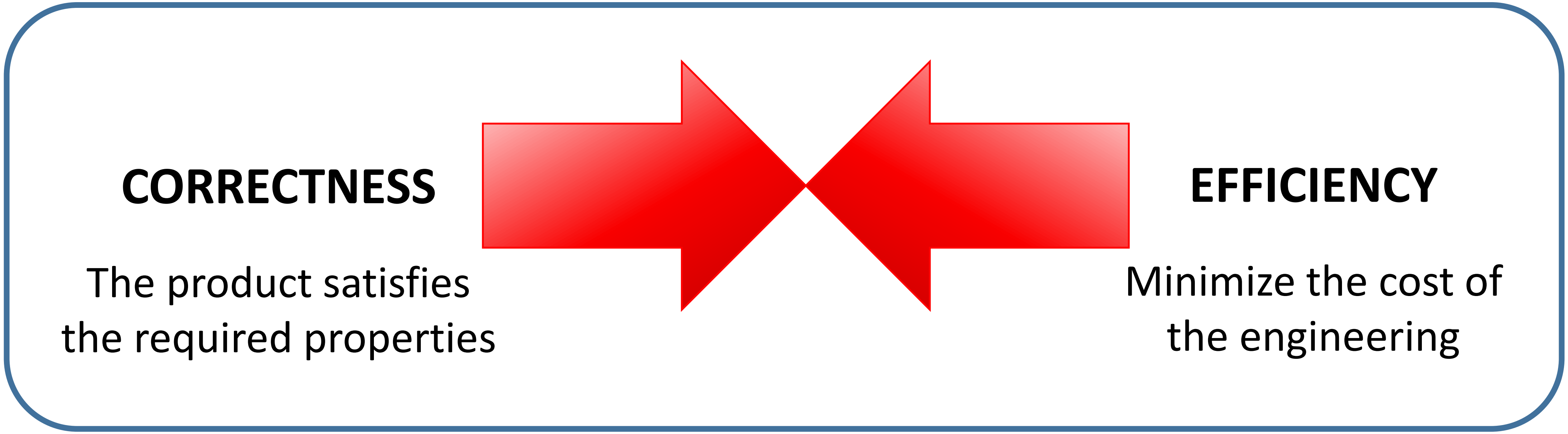
CORRECTNESS

The product satisfies
the required properties

EFFICIENCY

Minimize the cost of
the engineering

PROCESS



CORRECTNESS

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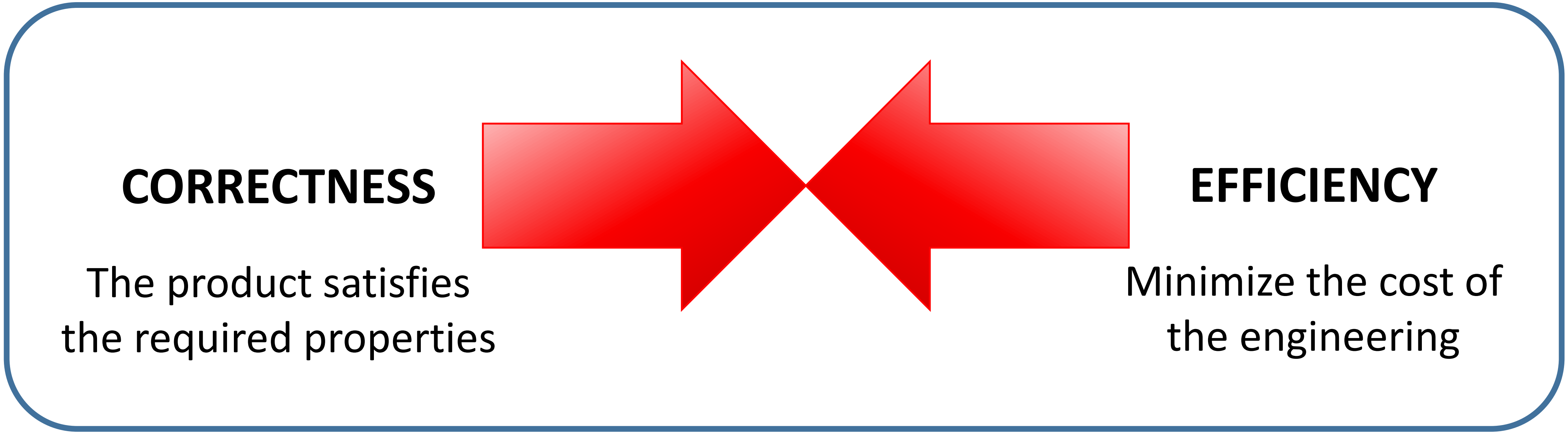
Minimize the cost of the engineering

Partially ordered set of activities,

manipulating artifacts (models)

Activity: manual vs automated

PROCESS



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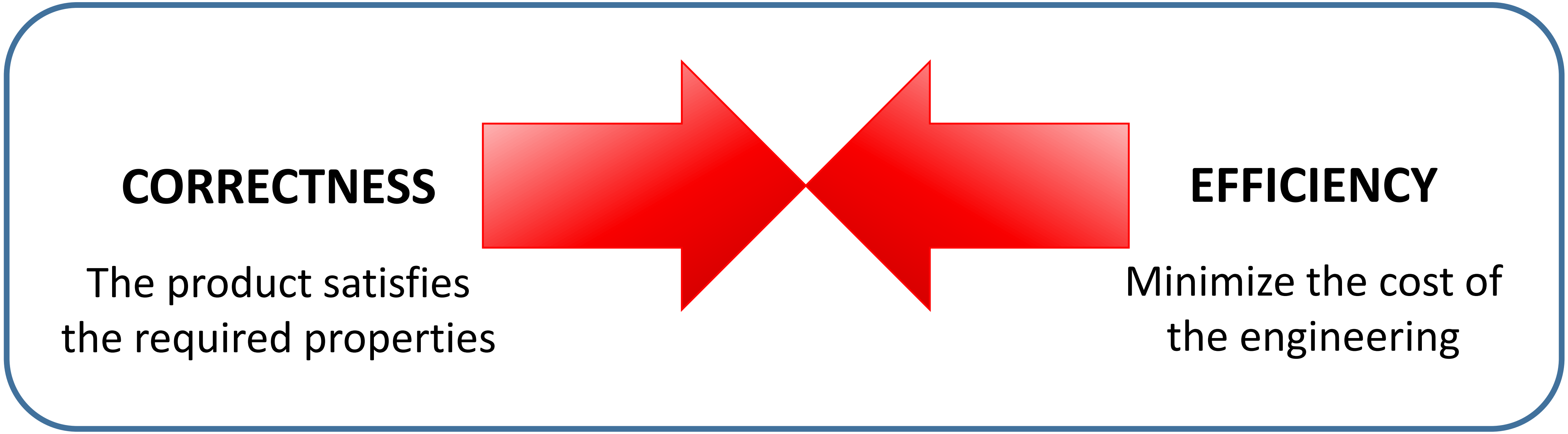
Optimize so that (i) a correct product is delivered; and (ii) the process is as efficient as possible.



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Minimize the cost of the engineering

$$inconsistent(D_i, D_j) \Rightarrow incorrect(D)$$

$$consistent(D_i, D_j) \nRightarrow correct(D)$$

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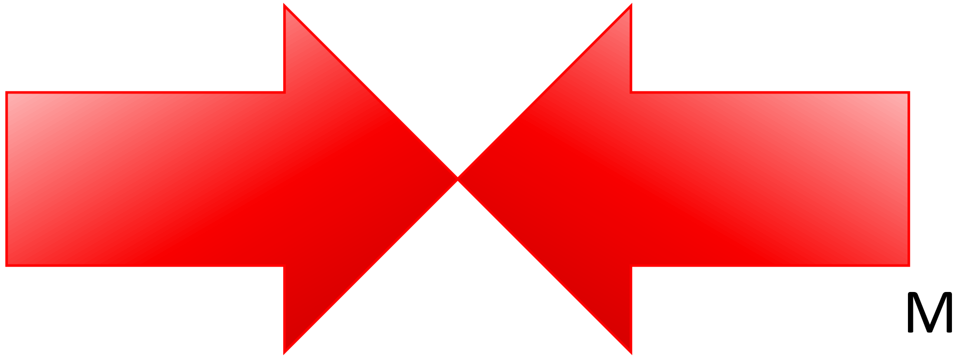

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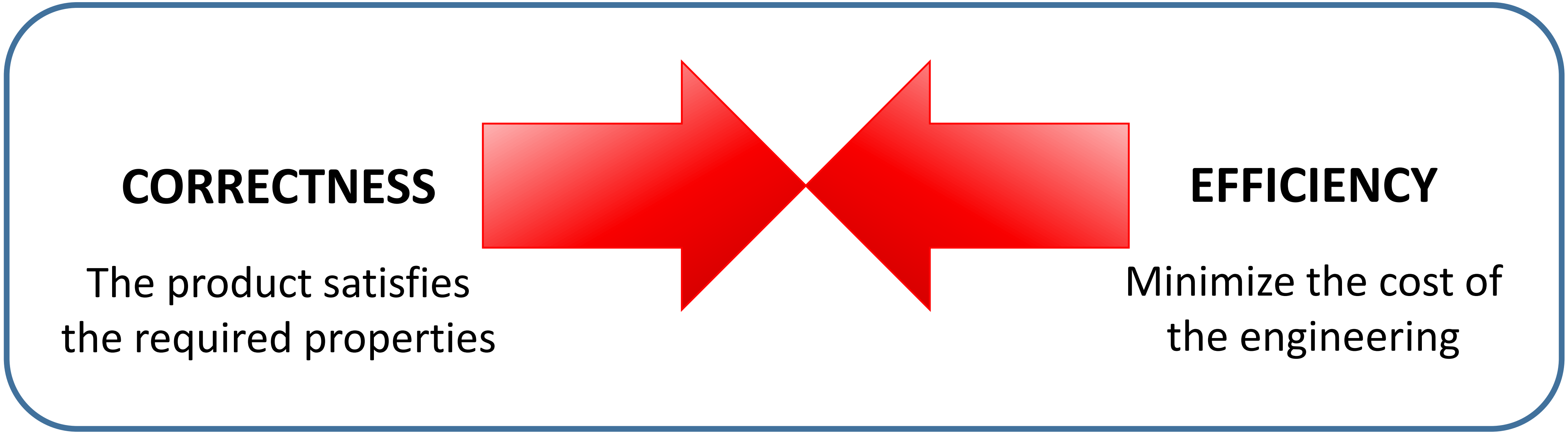

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Heuristic (Romanycia and Pelletier). Any device, be it a program, rule, piece of knowledge, etc., which one is not entirely confident will be useful in providing a practical solution, but which one has reason to believe will be useful, and which is added to a problem-solving system in expectation that on average the performance will improve.

$$\mathit{inconsistent}(D_i, D_j) \Rightarrow \mathit{incorrect}(D)$$

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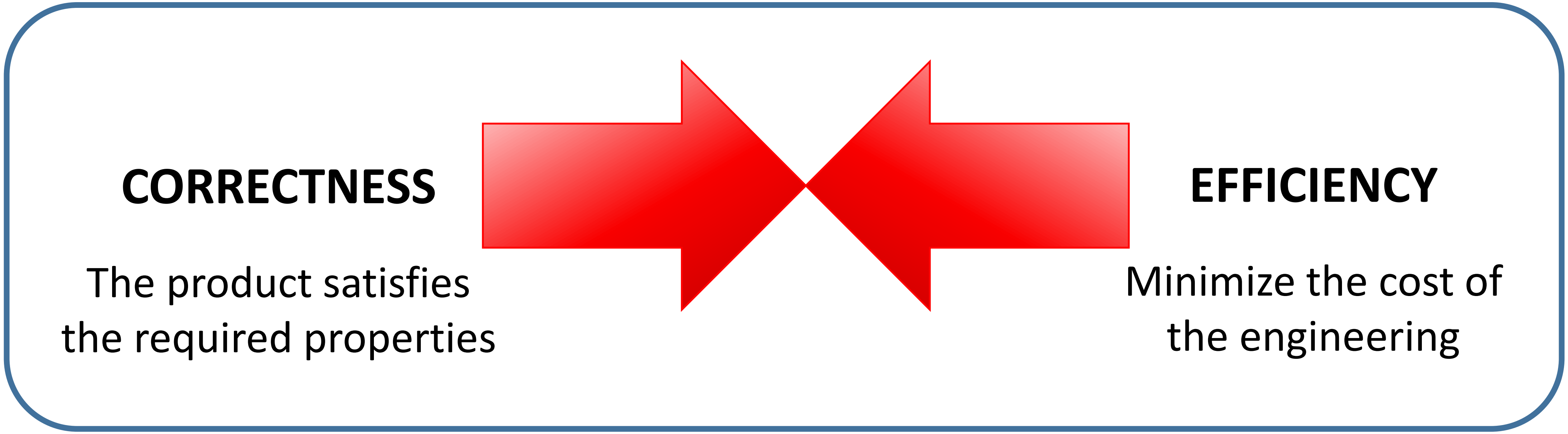

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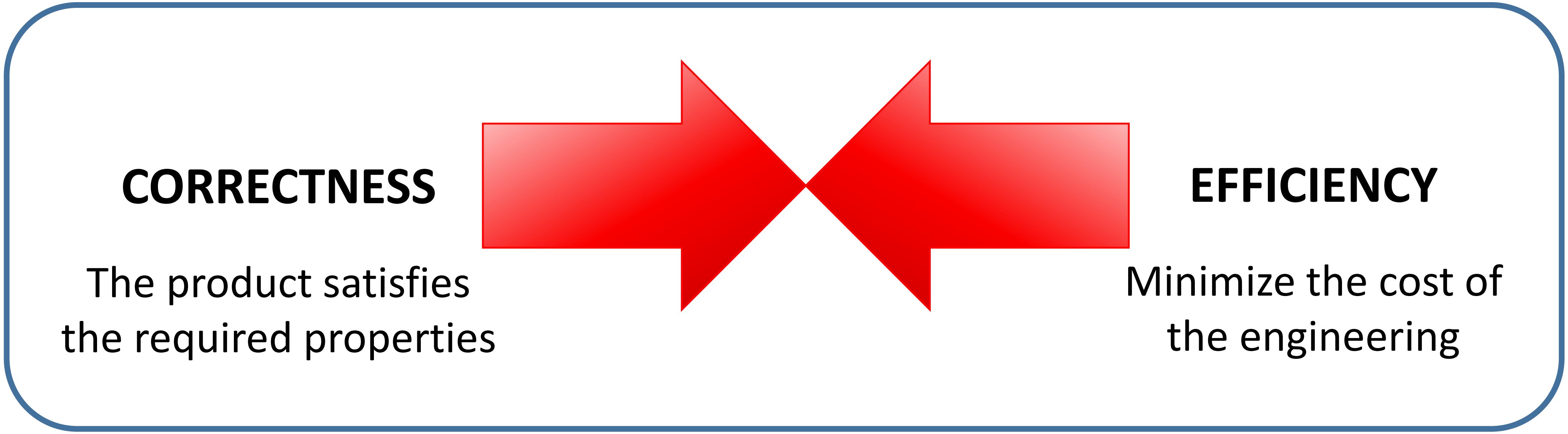

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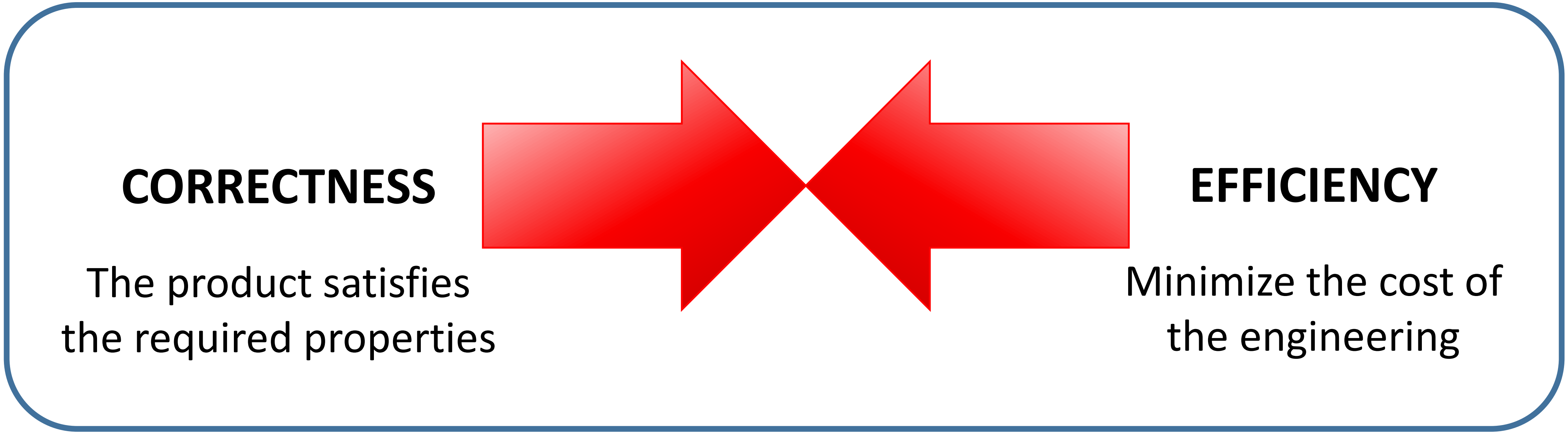

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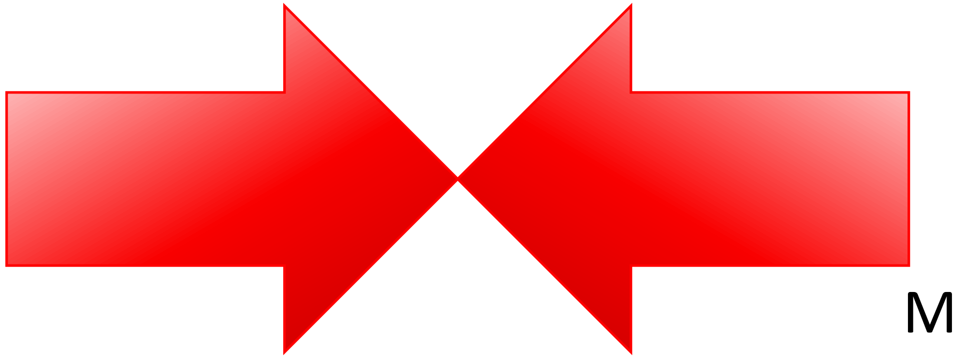

