Mastering Variability in Software-intensive Cyber-Physical Production Systems

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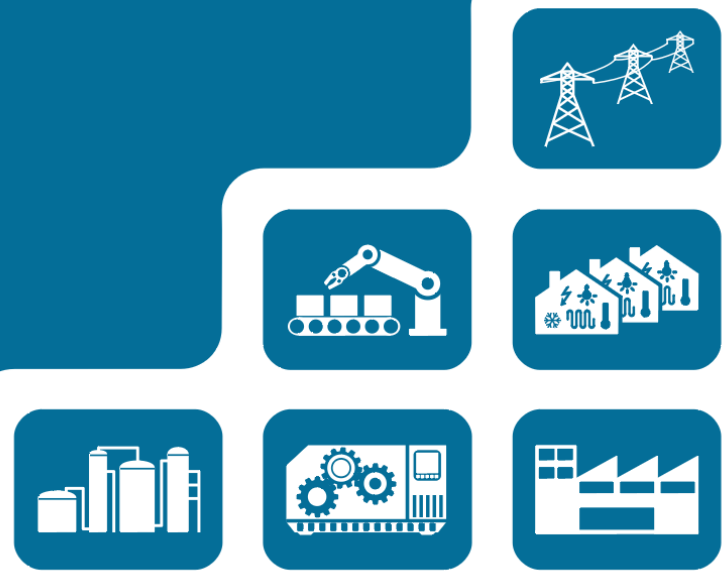
Christian Doppler Lab VaSiCS
LIT | Cyber-Physical Systems Lab
Johannes Kepler University Linz

PRIMETALS TECHNOLOGIES
ober österreich
Federal Ministry
Republic of Austria
Digital and
Economic Affairs



LIT Cyber-Physical Systems Lab

https://www.jku.at/lit/cps-lab

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Cyber-Physical Systems

- Term emerged in 2006, coined by Helen Gill at the National Science Foundation in the USA

- "*Cyber-physical systems (CPS) are engineered systems that are built from, and depend upon, the* ***seamless integration of computation and physical components***."

- "*Cyber-physical systems are everywhere —and are operated by everyone*" (M. Broy)

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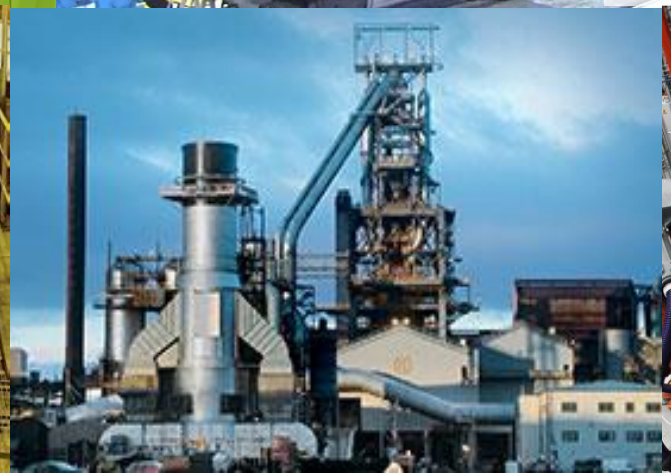
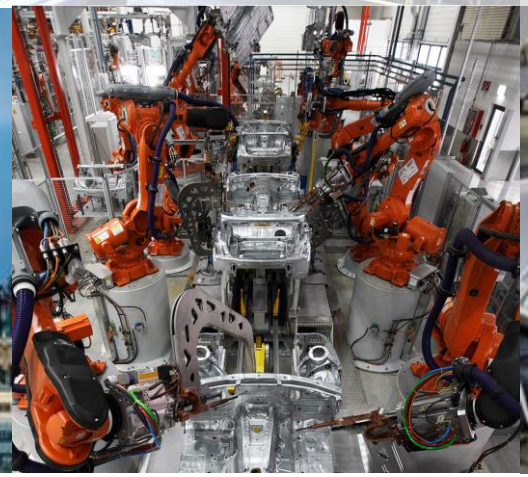
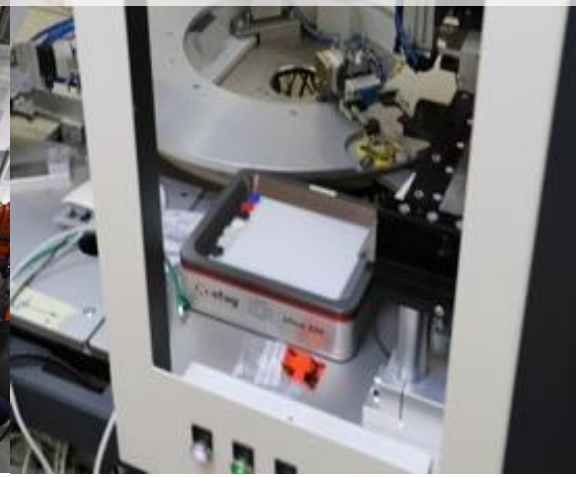
Cyber-Physical Production Systems (CPPS)

- CPPS reflect the characteristics of CPS to the production domain [Biffl et al. 2017]
- Increasing availability and use of distributed industrial CPS devices and systems (Industry 4.0) [Harrison et al. 2016]