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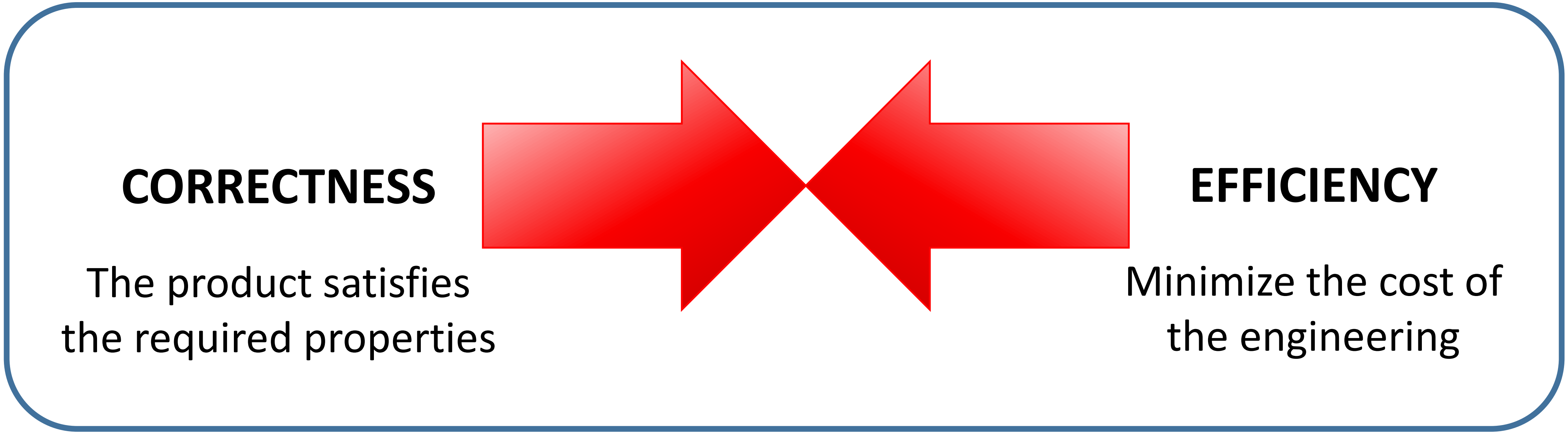

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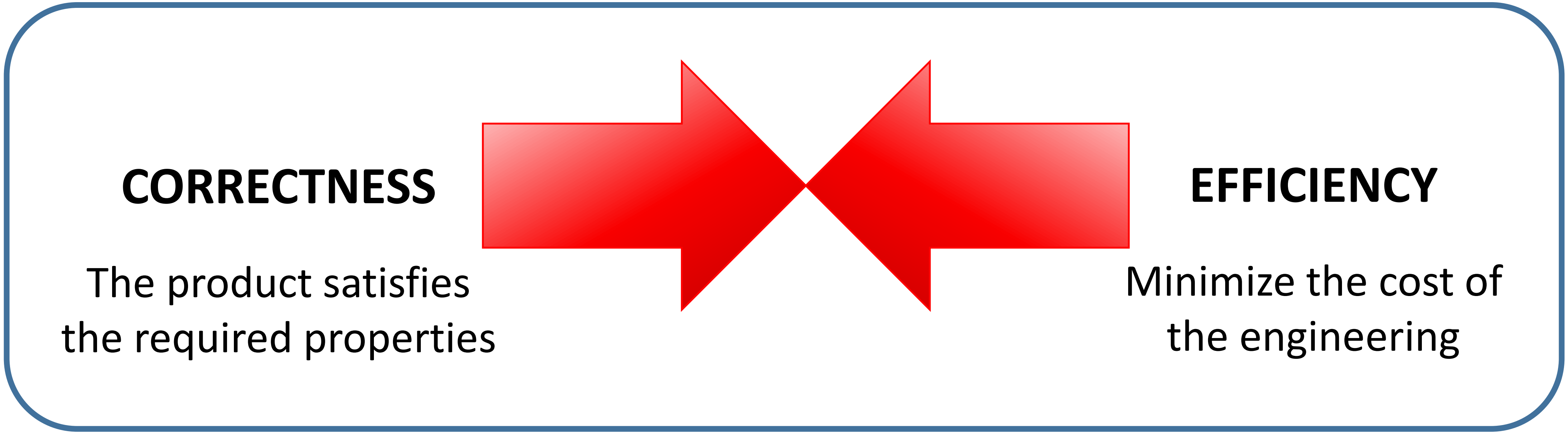

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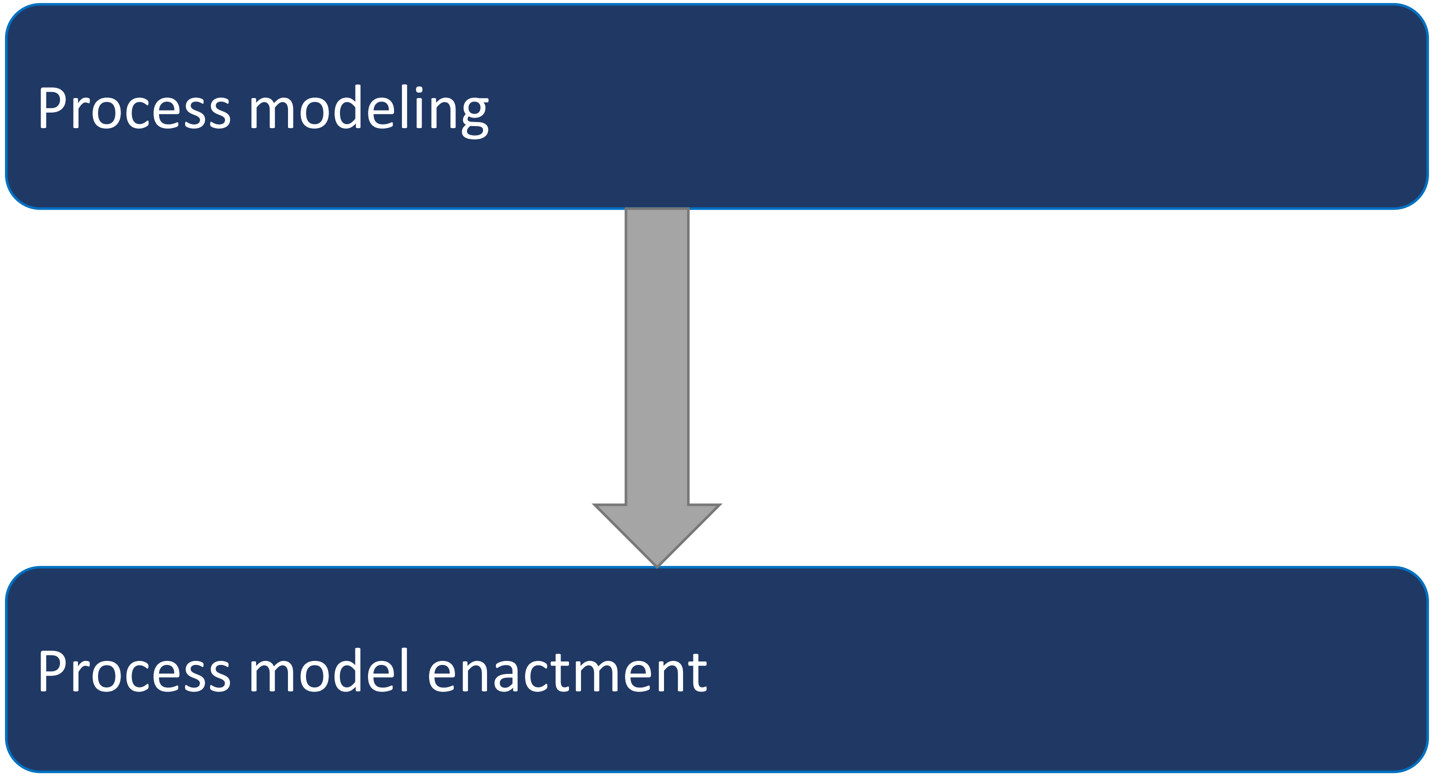
Approach

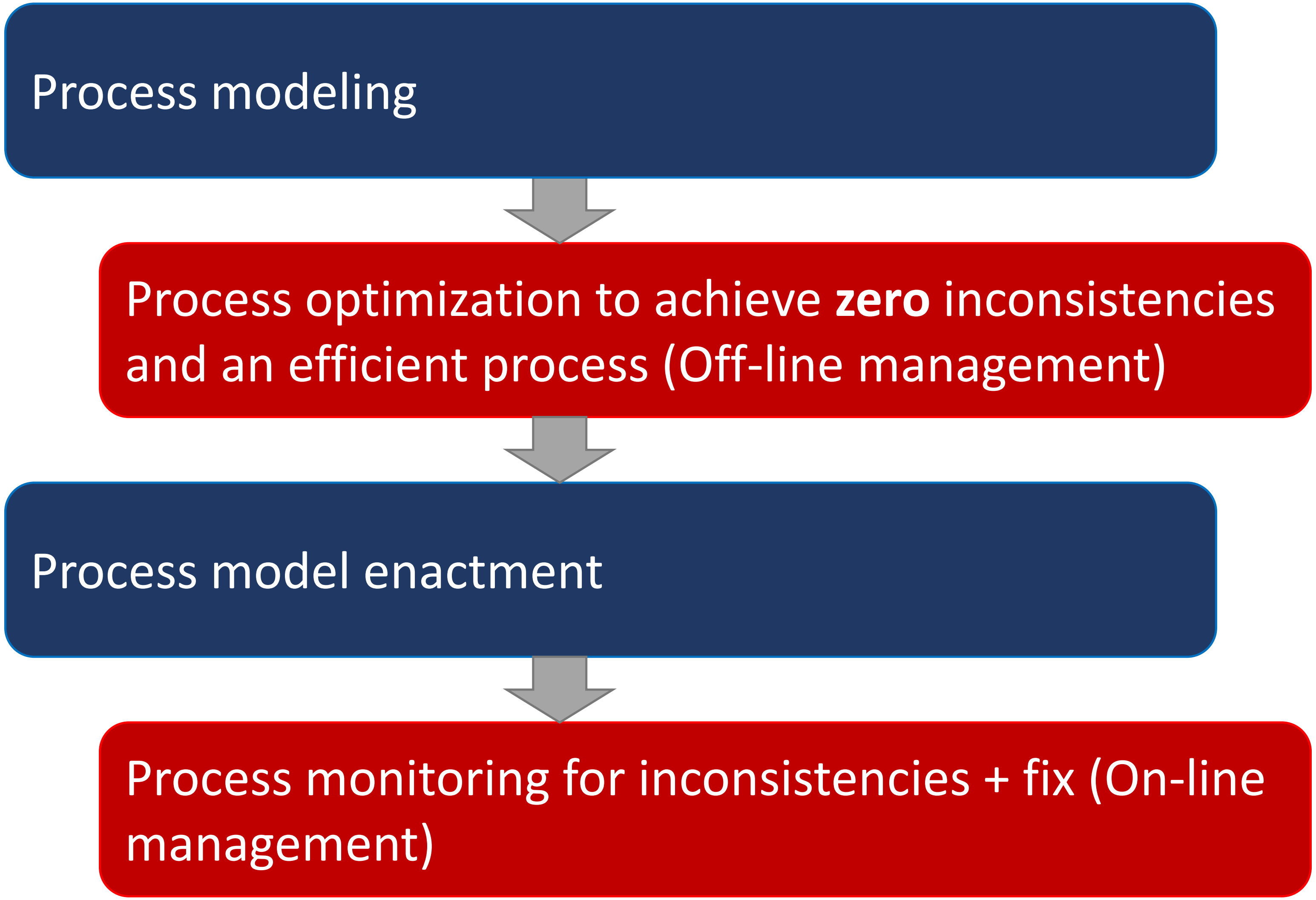
Approach



Process modeling

Process model enactment

Approach



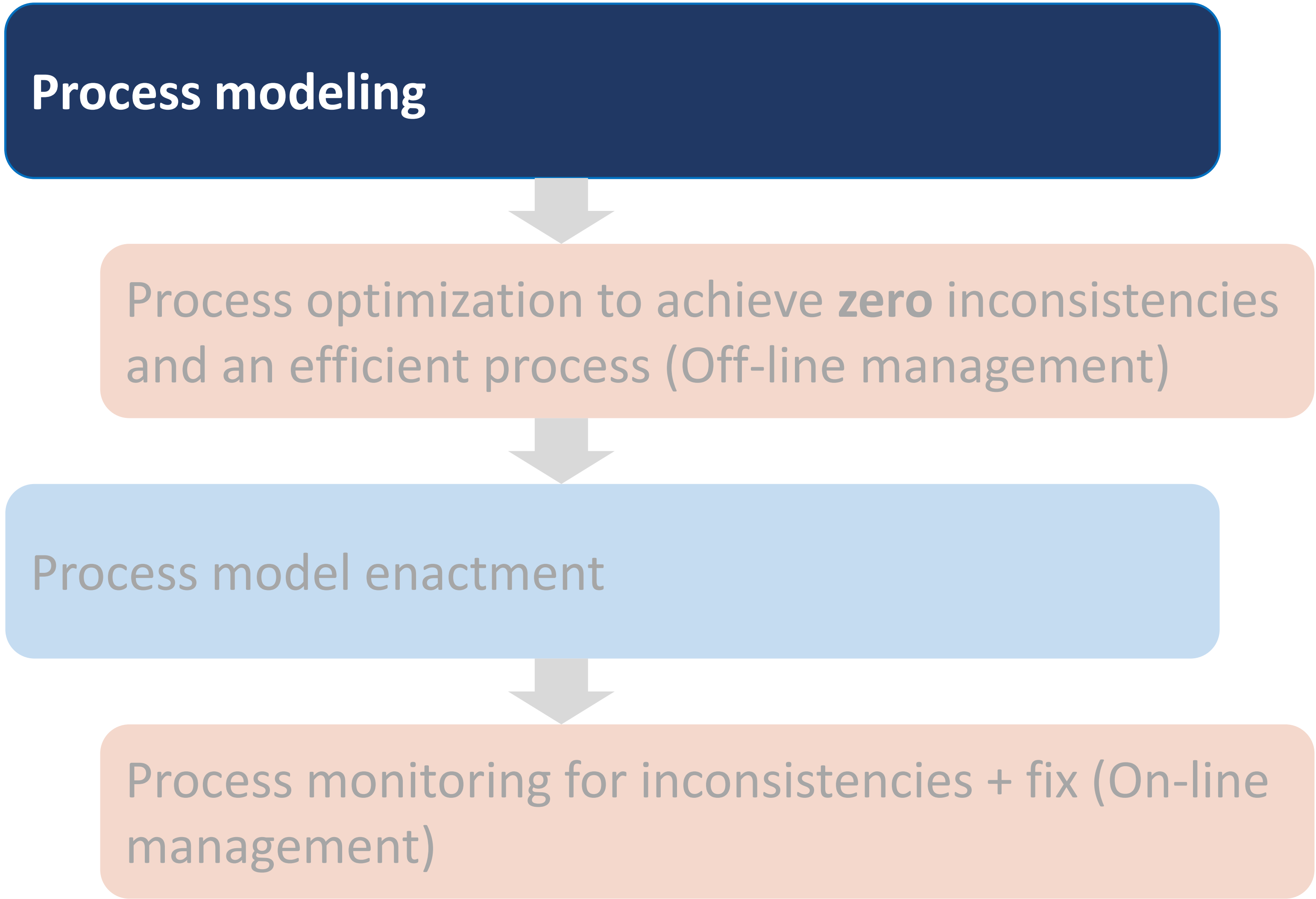
Process modeling

Process optimization to achieve **zero** inconsistencies and an efficient process (Off-line management)

Process model enactment

Process monitoring for inconsistencies + fix (On-line management)

Approach



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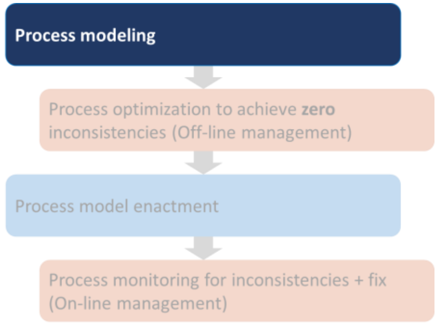


Process modeling

Process optimization to achieve **zero** inconsistencies (Off-line management)

Process model enactment

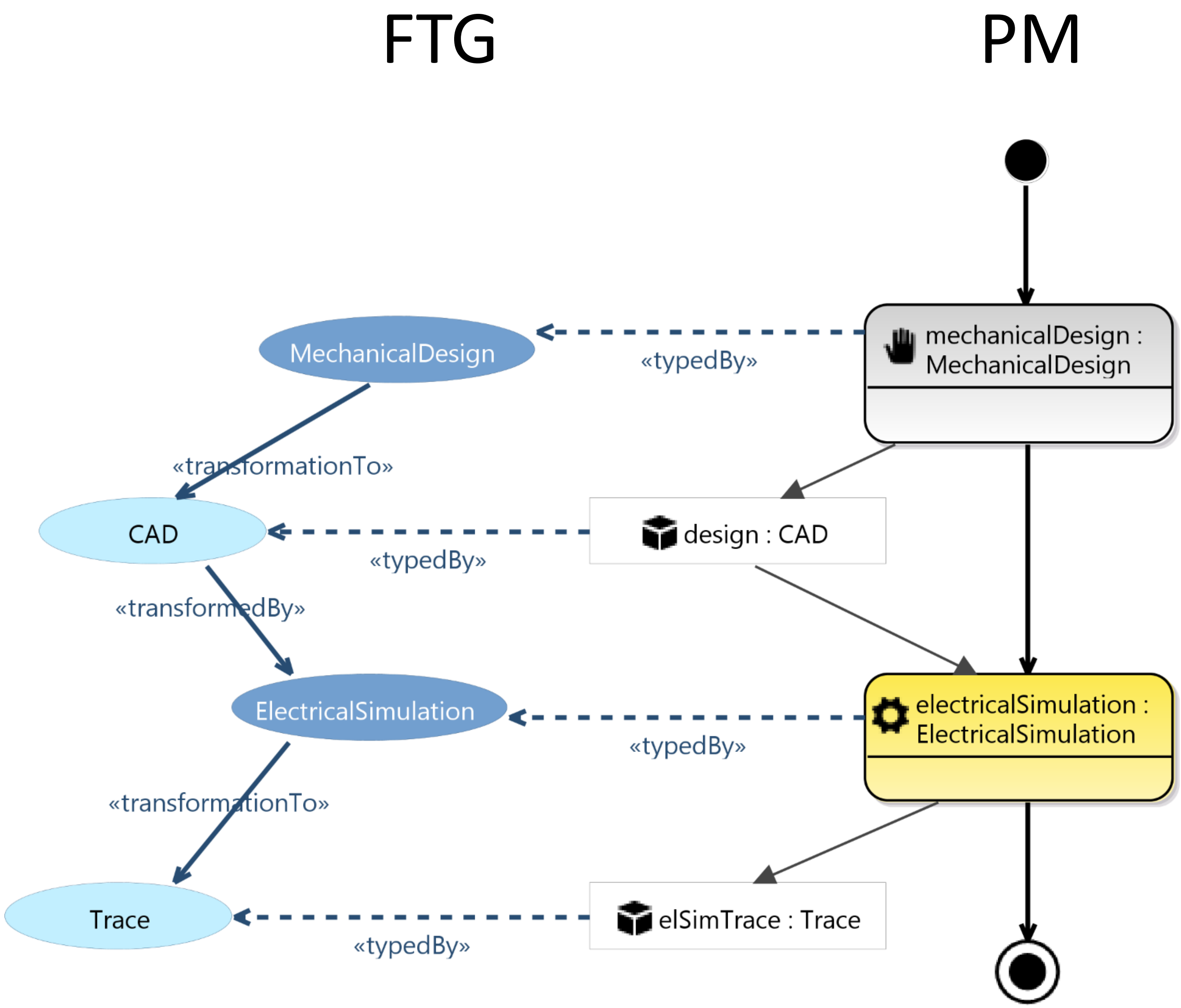
Process monitoring for inconsistencies + fix (On-line management)

Process modeling

- Built on the *Formalism Transformation Graph + Process Model* (FTG+PM) framework
- Modified to be able to capture relevant system information for inconsistency management purposes
  - Still conform to the original FTG+PM specification
- Constructed an advanced modeling tool
  - Eclipse-based
  - Various modeling interfaces (graphical and table-based)

Lúcio, Levi, Sadaf Mustafiz, Joachim Denil, Hans Vangheluwe, and Maris Jukss: „FTG+ PM: an integrated framework for investigating model transformation chains”. In *International SDL Forum*, pp. 182-202. Springer, Berlin, Heidelberg, 2013.