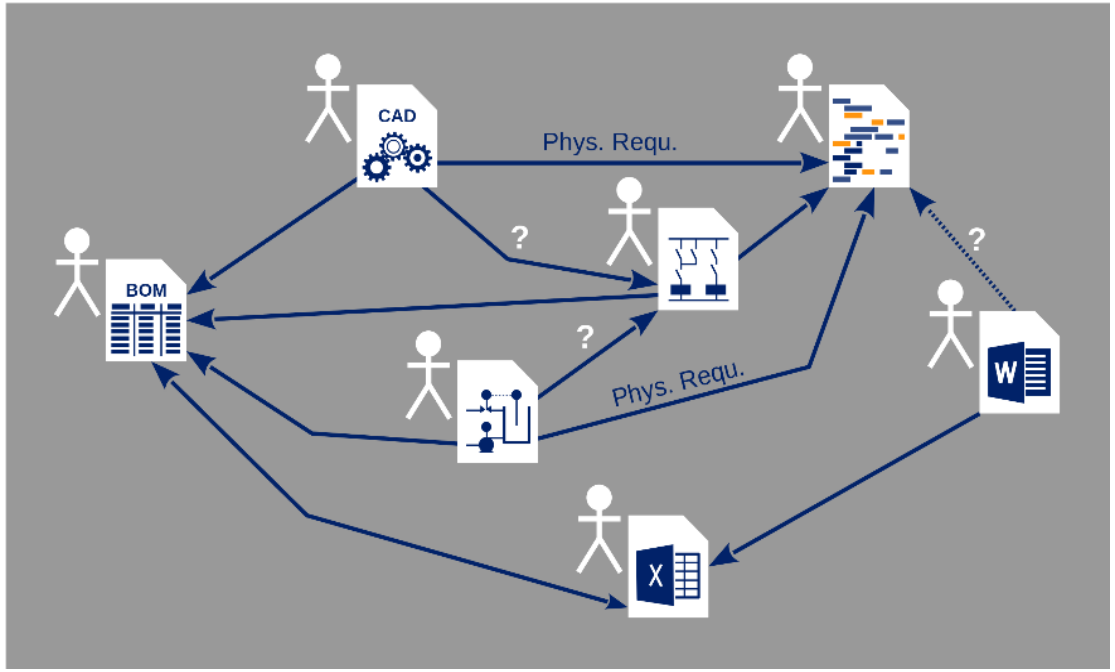


CP(P)S and Variability

- SiCPPS are **highly variable systems of systems** [Nielsen et al. 2015] that **frequently evolve**

- Variability* regards **hardware** and **software** artifacts, development **processes**, **disciplines** (mechanical, electrical, software engineering) and **methods** and **tools**

- Hardware is still one of the most significant **drivers** for variability in industry, directly followed by market pressure for customization [Berger et al. 2020]



* "*the ability of a system or artefact to be efficiently extended, changed, customized or configured for use in a particular context" [Capilla et al. 2013]*

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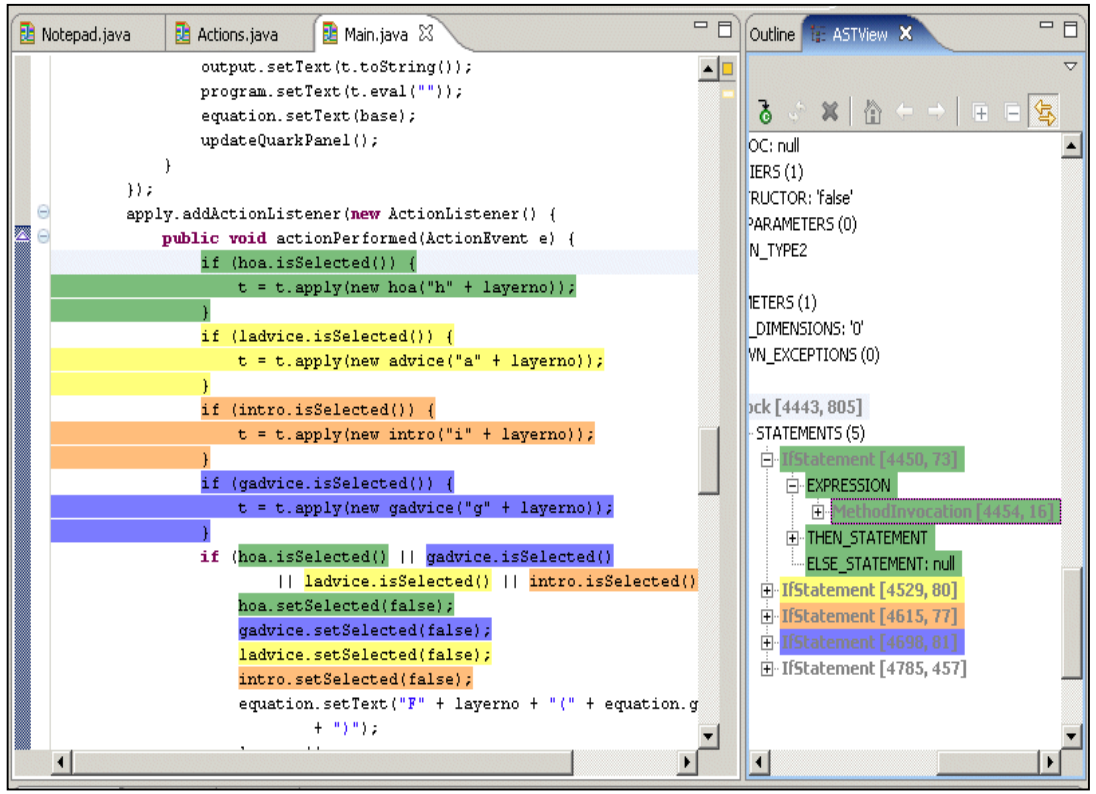
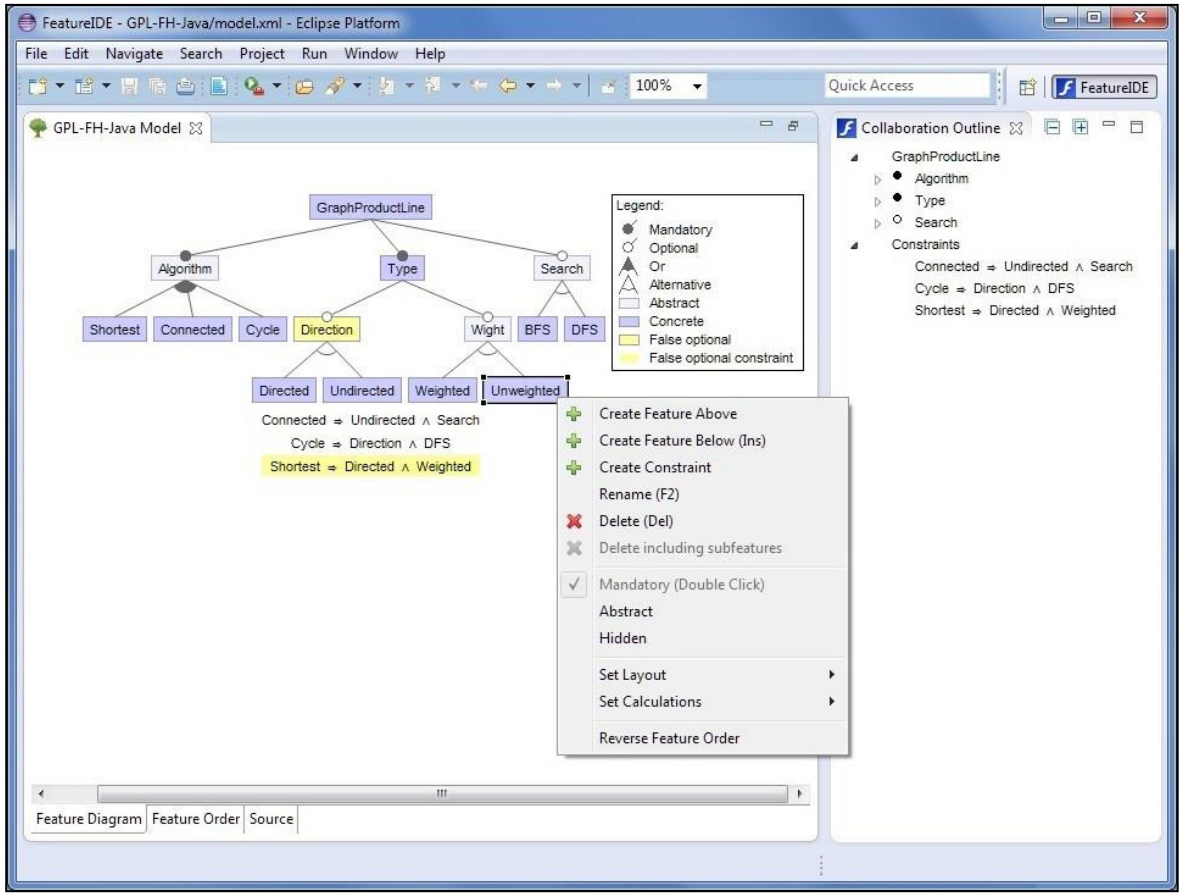
The Bottom-up vs. the Top-down View on Variability