Process modeling

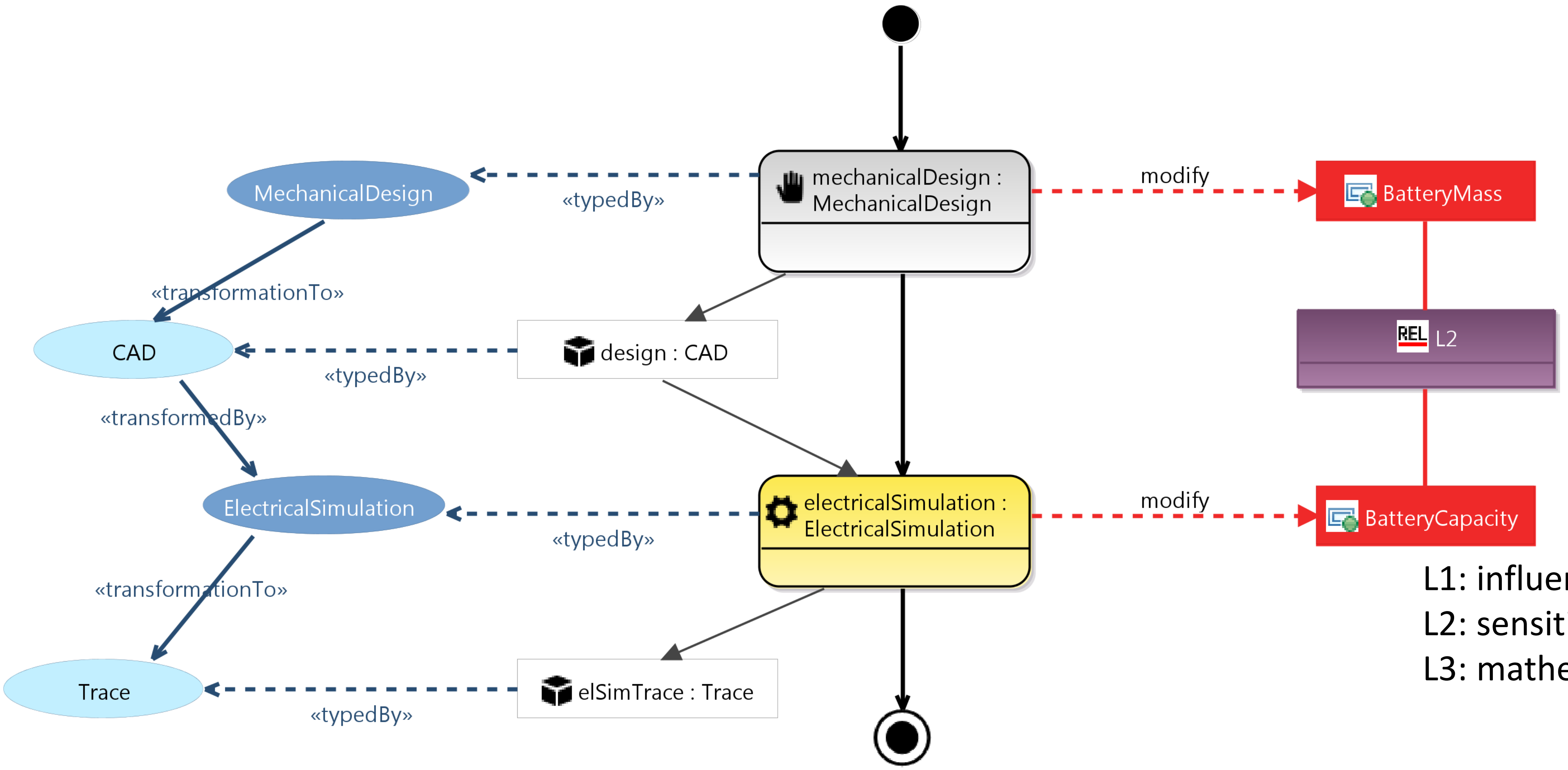


Process modeling

FTG

PM

System characteristics



L1: influence graph
L2: sensitivity
L3: mathematical relationship

Process modeling

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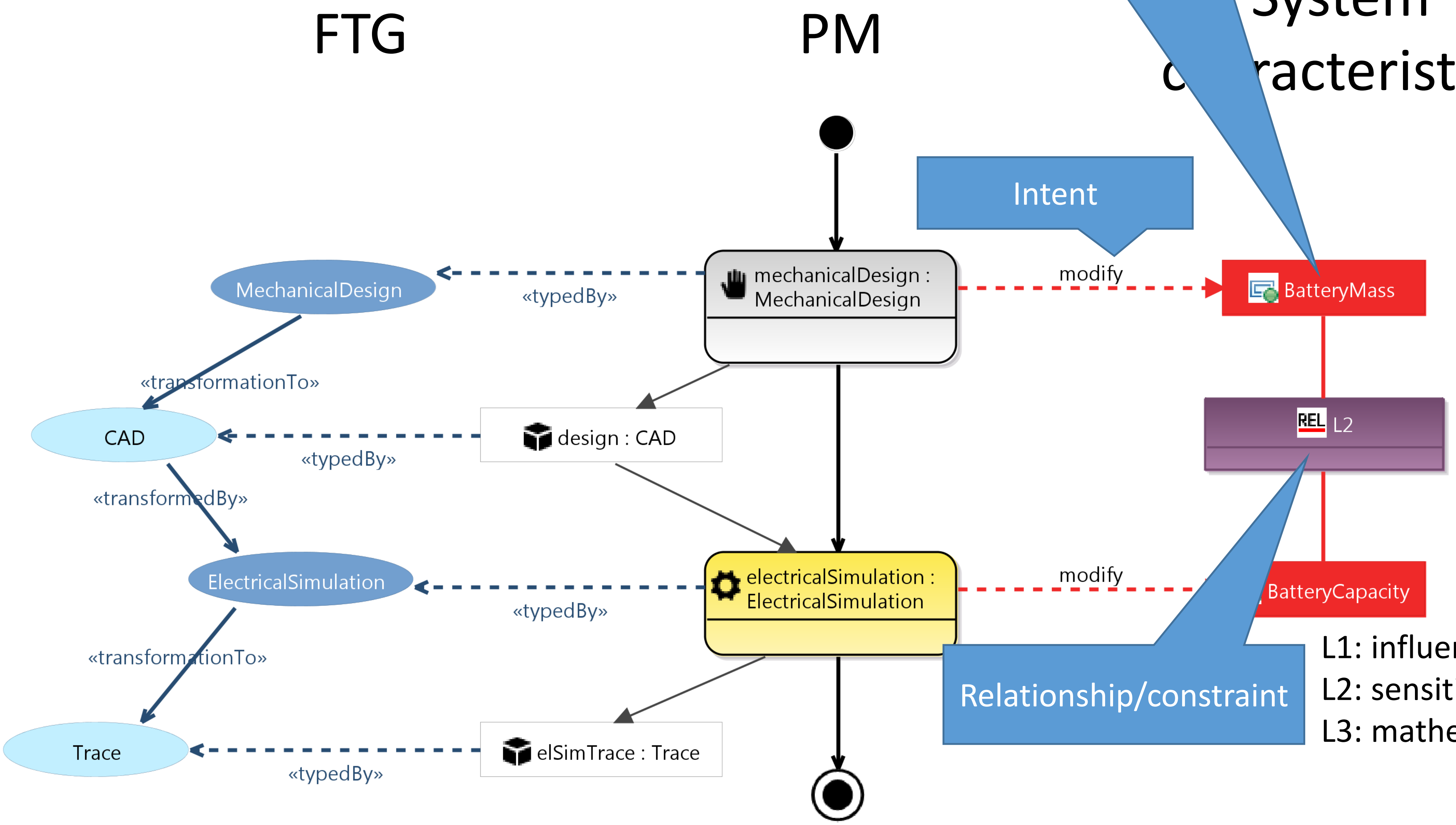
Process modeling



System attribute (conceptually: an extra artifact in the FTG+PM)

Intent

Relationship/constraint

L1: influence graph
L2: sensitivity
L3: mathematical relationship

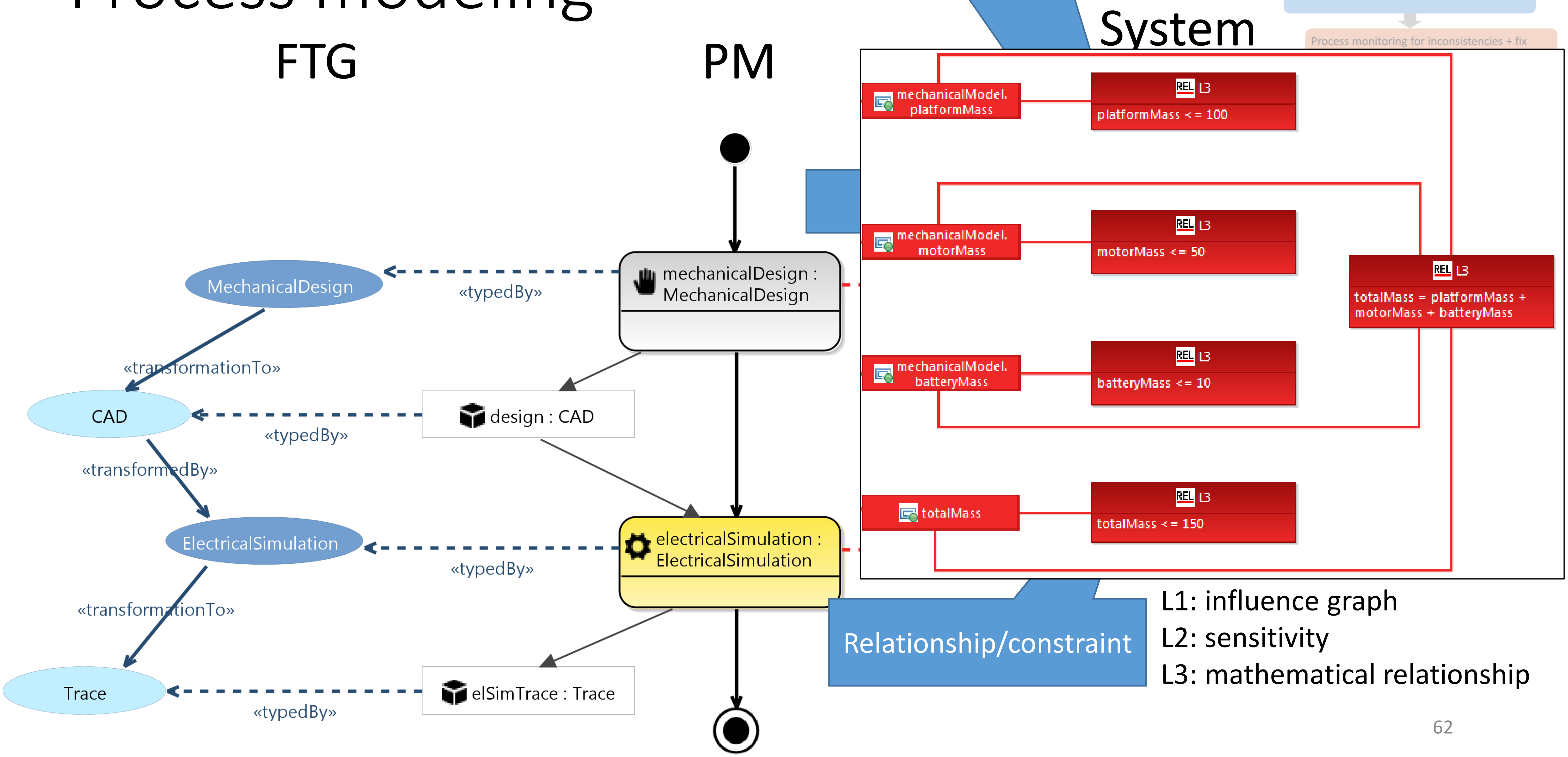
Process modeling

Process optimization to achieve **zero** inconsistencies (Off-line management)

Process model enactment

Process monitoring for inconsistencies + fix

Process modeling



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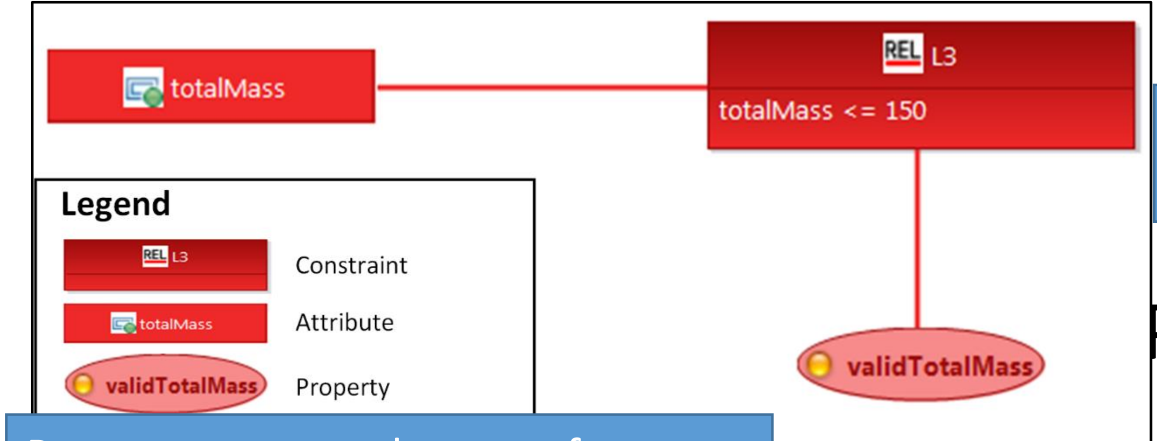
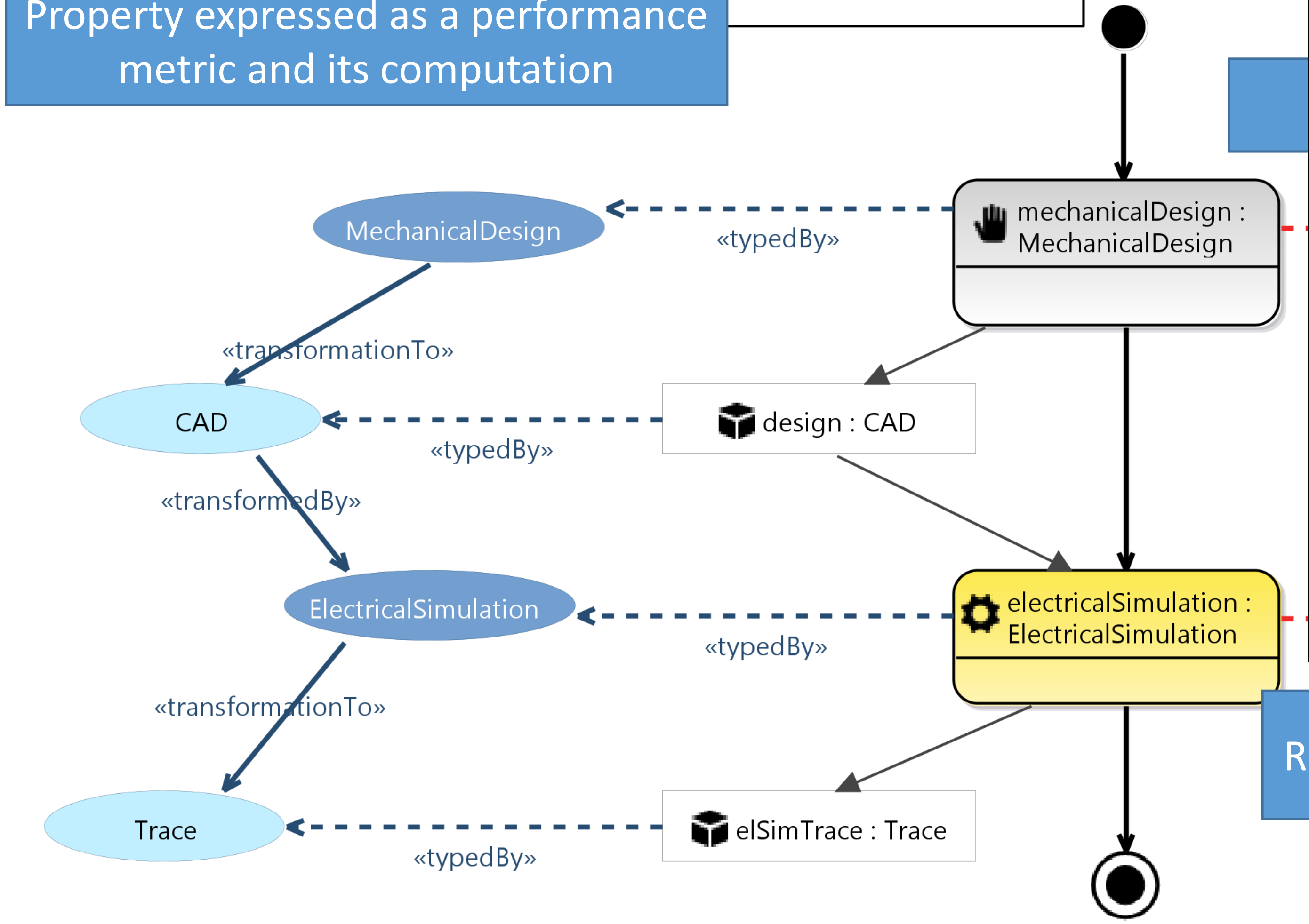
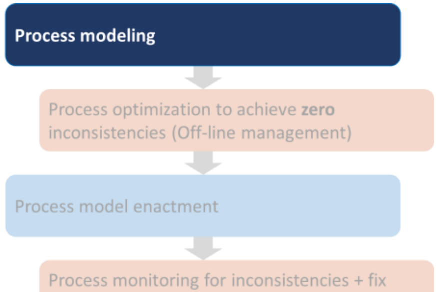