Implementing Variability



(c) http://ckaestne.github.io/CIDE/

Analyzing and Modeling Variability



(c) http://www.featureide.com/

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The Bottom-up vs. the Top-down View on Variability

Implementing Variability

- Modularization / Module Replacement (e.g., Mechatronic Modules, Software Components)
- (Software Project) Templates / Typicals / (Function Block) Types
- Configuration Parameters
- Conditional Execution (If/Switch Statements (can depend calculations or parameters))
- Conditional Compilation (in C: IFDefs)
- Cloning (aka Clone & Own, Copy/Paste)
- Object-orientation (Polymorphism, Inheritance, …)
- Microservices/SOA
- …

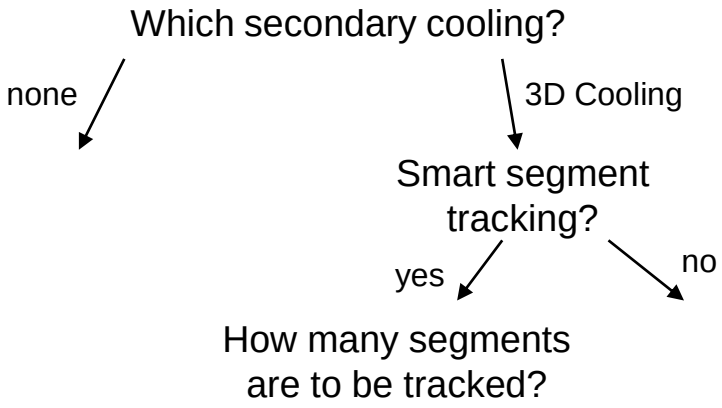
Analyzing and Modeling Variability

- **Feature-oriented** [Kang et al. 1990, Czarnecki and Eisenecker 2000]
- **Decision-oriented** [Synthesis 1991, Schmid and John 2004, Dhungana, Rabiser, Grünbacher 2011]
- Delta-oriented approaches [Schaefer et al. 2010]
- UML-based [Gomaa 2005, Jézéquel 2006]
- Orthogonal approaches [Pohl et al. 2005]
- Textual approaches [ter Beek et al. 2091]
- CVL [Haugen et al. 2013]
- …

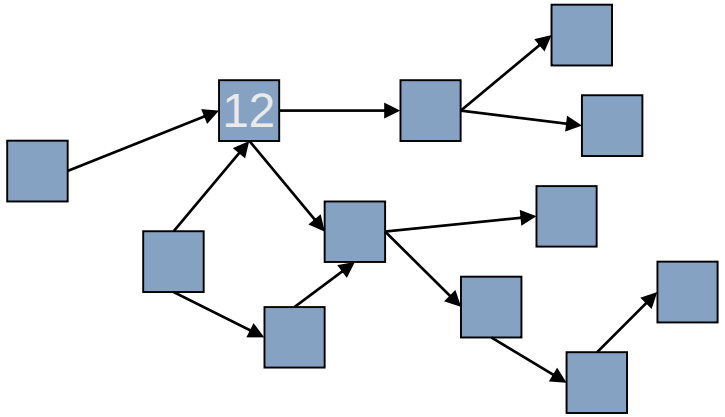
Past Work: Decision-Oriented Variability Modeling

DOPLER
Decision-Oriented Product Line Engineering for effective Reuse

Decisions



Assets



- Selection
  - which assets?
- Configuration
  - asset parameters

D. Dhungana, P. Grünbacher, and R. Rabiser: ***The DOPLER Meta-Tool for Decision-Oriented Variability Modeling: A Multiple Case Study****. Automated Software Engineering, vol. 18(1), 2011.*

R. Rabiser, P. Grünbacher, and M. Lehofer: A Qualitative Study on User Guidance Capabilities in Product Configuration Tools. Proc. of the 27th IEEE/ACM International Conference Automated Software Engineering (ASE'12), Essen, Germany, ACM, 2012, pp. 110-119.