Property expressed as a performance metric and its computation

PM




Process modeling
Process optimization to achieve zero inconsistencies (Off-line management)
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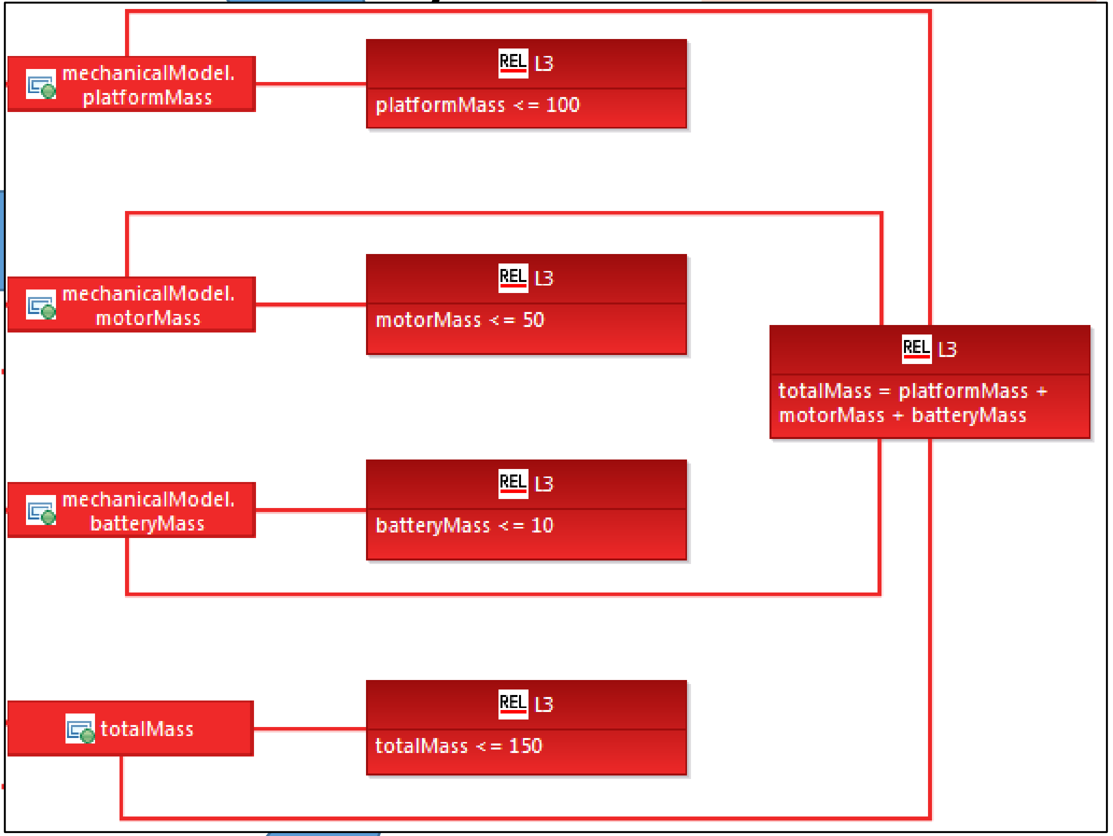
System attribute (conceptually: an extra artifact in the FTG+PM)

System


mechanicalModel.platformMass
REL L3
platformMass <= 100
mechanicalModel.motorMass
REL L3
motorMass <= 50
REL L3
totalMass = platformMass + motorMass + batteryMass
mechanicalModel.batteryMass
REL L3
batteryMass <= 10
totalMass
REL L3
totalMass <= 150

Relationship/constraint

L1: influence graph
L2: sensitivity
L3: mathematical relationship

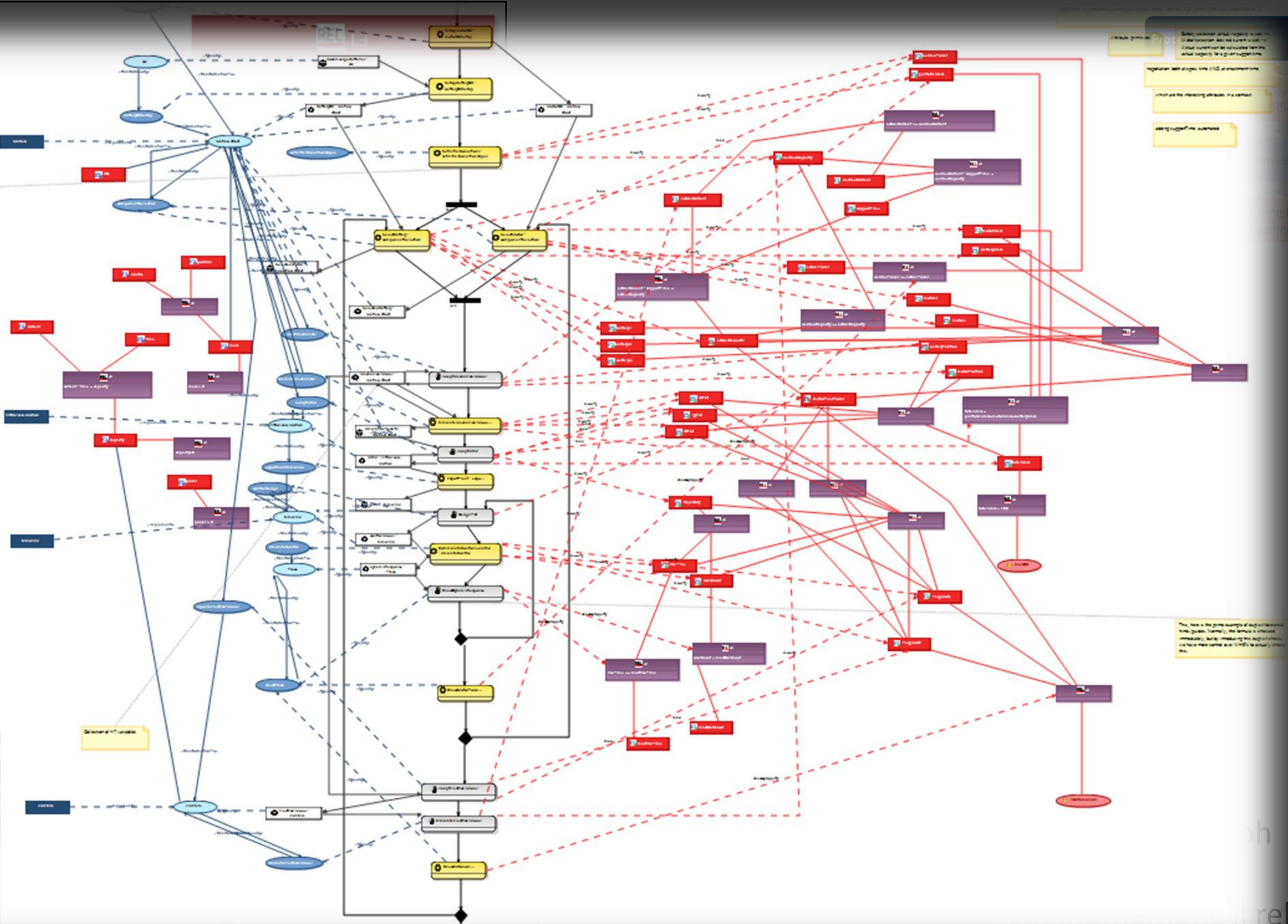
Legend

totalM

validTotal

Property

met



…on to achieve **zero** …ff-line management)

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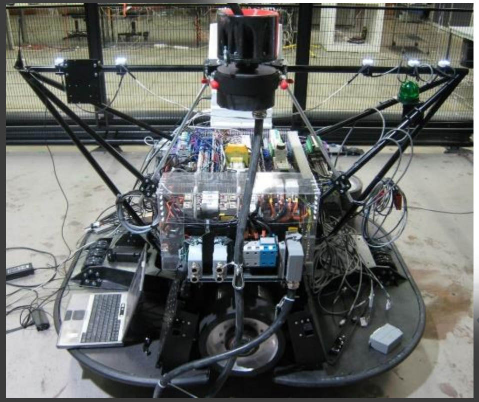
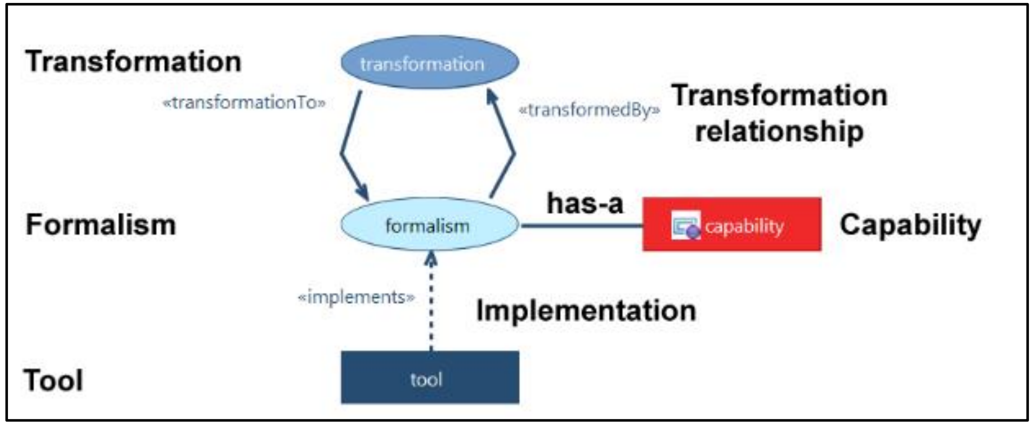
«typedBy»

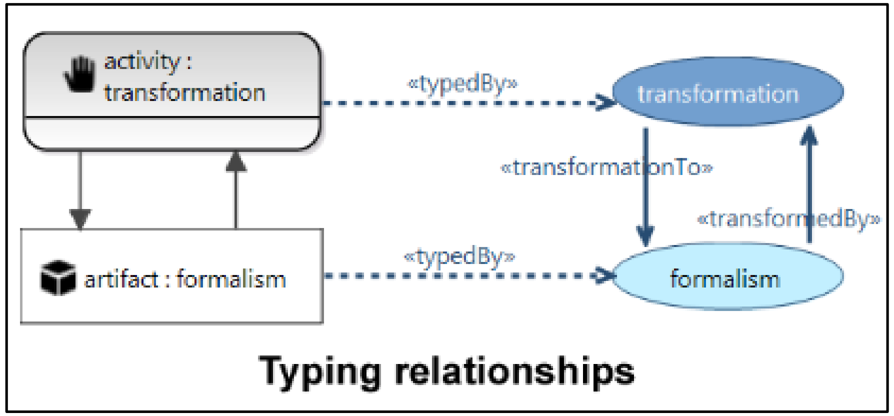
elSimTrace : Trace

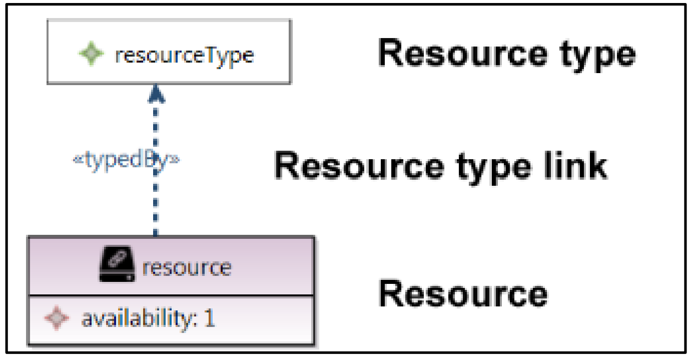
relationship

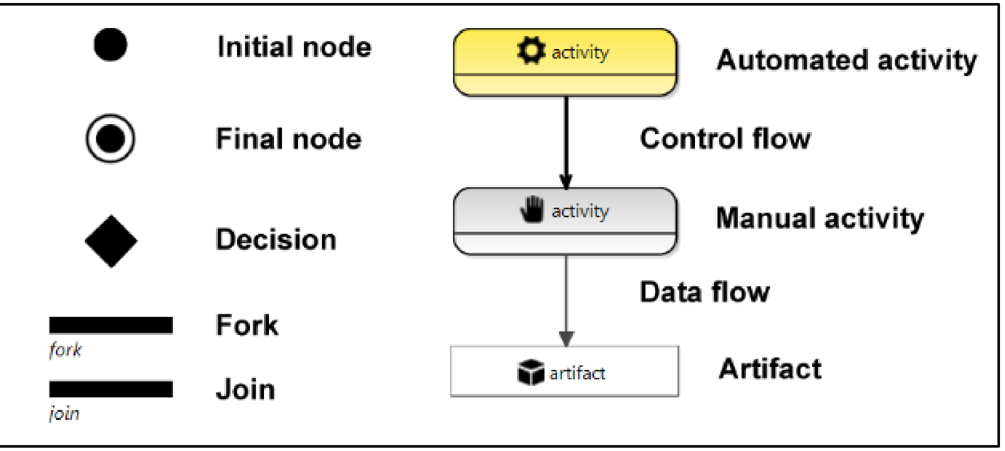


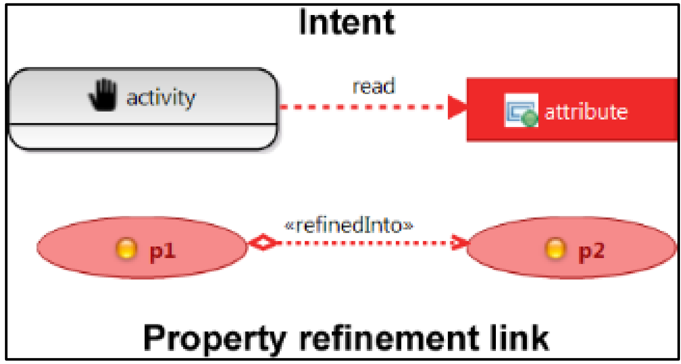
Elements of the formalism

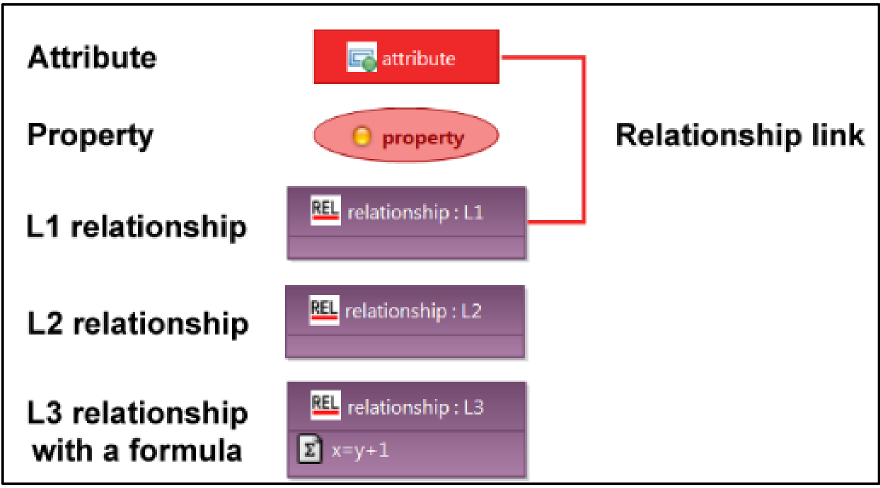




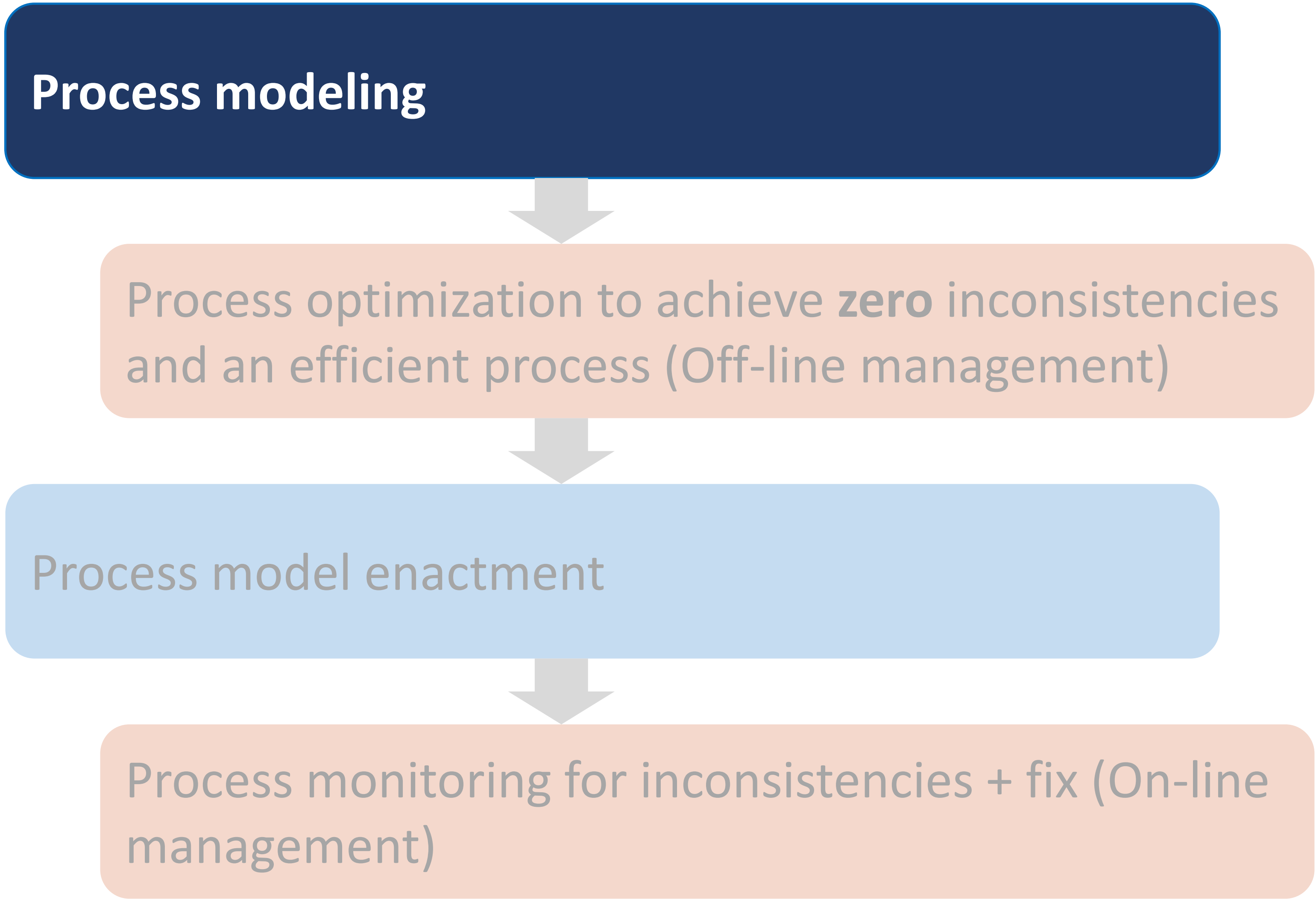








Approach



Process modeling

Process optimization to achieve **zero** inconsistencies and an efficient process (Off-line management)

Process model enactment

Process monitoring for inconsistencies + fix (On-line management)