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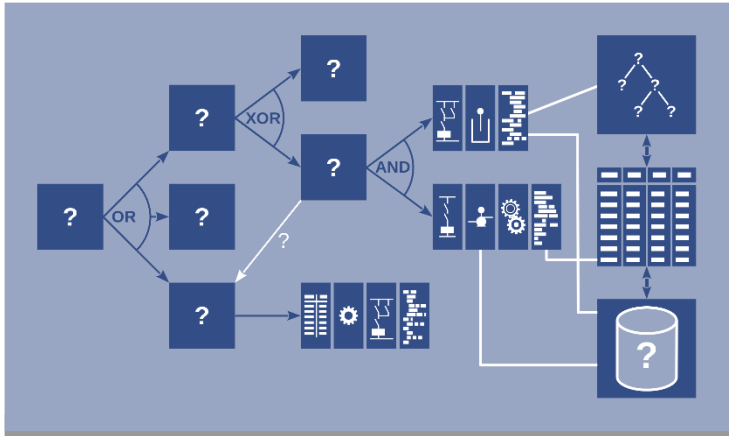
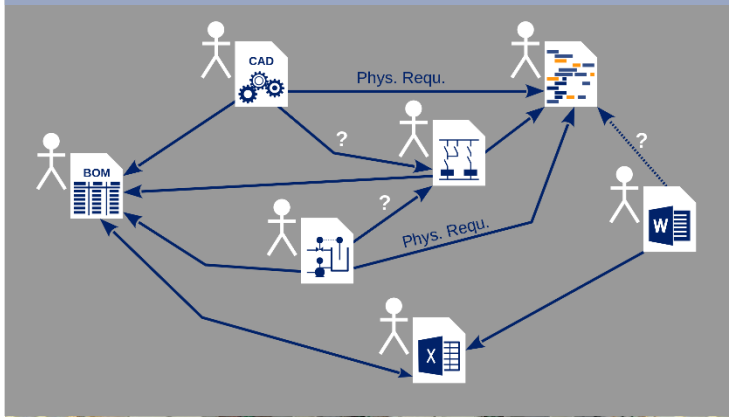
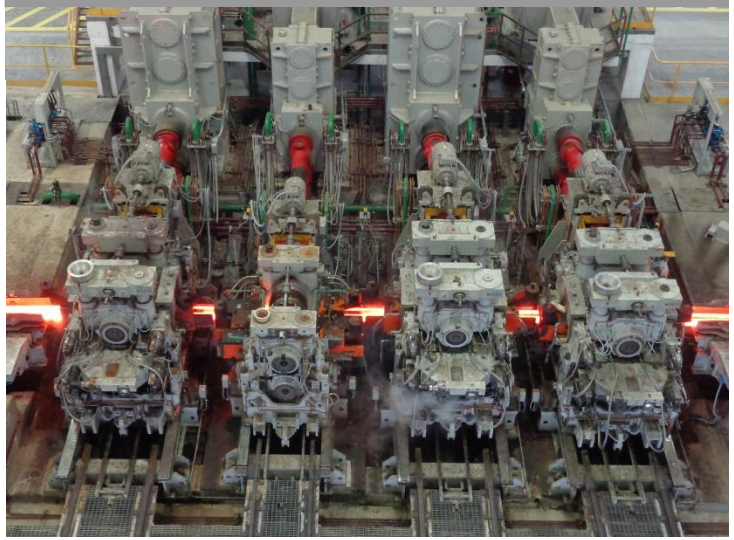
Current Work: Christian Doppler Lab VaSiCS (2/2021-1/2028)

- **VaSiCS: Mastering Variability in Software-intensive Cyber-Physical Production Systems**
  - CPPS variability modeling approach
  - automatically mine and model variability
  - support configuring and generating CPPS target artifacts
  - support CPPS roundtrip/evolution







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https://www.jku.at/cdl-vasics/

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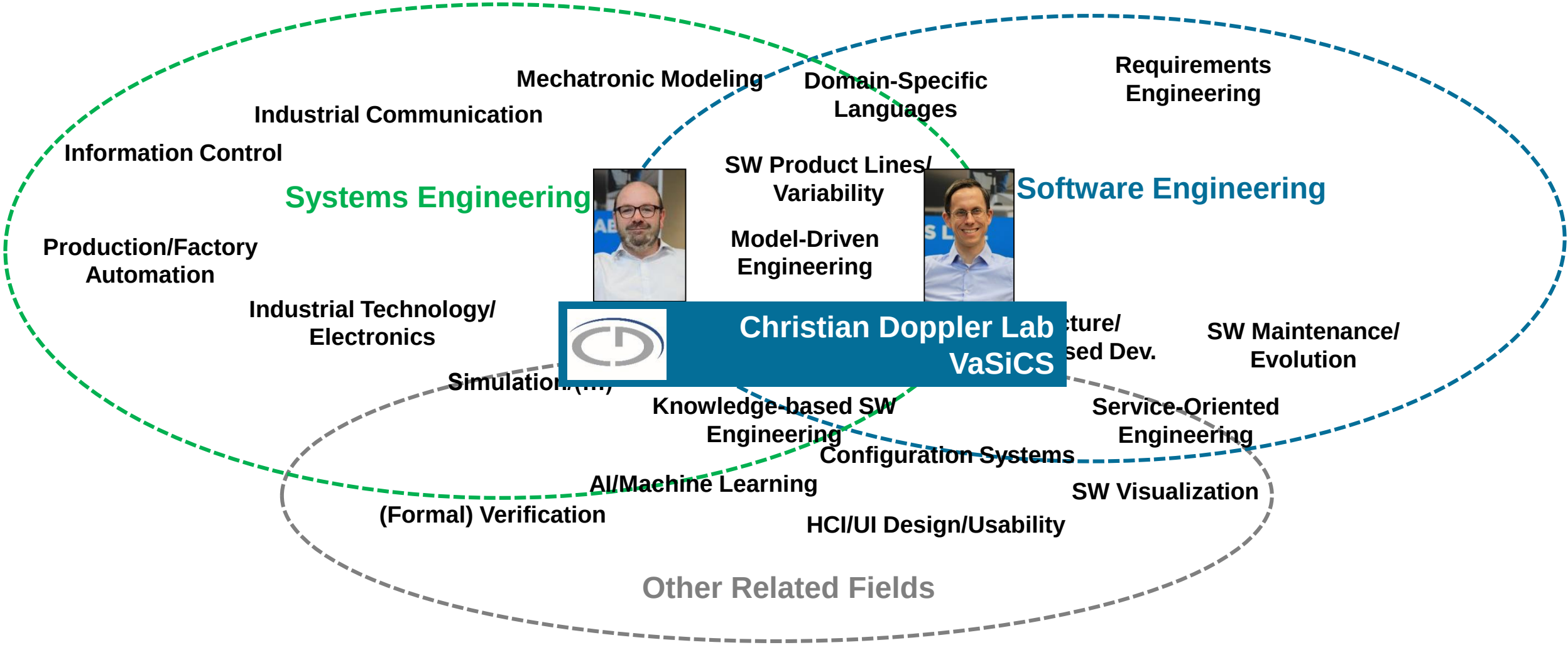
Scientific Landscape relevant for the CDL