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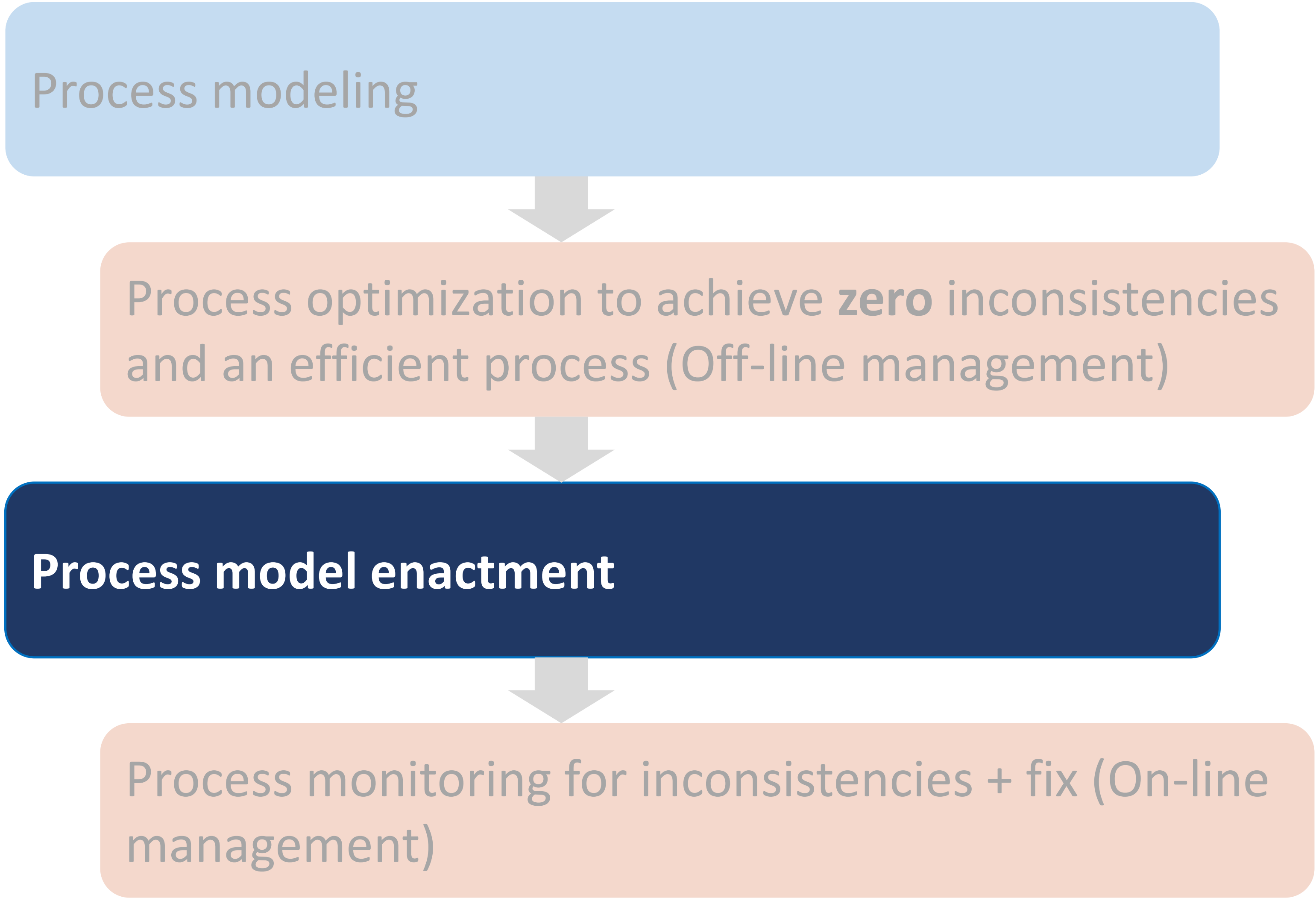

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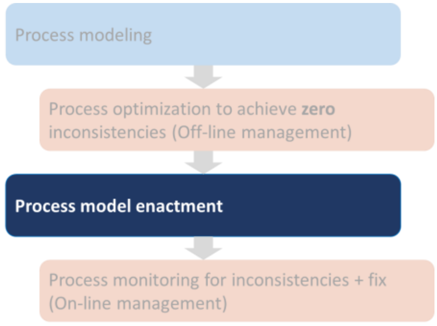
Enactment of the FTG+PM



Process modeling
Process optimization to achieve **zero** inconsistencies (Off-line management)
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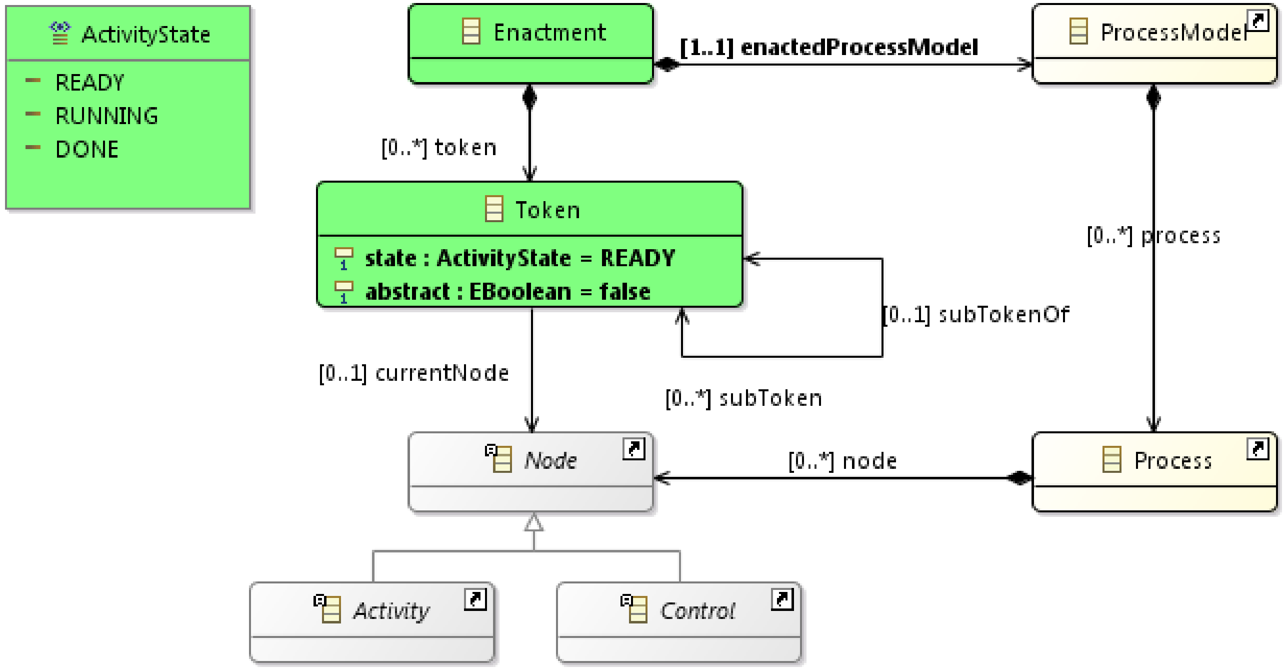
- Execution semantics (based on enactment of model transformations) published by J. Denil
- Eclipse-based engine
  - Explicitly modeled internals
  - External service interoperability



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J. Denil: „*Design, Verification and Deployment of Software Intensive Systems – A Multi-Paradigm Modelling Approach*”. PhD Thesis, 2013.

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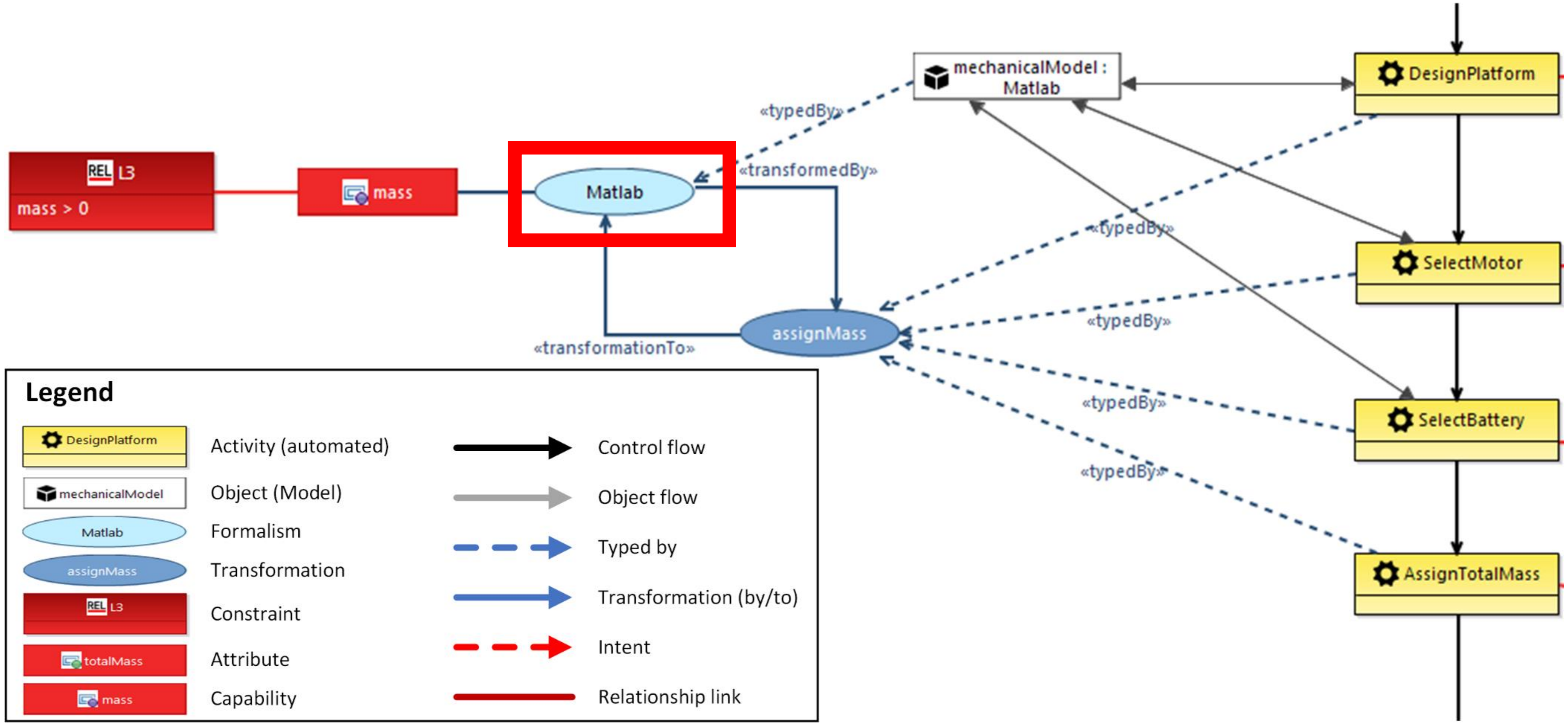

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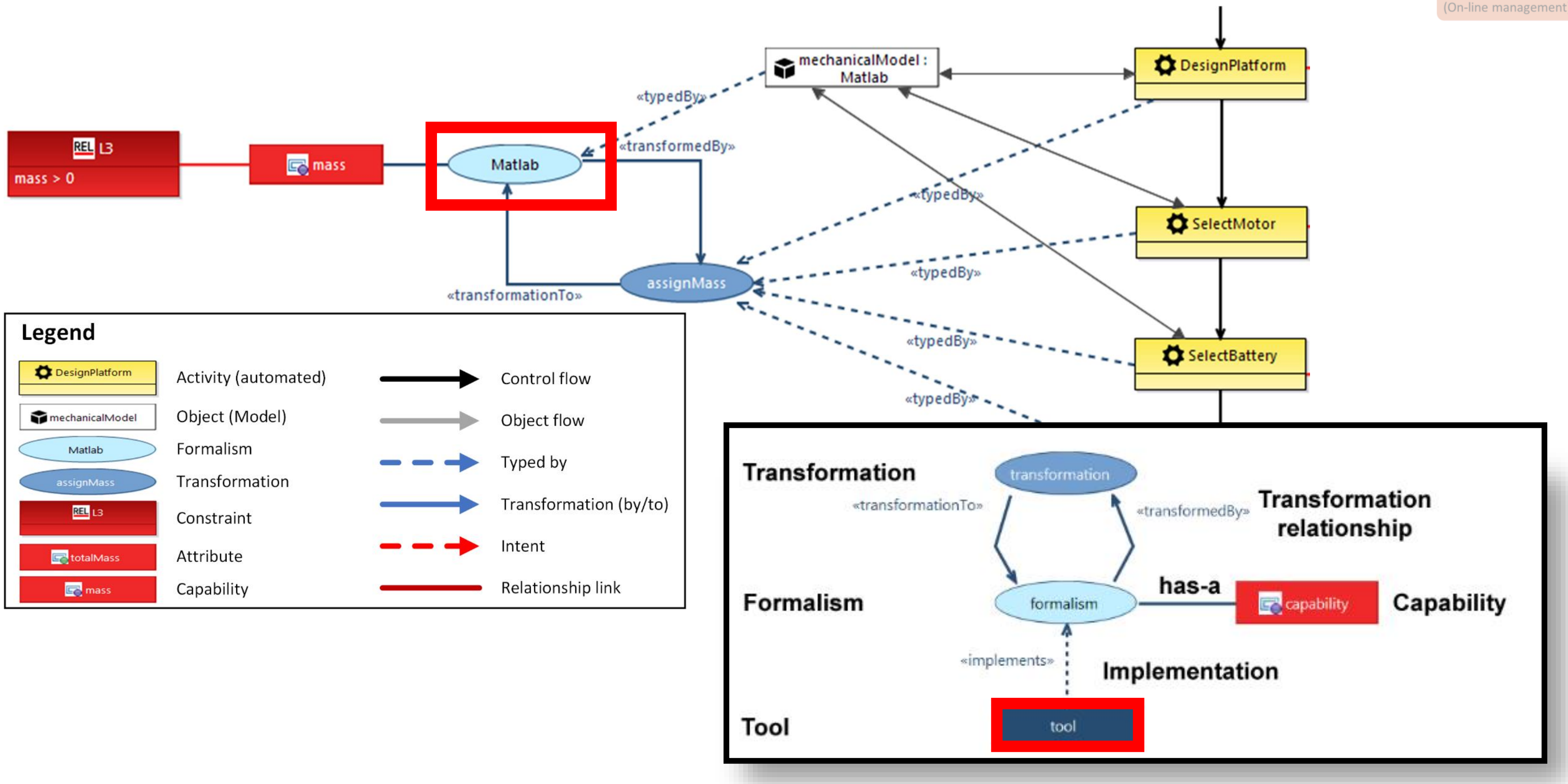

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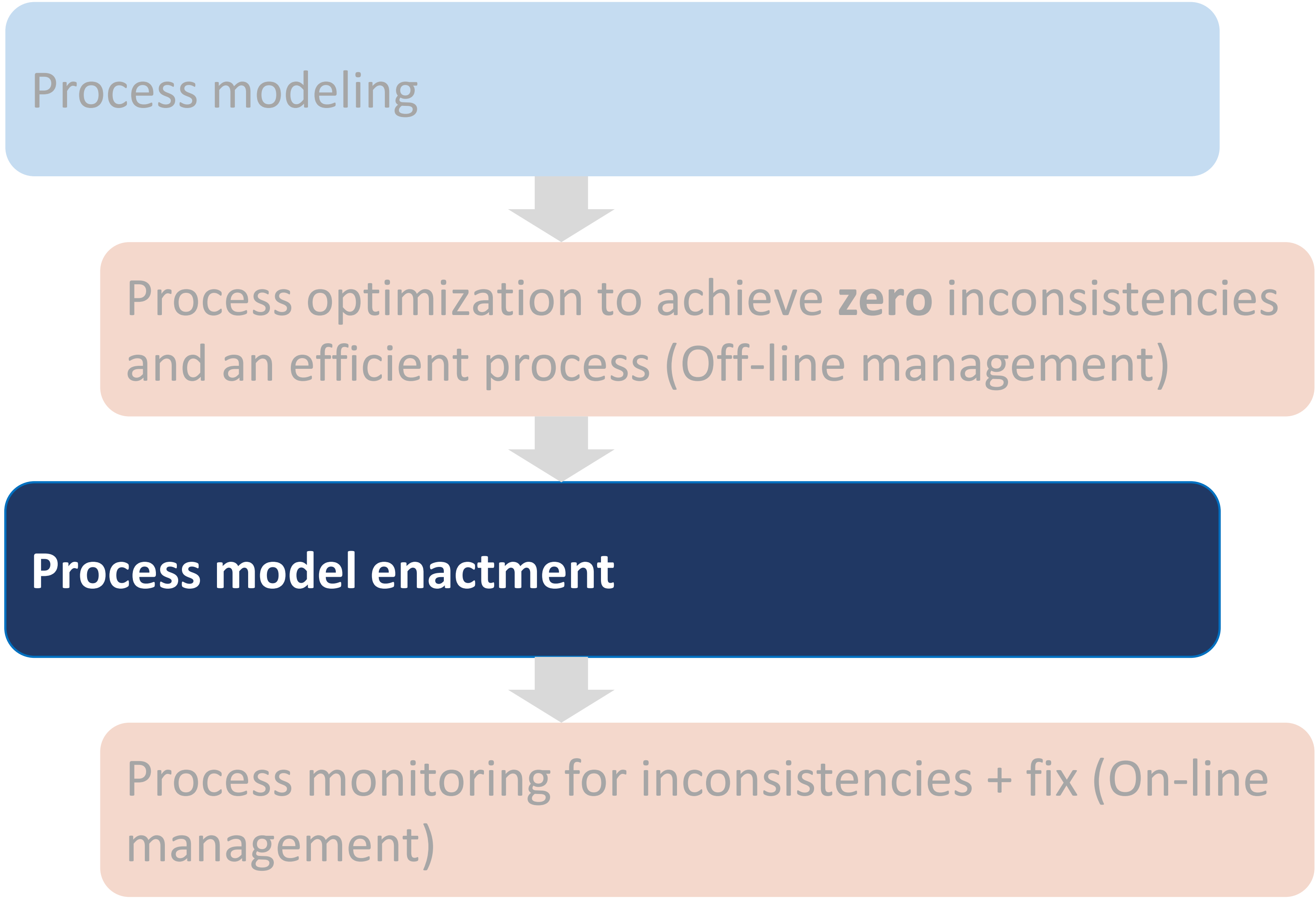

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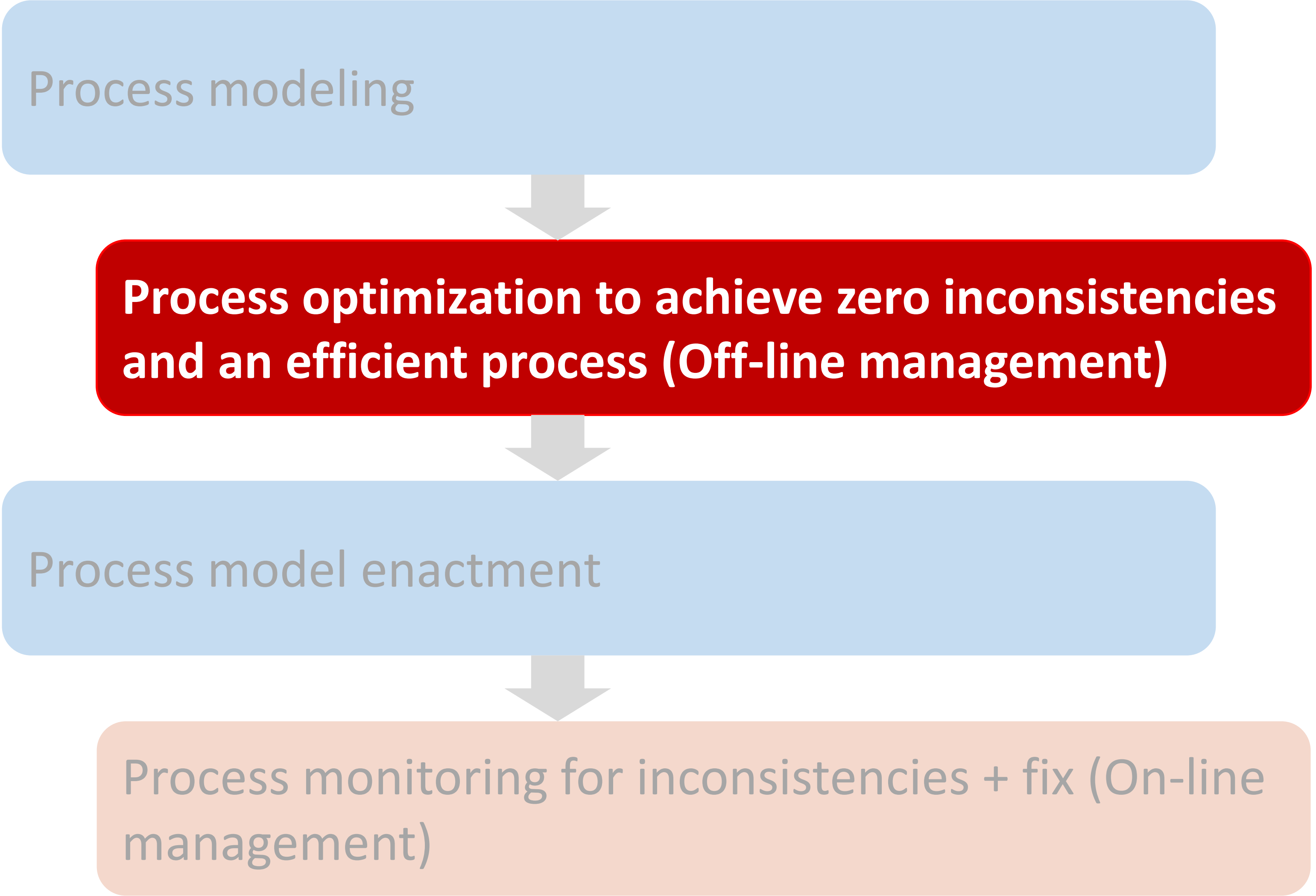


Process modeling

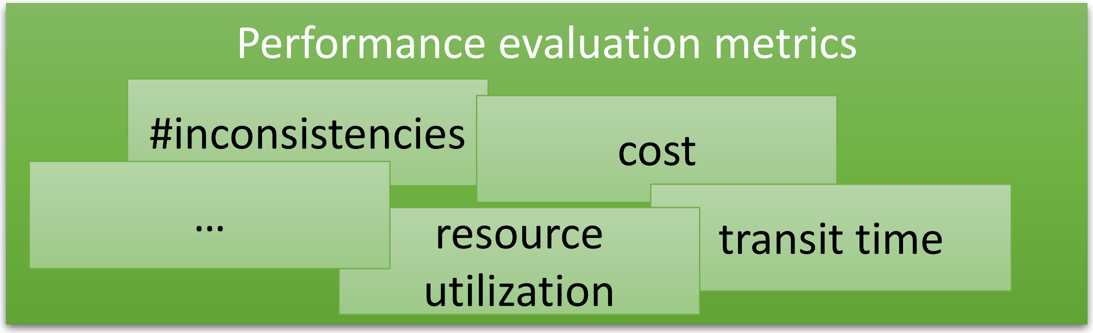
Process optimization to achieve zero inconsistencies and an efficient process (Off-line management)

Process model enactment

Process monitoring for inconsistencies + fix (On-line management)

Evaluating processes

- Quantitative (performance) metrics are required



Performance evaluation metrics

#inconsistencies

cost

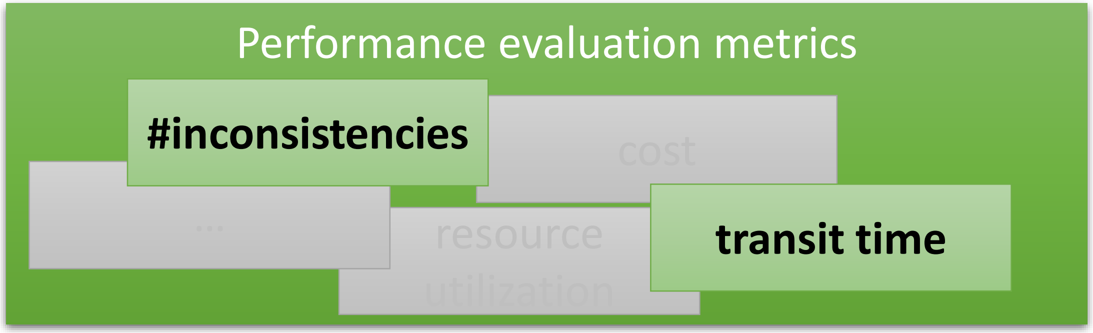
…

resource utilization

transit time

Evaluating processes

- Quantitative (performance) metrics are required



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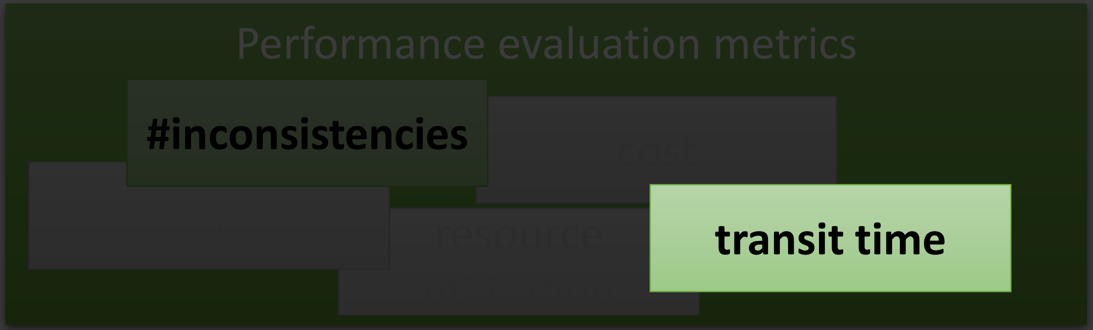
- Quantitative (performance) metrics are required



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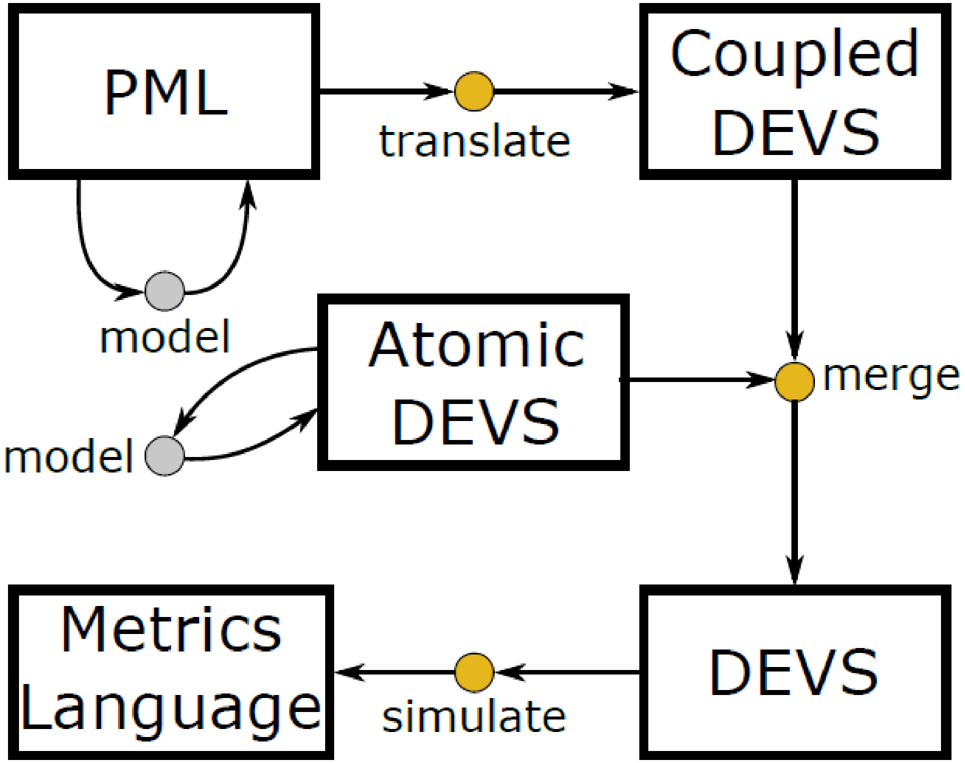
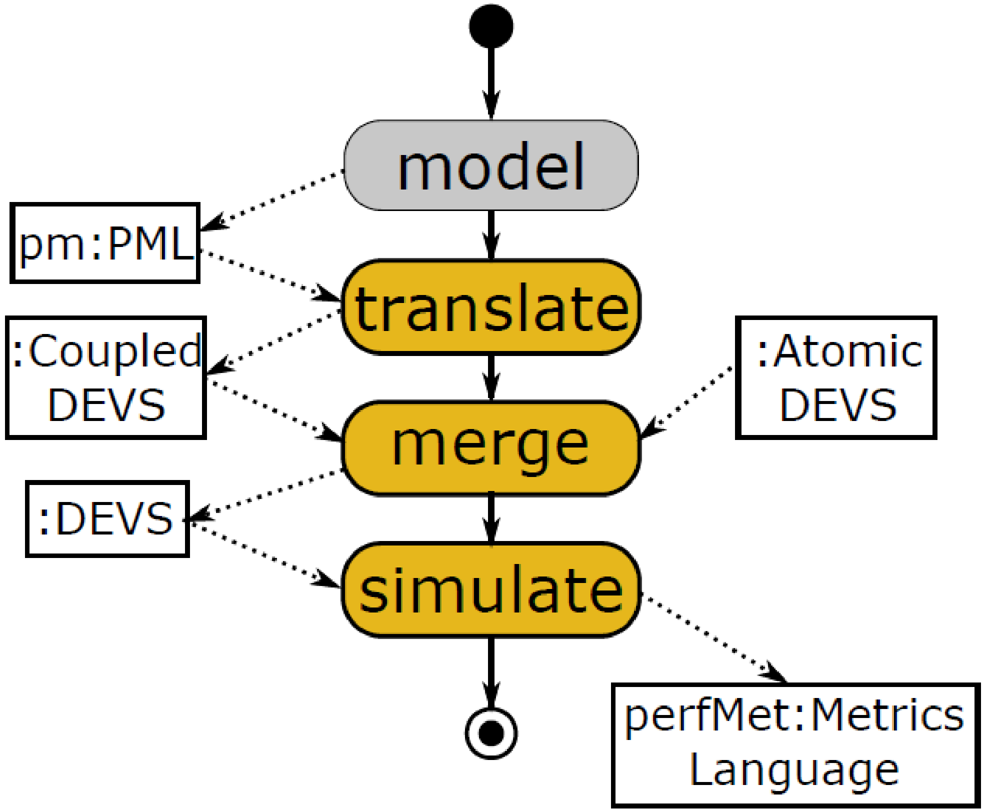
Stochastic simulations of transit time

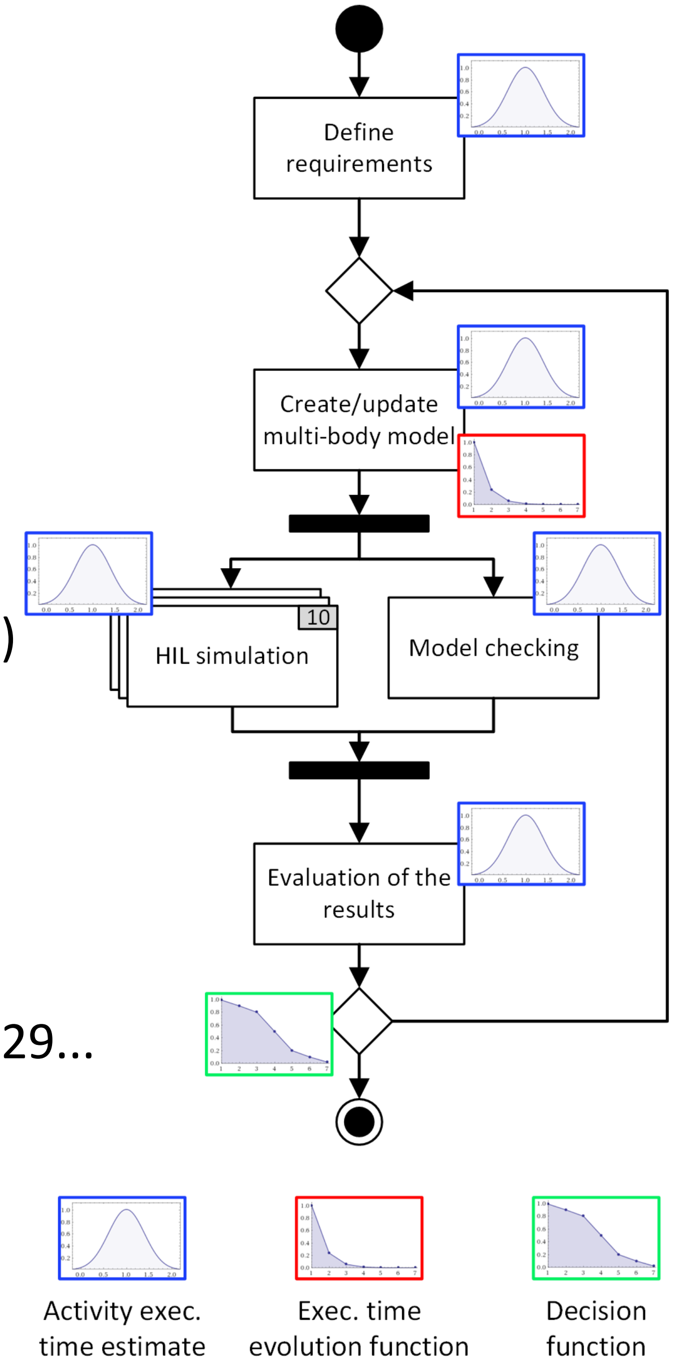


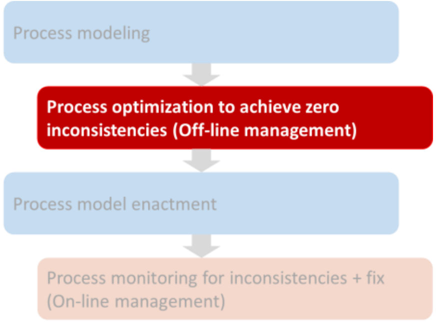


I. Dávid, Y. Van Tendeloo, H. Vangheluwe: „*Translating Engineering Workflow Models to DEVS for Performance Evaluation*”. In Proceedings of the 2018 Winter Simulation Conference, pp. 616-627. IEEE Press, 2018.

Calibration

- Activity execution time
  - Rule
    - Gaussian distribution
    - 80% of the estimations within the 20% error range: t(a)=N(μ, 0.15625μ)
- Execution time evolution
  - Rule
    - $e^{-1/0.7i}$ (i: iteration)
  - Resulting values
    - 1.0, 0.2397, 0.05743, 0.01376, 0.00329…
- Decision function
  - Manually set
  - 0.99, 0.9, 0.8, 0.5, 0.2, 0.1


Define requirements
Create/update multi-body model
HIL simulation
10
Model checking
Evaluation of the results
Activity exec. time estimate
Exec. time evolution function
Decision function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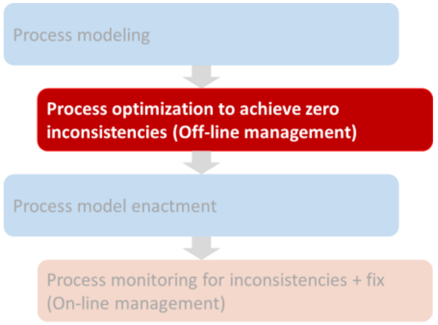
A catalogue of workflow patterns

- Wil van der Aalst (RWTH Aachen University)
- http://www.workflowpatterns.com/
- Patterns
  - Control (2003, rev. 2006)
  - Resource (2004)
  - Data (2004)
  - Exception handling (2006)
  - Presentation (2011)
  - Log imperfection (added in 2017)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  - Resource (2004)
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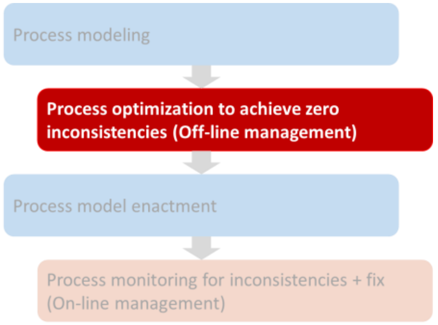

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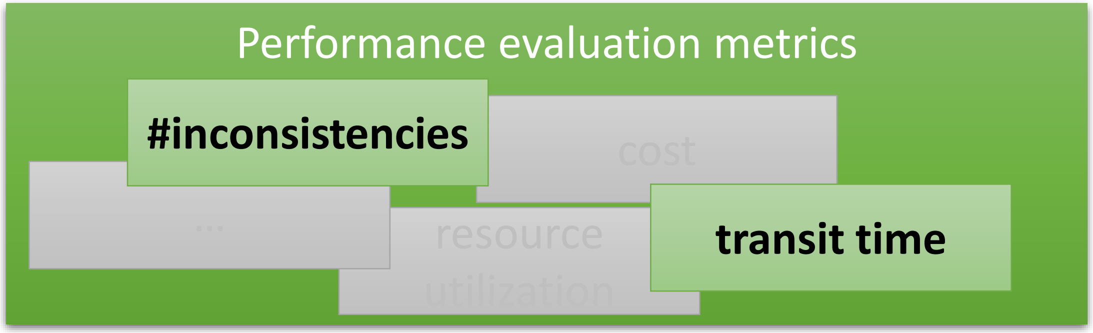


Performance evaluation metrics

#inconsistencies

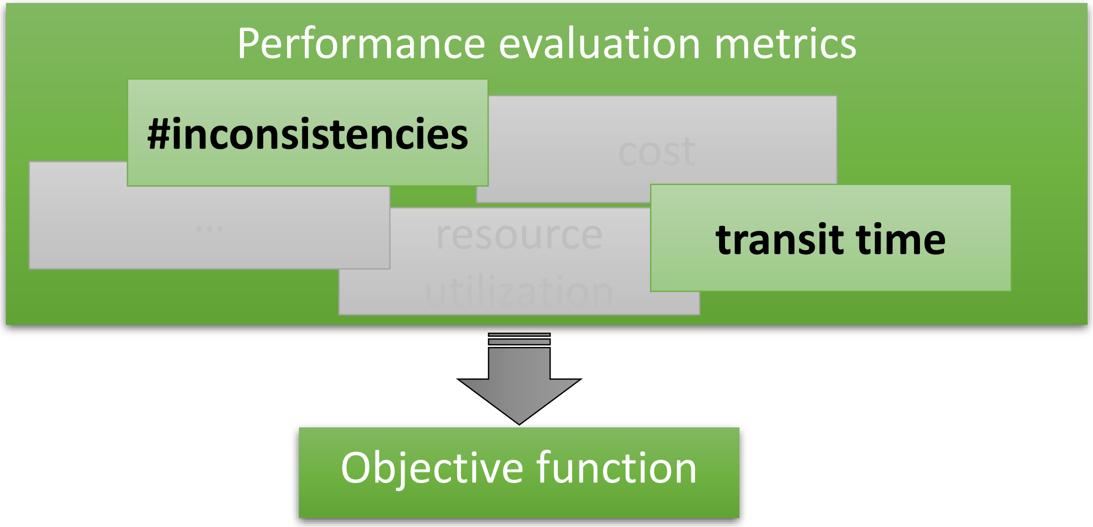
cost

...