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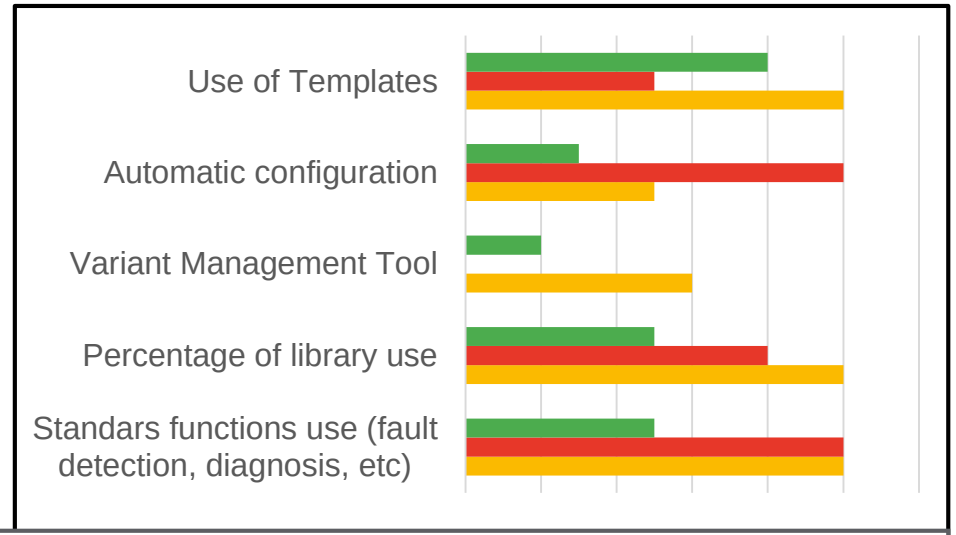
First Results

State of the Practice Analyses (Antonio Gutierrez)

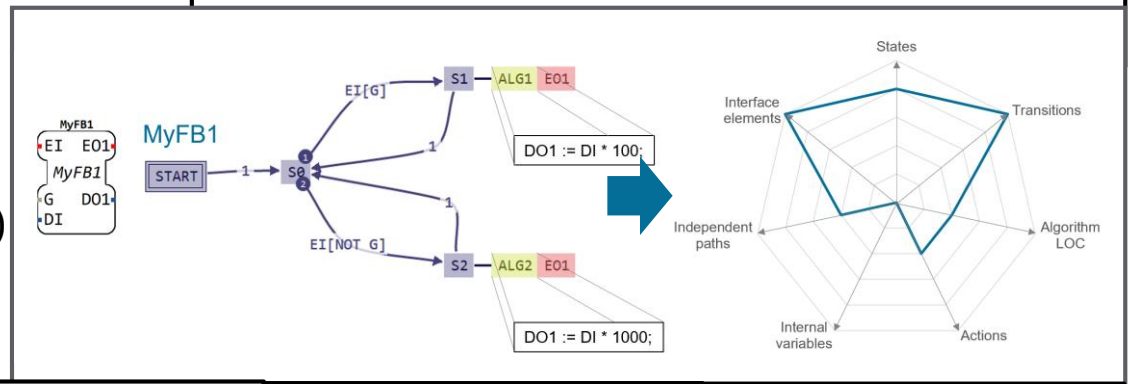
- **e.g., Survey I4.0 (coop. with TUM) and SiCPPS Variability**

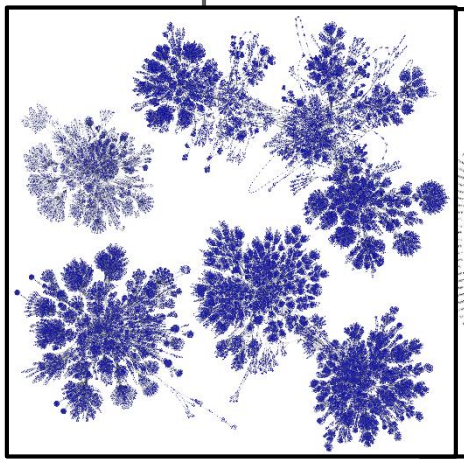


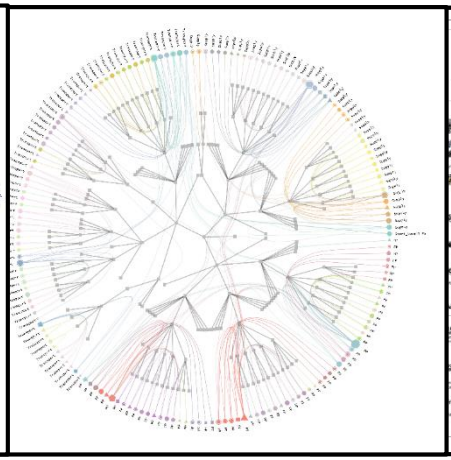
State of the Art Analyses

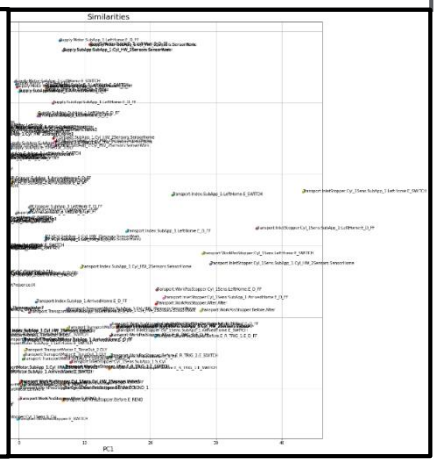
Approaches to Master Variability in SiCPPS

- **Better SiCPPS SW Design** (Lisa Sonnleithner, Ernst Blecha)
  - Metrics, **Bad Smells**, Design Patterns for IEC 61499
- **SiCPPS Variability Modeling with Deltas** (Hafiyyan Fadhlillah, Philipp Bauer)
- Graph-based/ML-based Analysis for
  - Variability Mining (Markus Unterdechler)
  - Analyzing Modularization (Markus Unterdechler)
  - Clone Detection (Elene Kutsia)









https://www.jku.at/en/cdl-vasics/research/publications

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Better SiCPPS SW Design/Architectures

Bad Smells

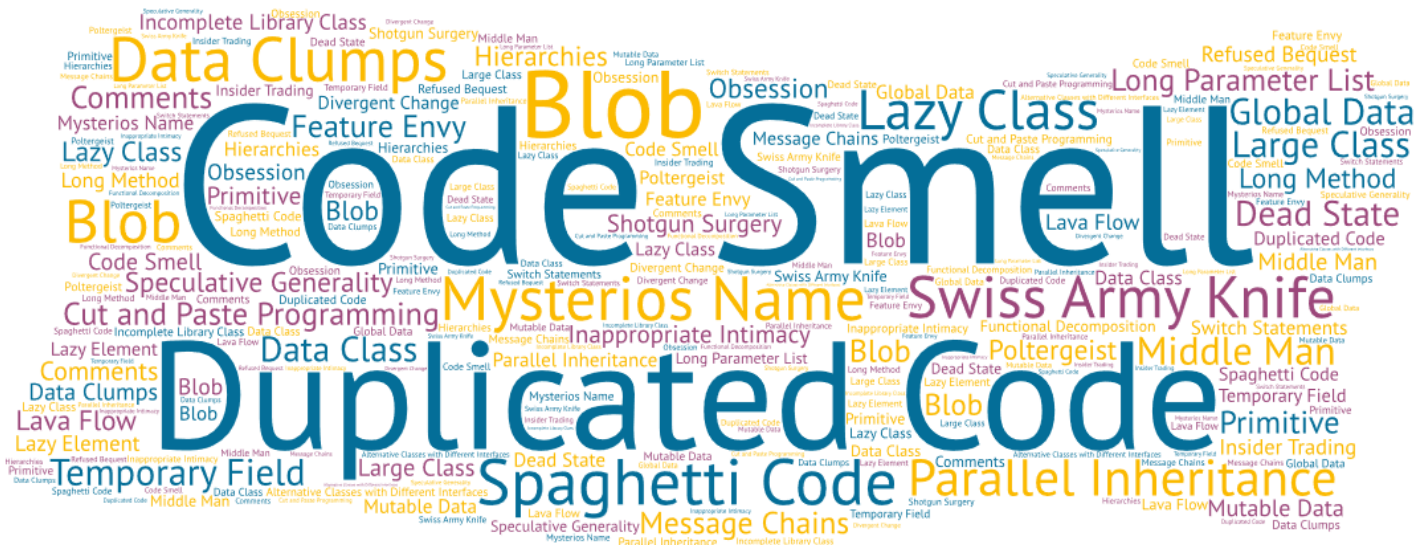
Certain suboptimal structures or patterns in software

Bad Smells lead to

Maintenance issues, low software quality, poor understandability, etc.

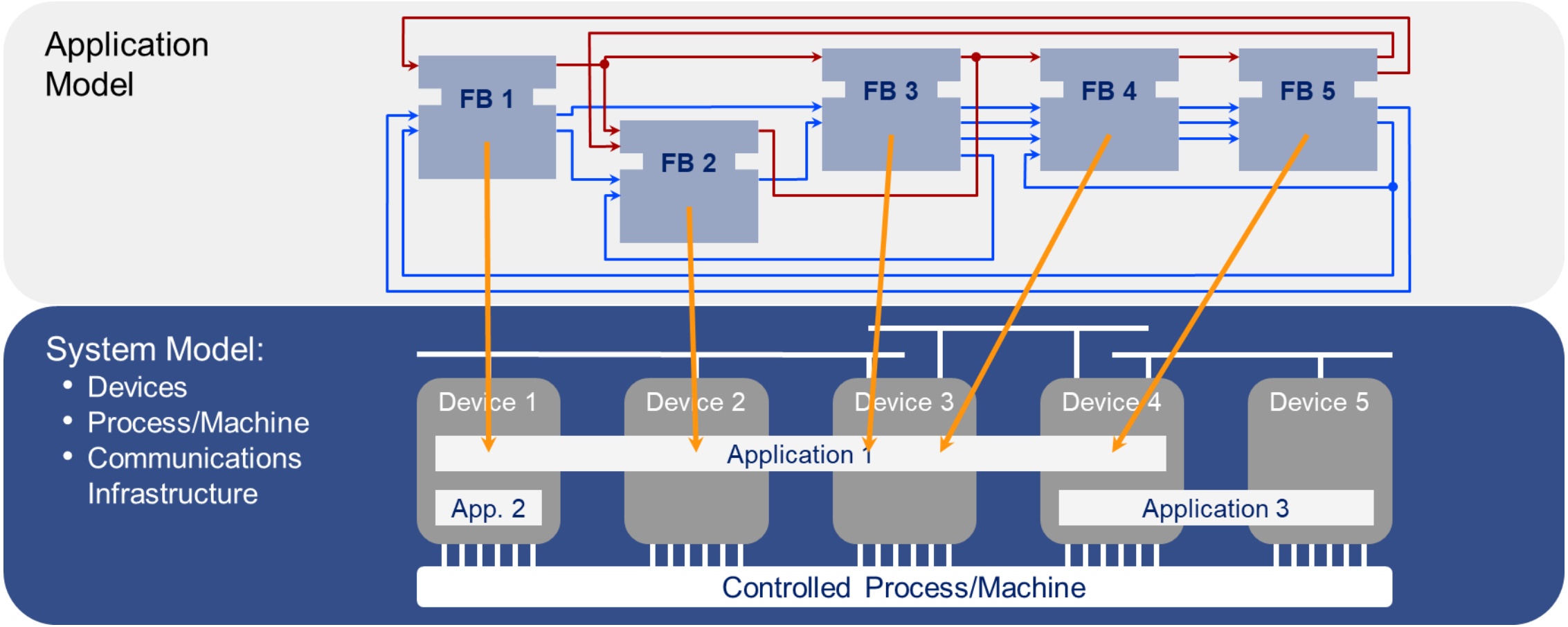
Our goal

Identifying IEC 61499 Bad Smells



IEC 61499

Domain-specific Modeling Language for Distributed Industrial Process Measurement and Control Systems