resource utilization

transit time

Process space exploration



Performance evaluation metrics

#inconsistencies

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…

resource utilization

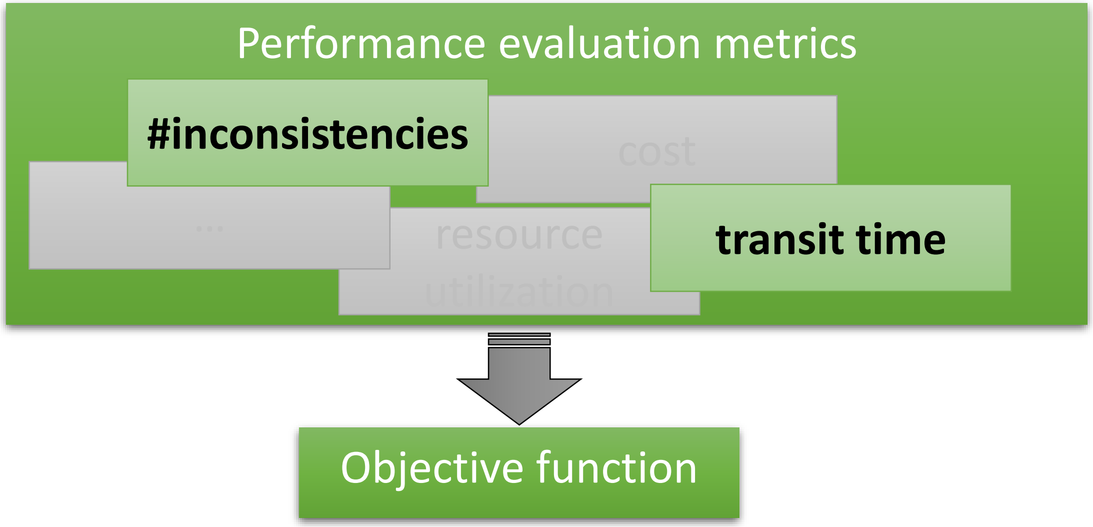
transit time

Objective function

Process space exploration

R_p Process rewrite rules

- Inconsistency management rules
- Performance improvement rules



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#inconsistencies

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Objective function

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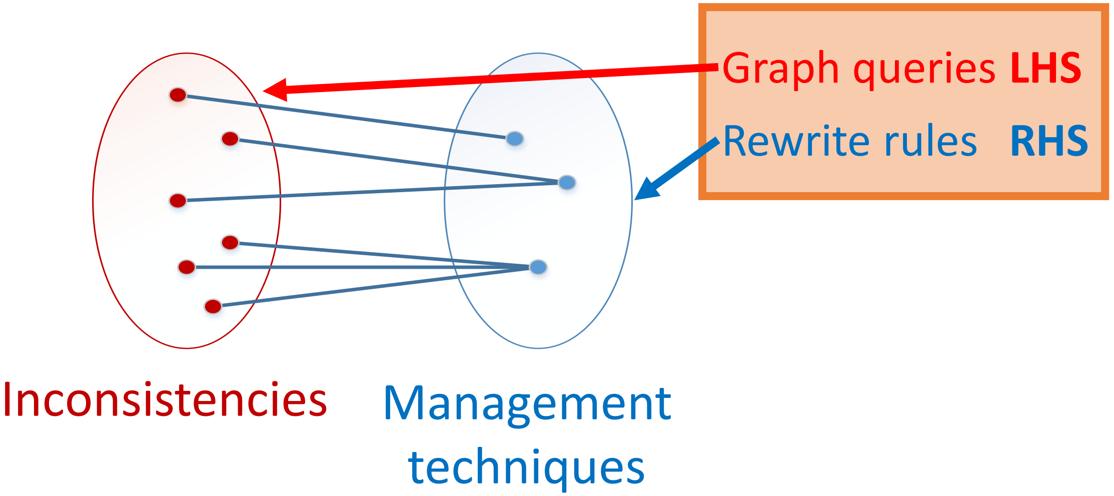
Performance evaluation metrics

- **#inconsistencies**
- cost
- …
- resource utilization
- **transit time**

Objective function

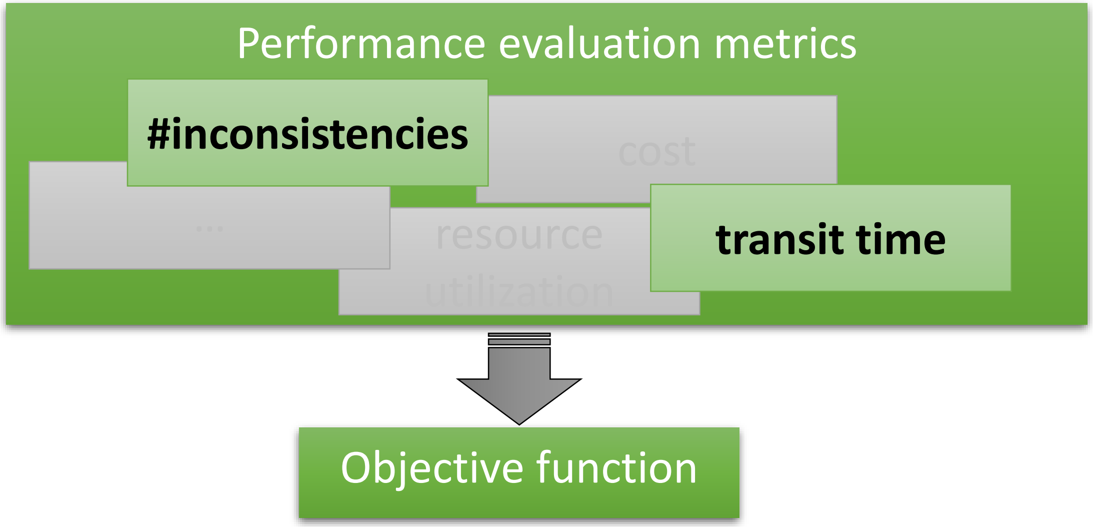


Applying an inconsistency management rule
==
executing a model transformation

Process space exploration

R_p Process rewrite rules

- Inconsistency management rules
- Performance improvement rules



Performance evaluation metrics

#inconsistencies

cost

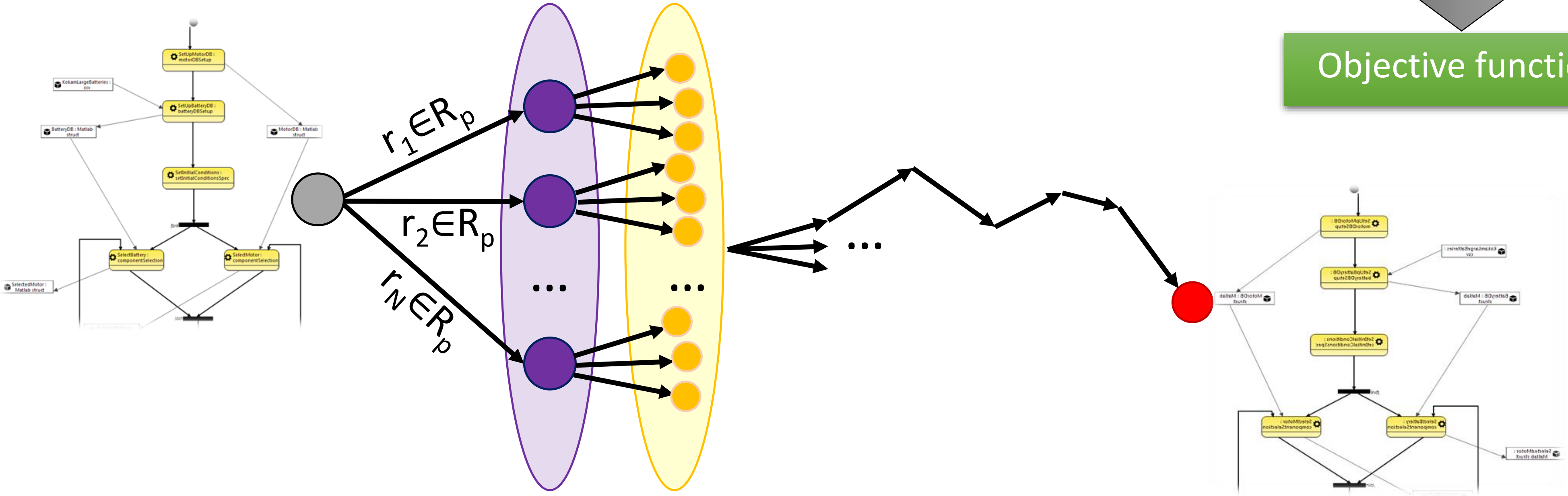
...

resource utilization

transit time

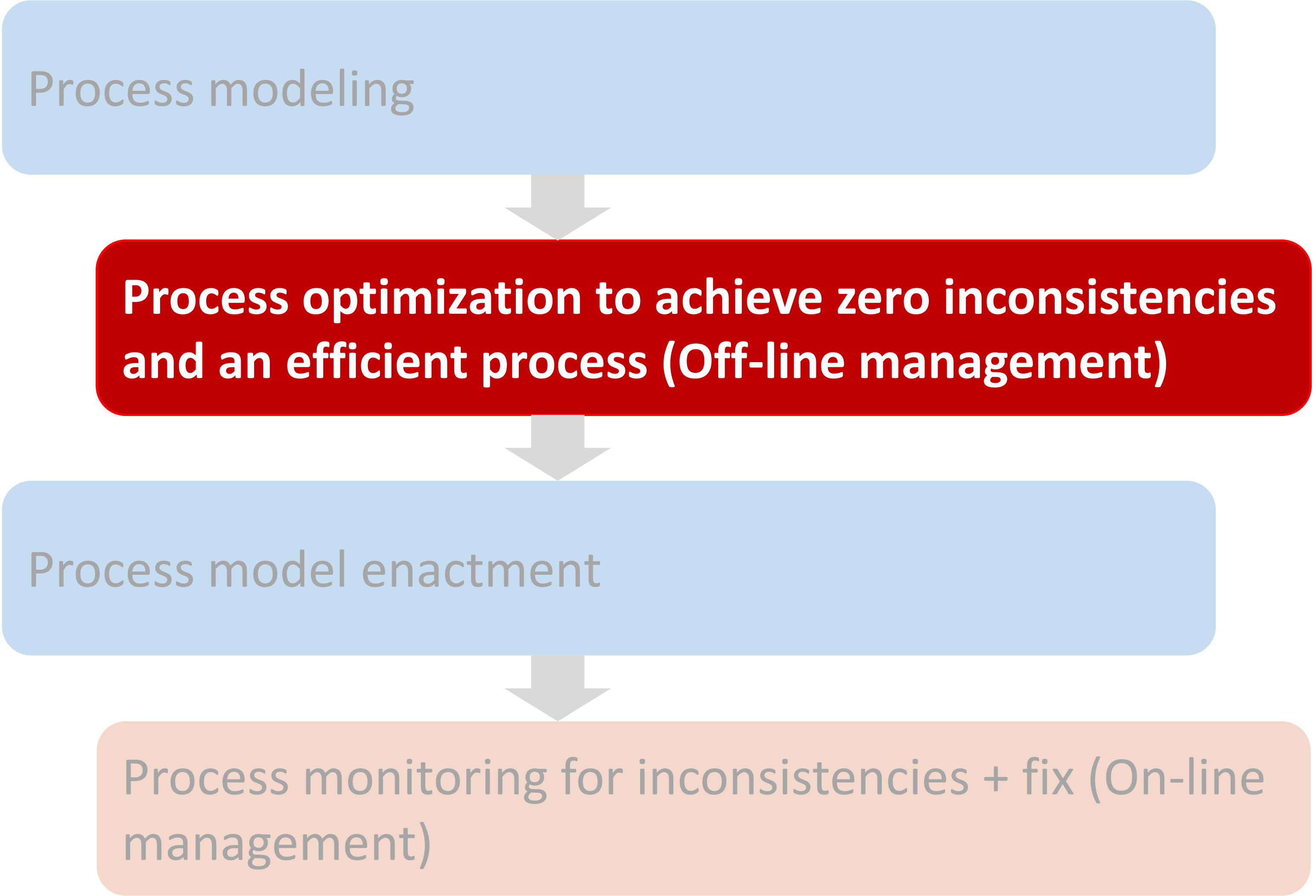
Objective function

$$P(1) = \cup_{\forall r \in R_p} r(P_0)$$



$$P(2) = \cup_{\forall r \in R_p,\, p \in P(1)} r(p)$$

Approach



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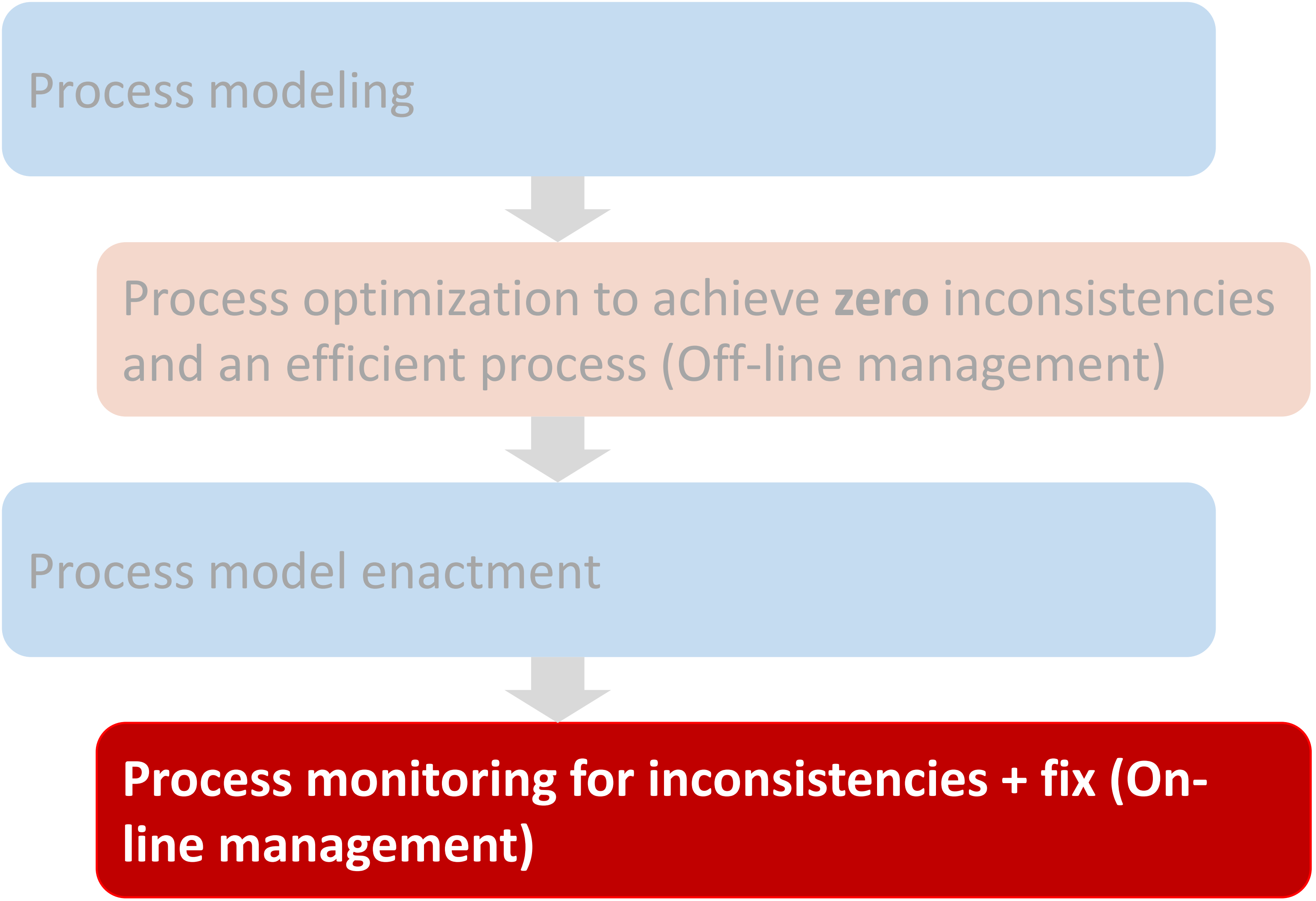
Approach



Process modeling

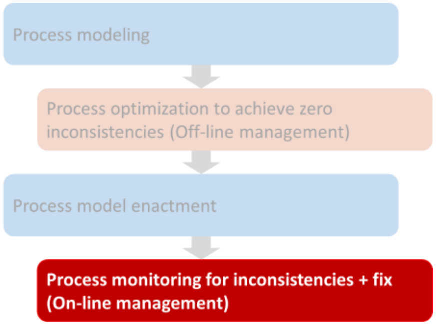
Process optimization to achieve **zero** inconsistencies and an efficient process (Off-line management)

Process model enactment

Process monitoring for inconsistencies + fix (On-line management)

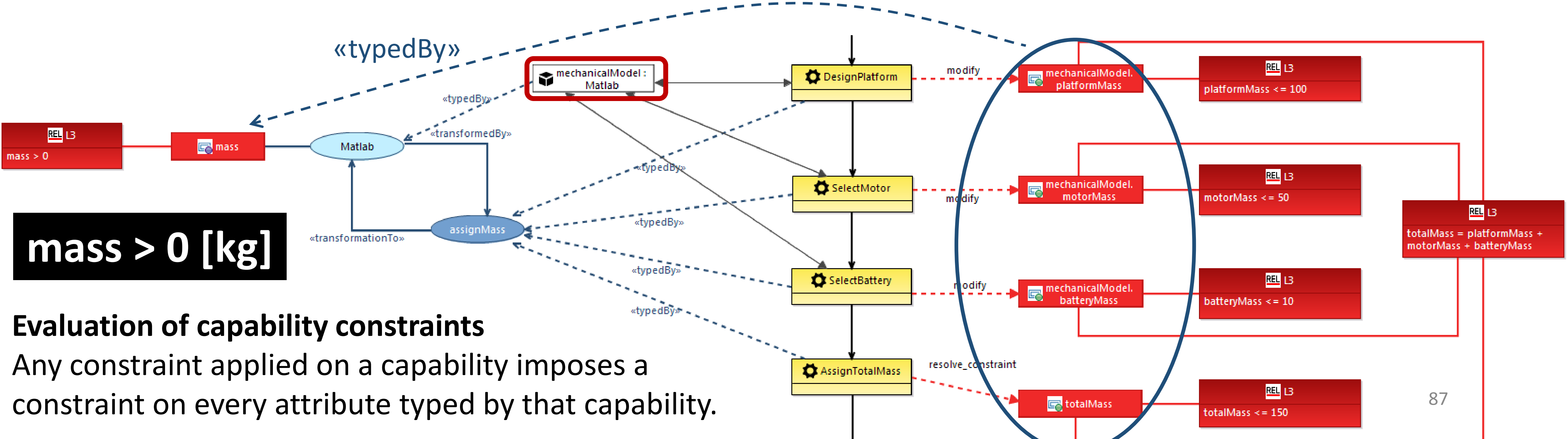
On-line management

SymPy



Process modeling
Process optimization to achieve zero inconsistencies (Off-line management)
Process model enactment
Process monitoring for inconsistencies + fix (On-line management)

- Continuous maintenance of constraints
  - Symbolic mathematical computation
- Forward/backward propagation of solution sets