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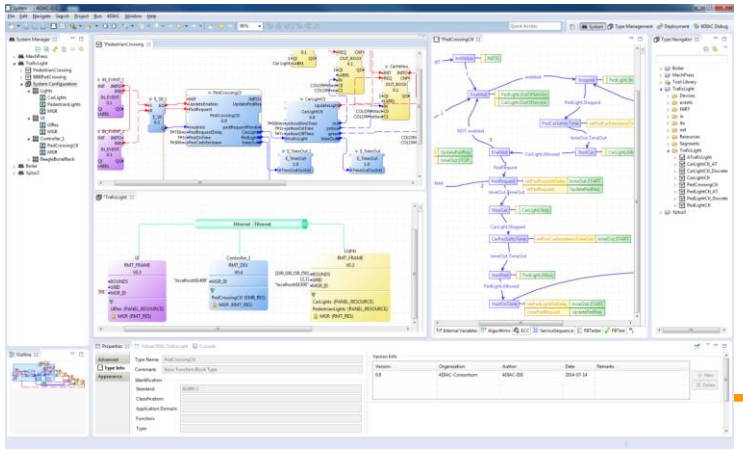
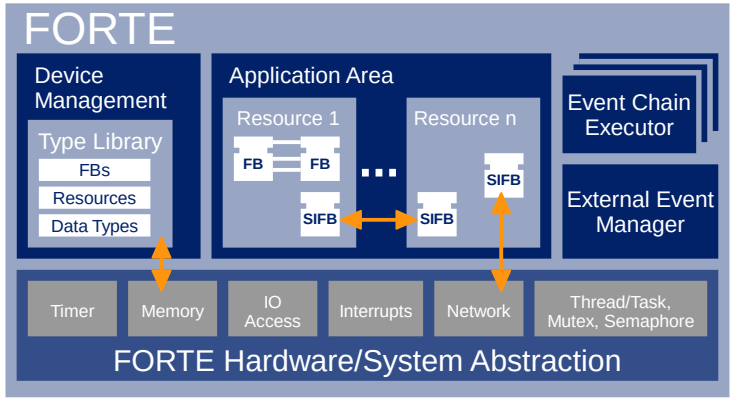
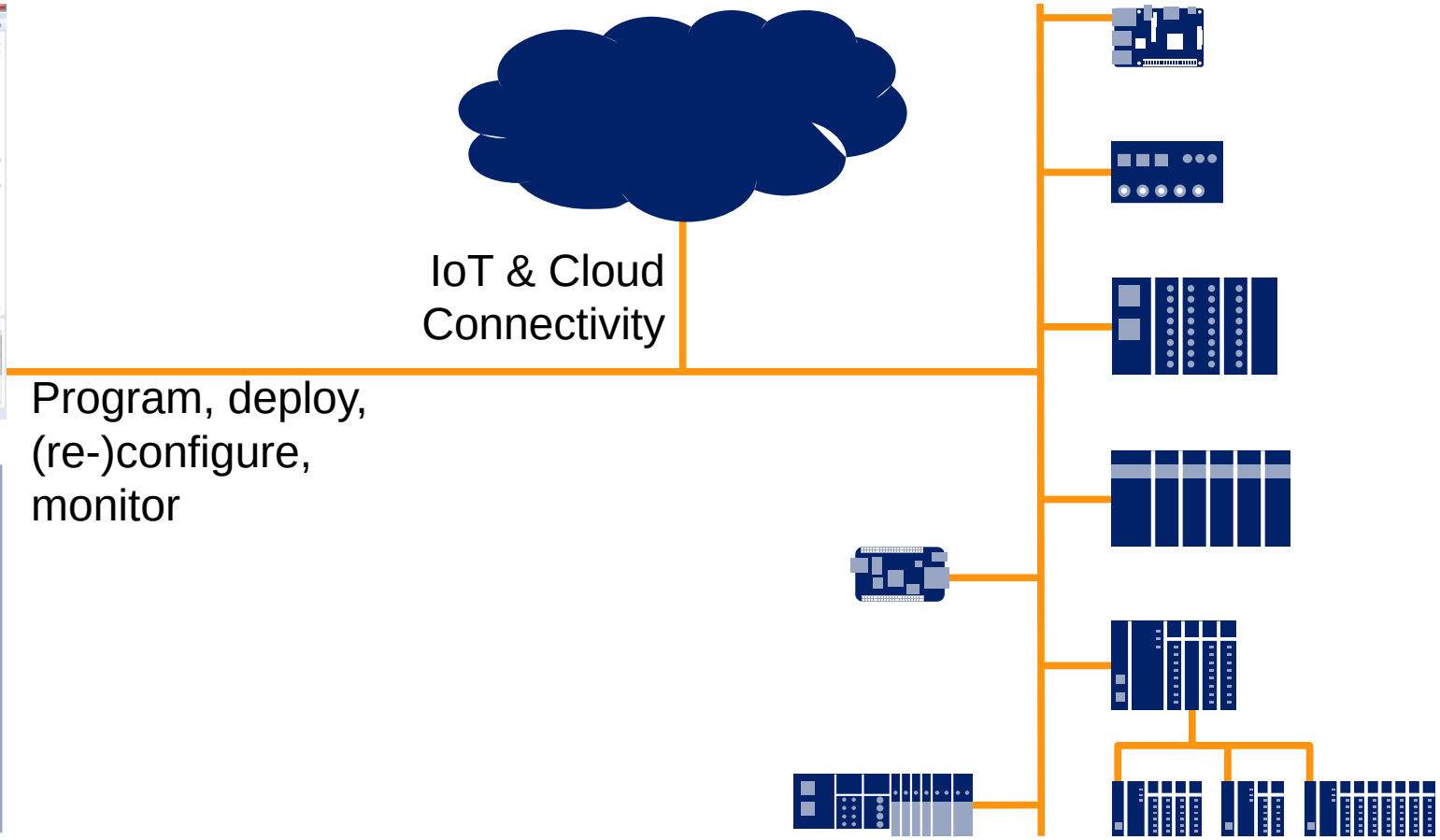
Eclipse 4diac







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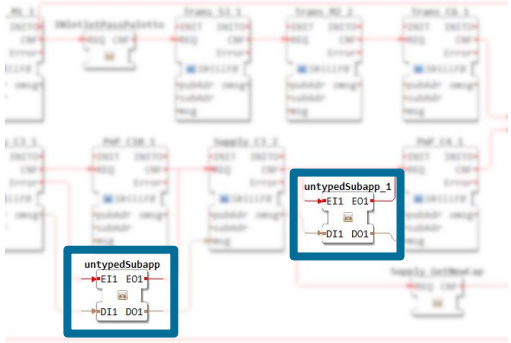
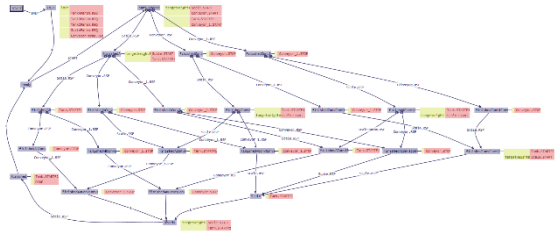
Proposed Bad Smells Catalog

Name	Level	Description	Impl.
Duplicated Code	ALL	The same or similar code appearing more than once.	N
Long Algorithm	FB	An algorithm that is too long and complex.	N
Large Type	FB	An FB type that is too large and complex.	N
Large Interface	FB	Too many interface elements.	N
Divergent Change	FB	One change leading to many changes within the same FB type.	N
Shotgun Surgery	FB	One change leading to changes in many different FB types.	N
Feature Envy	ALL	An IEC 61499 component having high cohesion to another that should not be coupled tightly.	N
Data Clumps	FBN	A group of interface elements that always appear together.	N
Lazy Element	ALL	An IEC 61499 component without purpose (e.g., CFB only containing one FB).	N
Dead State	ECC	State (except start state) which does not have any input transitions or to which a path cannot be found from the EC initial state by following the directed links.	Y
Dead Transition	ECC	Transition with lower priority than the 1 transition condition	Y
Dead FB	FB	FB (except start FB) which does not have any input event connections.	Y
Terminal State	ECC	State that is reachable, but which does not have any outgoing EC transitions.	Y
Unused Event	FB	Event input/output of the FB type containing the ECC that is not used in any EC transitions.	Y
Unused Data	FB	When the particular input event is connected, the associated data input is unconnected or not configured.	Y
Mutable Data	ALG	The algorithm writes on a data input.	N
Dead Event	FB	An event that is not used in the transition condition of any stable ECC state and is thus always ignored.	N