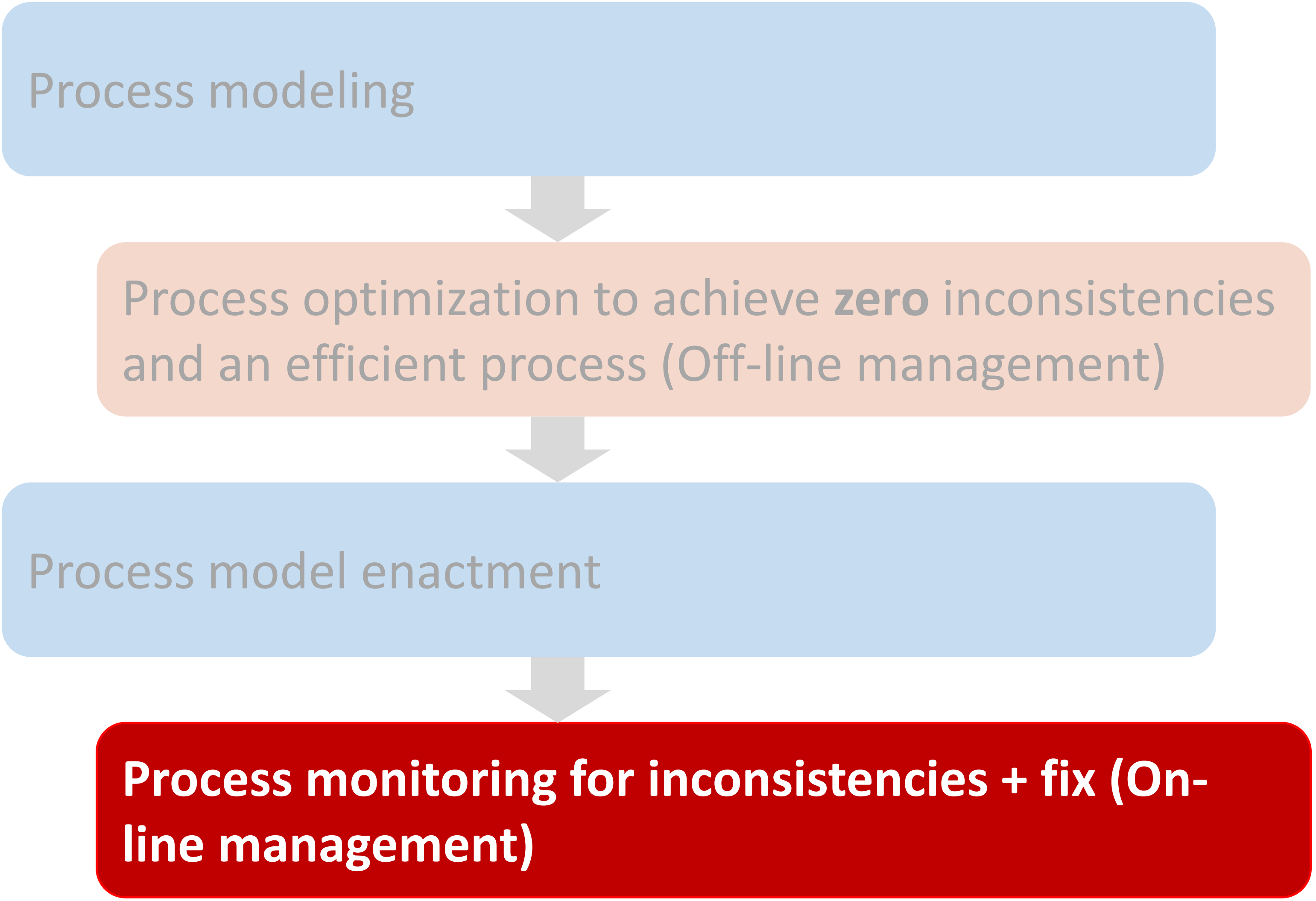


mass > 0 [kg]

Evaluation of capability constraints

Any constraint applied on a capability imposes a constraint on every attribute typed by that capability.

Approach



Process modeling

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Inconsistency Management

Theory/Foundations | Formalism | Additional enablers

Contributions

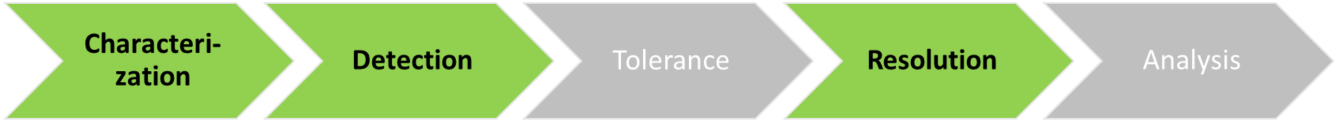
- Contribution 1: A **mapping study of the state of the art**, in order to identify the shortcomings of the currently available inconsistency management techniques.
- Contribution 2: A revised **definition of model (in)consistency**, in order to support the management of semantic inconsistencies.
- Contribution 3: A **process modeling formalism**, serving as the foundation for the rest of the contributions.
- Contribution 4: **Off-line management of inconsistencies** by the means of rule-based multi-objective process-space exploration.
- Contribution 5: **Enactment of the optimized process** by the means of explicit model transformations.
- Contribution 6: **On-line management of inconsistencies** by monitoring the process under enactment.
- Contribution 7: **DEVS-based simulation of process models** for evaluating the performance of the process candidates in the off-line management phase.
- Contribution 8: **External service integration** in processes under enactment, by explicit transformations over SCCD models.

Publications

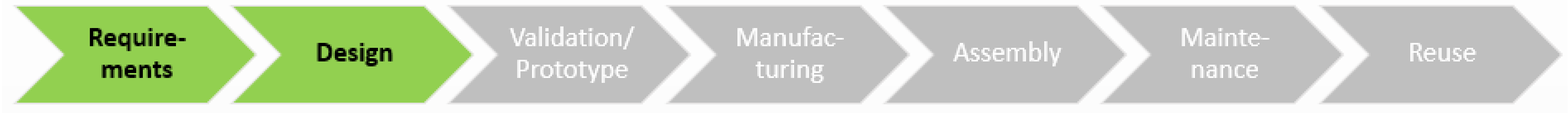
- **Translating Engineering Workflow Models to DEVS for Performance Evaluation**, I. Dávid, Y. Van Tendeloo, H. Vangheluwe. In Proceedings of the 2018 Winter Simulation Conference, pp. 616-627. IEEE Press, 2018.
- **Process-oriented Inconsistency Management in Collaborative Systems Modeling**, I. Dávid, J. Denil, H. Vangheluwe, 16th annual Industrial Simulation Conference, 2018.
- **A Multi-Paradigm Approach for Modelling Service Interactions in Model-Driven Engineering Processes**, S. Van Mierlo, Y. Van Tendeloo, I. Dávid, B. Meyers, A. Gebremichael, H. Vangheluwe, Model-driven Approaches for Simulation Engineering Symposium (MOD4SIM) -- Spring Simulation Multi-Conference, 2018.
- **Modeling and Enactment Support for Early Detection of Inconsistencies in Engineering Processes**, I. Dávid, B. Meyers, K. Vanherpen, Y. Van Tendeloo, K. Berx, H. Vangheluwe, 2nd International Workshop on Collaborative Modelling in MDE, 2017.
- **Towards Inconsistency Tolerance by Quantification of Semantic Inconsistencies**, I. Dávid, E. Syriani, C. Verbrugge, D. Buchs, D. Blouin, A. Cicchetti, K. Vanherpen, 1st International Workshop on Collaborative Modelling in MDE, 2016.
- **Engineering Process Transformation to Manage (In)consistency**, I. Dávid, J. Denil, K. Gadeyne, H. Vangheluwe, 1st International Workshop on Collaborative Modelling in MDE, 2016.
- **A Multi-Paradigm Modeling Foundation for Collaborative Multi-view Model/System Development**, I. Dávid, ACM Student Research Competition (SRC) MoDELS 2016.
- **Ontological Reasoning for Consistency in the Design of Cyber-Physical Systems**, K. Vanherpen, J. Denil, I. Dávid, P. De Meulenaere, P. J. Mosterman, M. Törngren, A. Qamar, H. Vangheluwe. CPPS 2016 - 1st International Workshop on Cyber-Physical Production Systems, 2016.
- **Patterns of inconsistency management in mechatronics - A survey**, I. Dávid, J. Denil, H. Vangheluwe. Technical report, 2015.
- **Towards Inconsistency Management by Process-Oriented Dependency Modeling**, I. Dávid, J. Denil, H. Vangheluwe. 9th International Workshop on Multi-Paradigm Modeling, 2015.

Potential future directions

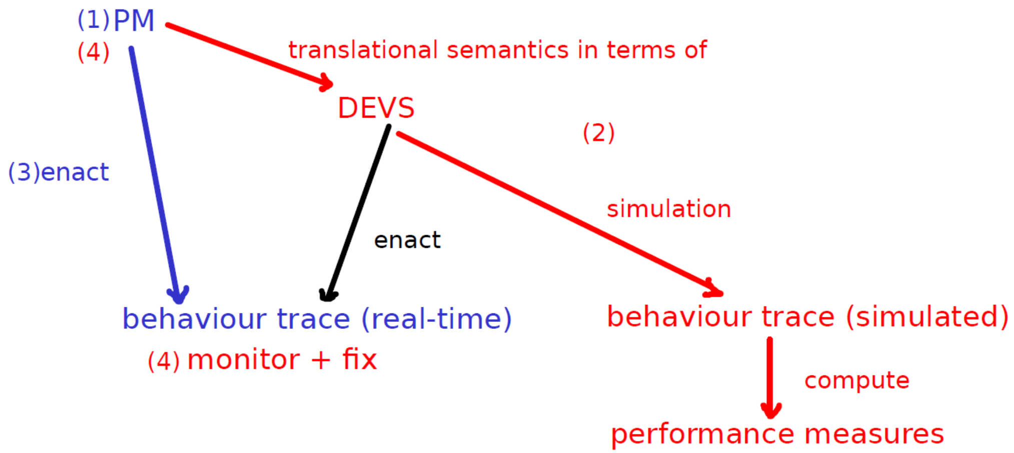
- Extending the scope to Tolerance and Analysis


Characteri-zation
Detection
Tolerance
Resolution
Analysis

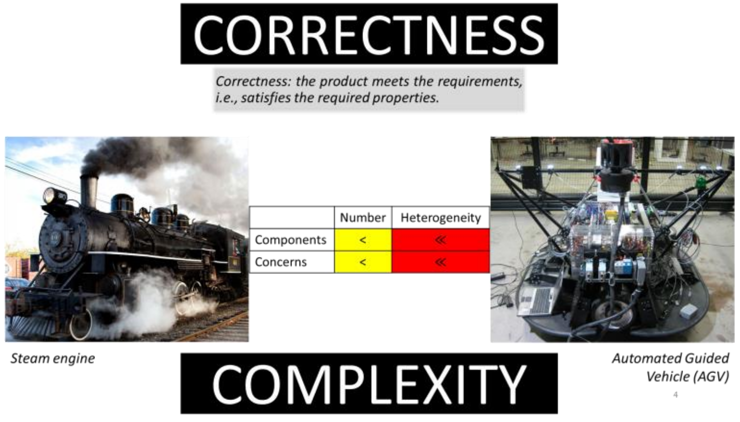
- Explicit reasoning about the trade-off between Prevention and Detect-and-Resolve
- Extending the scope of the technique over the entire engineering process


Require-ments
Design
Validation/ Prototype
Manufac-turing
Assembly
Mainte-nance
Reuse

- Enactment by DEVS
- Partial process inference


(1)PM
(4)
translational semantics in terms of
DEVS
(2)
(3)enact
simulation
enact
behaviour trace (real-time)
(4) monitor + fix
behaviour trace (simulated)
compute
performance measures

Conclusions



CORRECTNESS

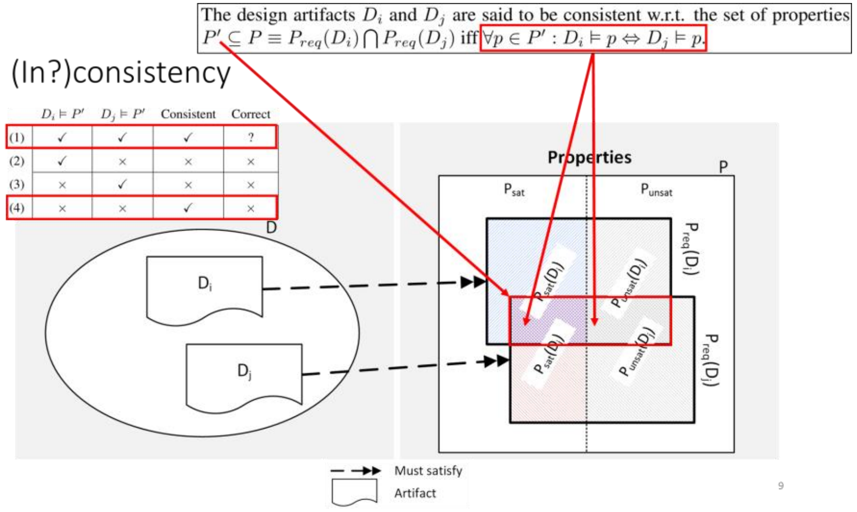
Correctness: the product meets the requirements, i.e., satisfies the required properties.

	Number	Heterogeneity
Components	<	≪
Concerns	<	≪

Steam engine

Automated Guided Vehicle (AGV)

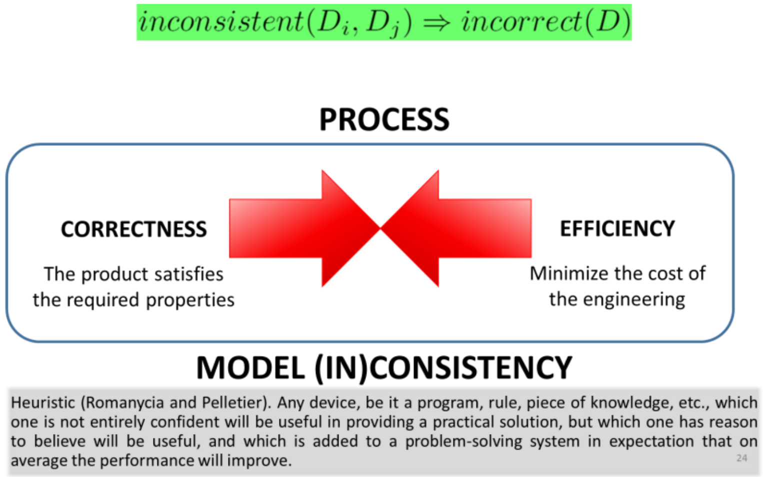
COMPLEXITY



The design artifacts D_i and D_j are said to be consistent w.r.t. the set of properties $P' \subseteq P \equiv P_{req}(D_i) \bigcap P_{req}(D_j)$ iff $\forall p \in P' : D_i \models p \Leftrightarrow D_j \models p$.

(In?)consistency

	$D_i \models P'$	$D_j \models P'$	Consistent	Correct
(1)	✓	✓	✓	?
(2)	✓	×	×	×
(3)	×	✓	×	×
(4)	×	×	✓	×



$inconsistent(D_i, D_j) \Rightarrow incorrect(D)$

PROCESS

CORRECTNESS

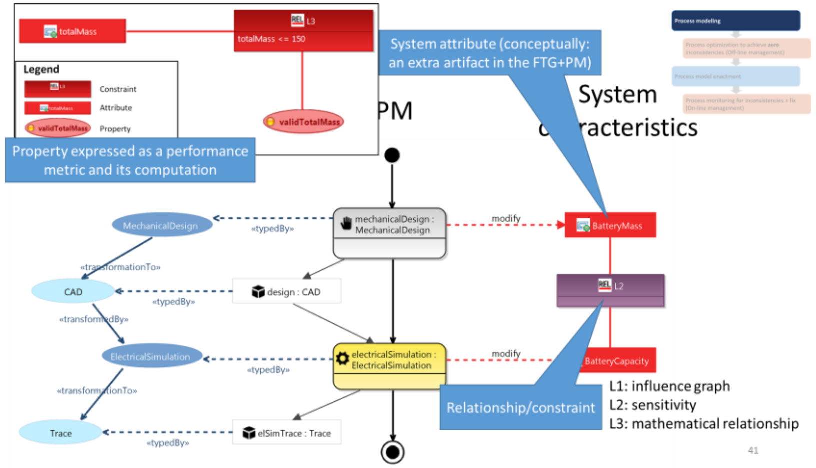
The product satisfies the required properties

EFFICIENCY

Minimize the cost of the engineering

MODEL (IN)CONSISTENCY

Heuristic (Romanycia and Pelletier). Any device, be it a program, rule, piece of knowledge, etc., which one is not entirely confident will be useful in providing a practical solution, but which one has reason to believe will be useful, and which is added to a problem-solving system in expectation that on average the performance will improve.

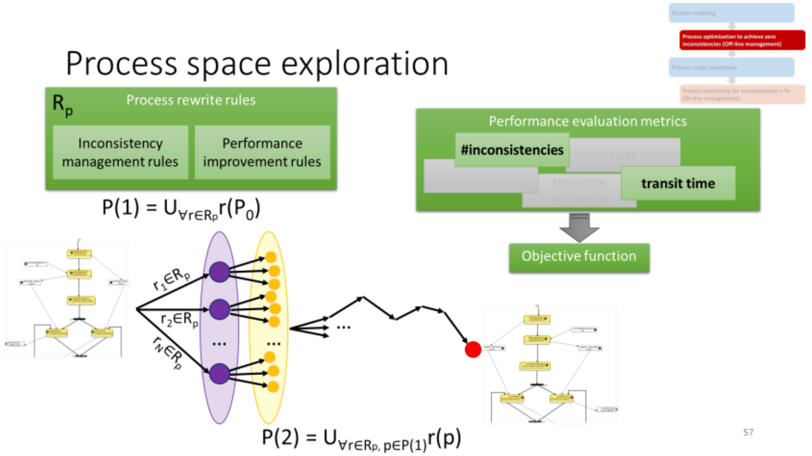


System attribute (conceptually: an extra artifact in the FTG+PM)

Property expressed as a performance metric and its computation

Relationship/constraint

L1: influence graph
L2: sensitivity
L3: mathematical relationship



Process space exploration

R_p
Process rewrite rules
Inconsistency management rules
Performance improvement rules
Performance evaluation metrics
#inconsistencies
cost
resource
transit time
Objective function
$r_1 \in R_p$
$r_2 \in R_p$
$r_N \in R_p$
...
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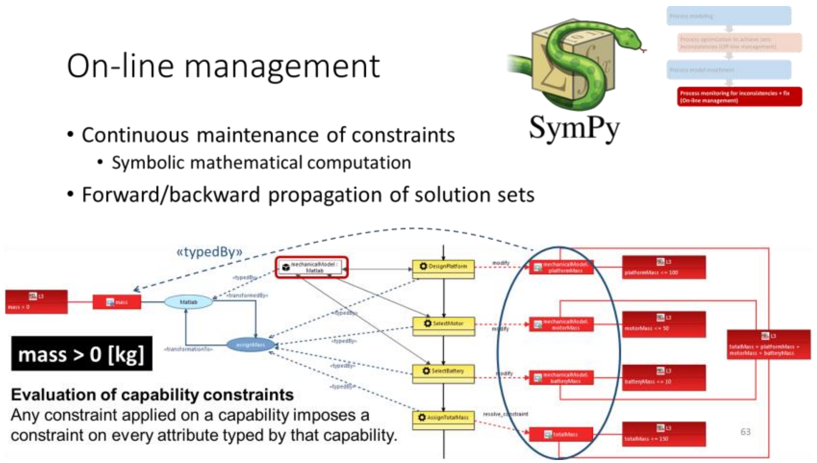
57

$P(1) = \mathrm{U}_{\forall r \in R_p} r(P_0)$

$P(2) = \mathrm{U}_{\forall r \in R_p,\, p \in P(1)} r(p)$



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