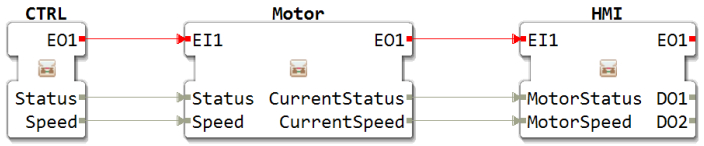
Duplicated Code



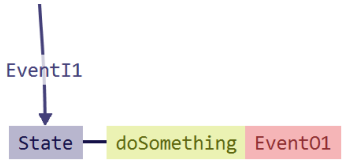
Large Type



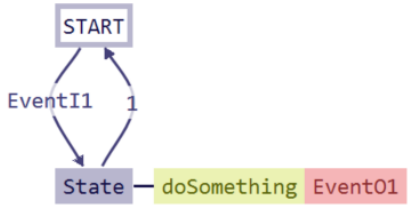
Data Clumps



Terminal State



Lazy Element



Lisa Sonnleithner, Sándor Bácsi, Michael Oberlehner, Elene Kutsia, and Alois Zoitl: Do you smell it too? Towards IEC 61499 Bad Smells. ETFA, IEEE, 2021.

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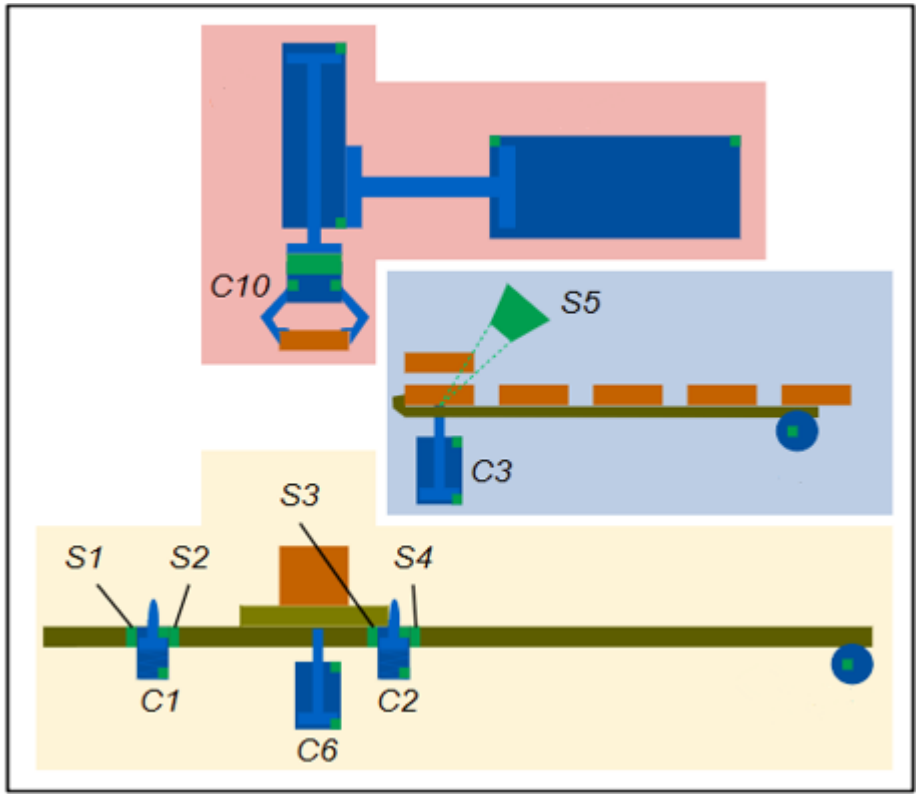
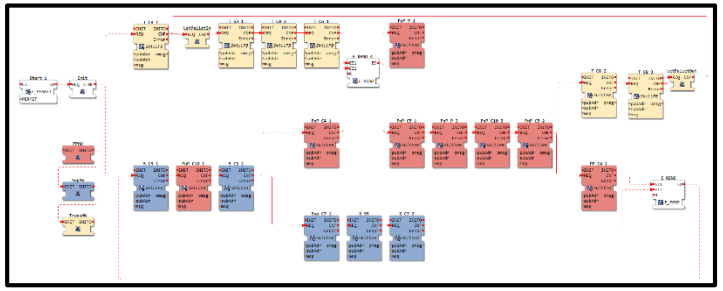
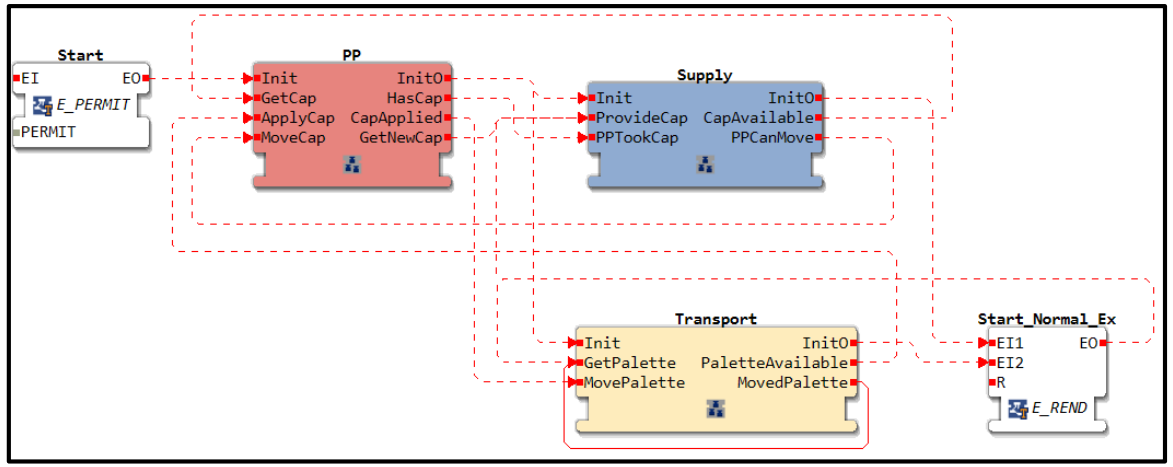
Running Example: Capping Station that can cap 1 Bottle with a Finger Gripper



Capping Station
Pick and Place Unit
Supply Unit
Transport Unit
Sensor
Actuator
Product
Structure





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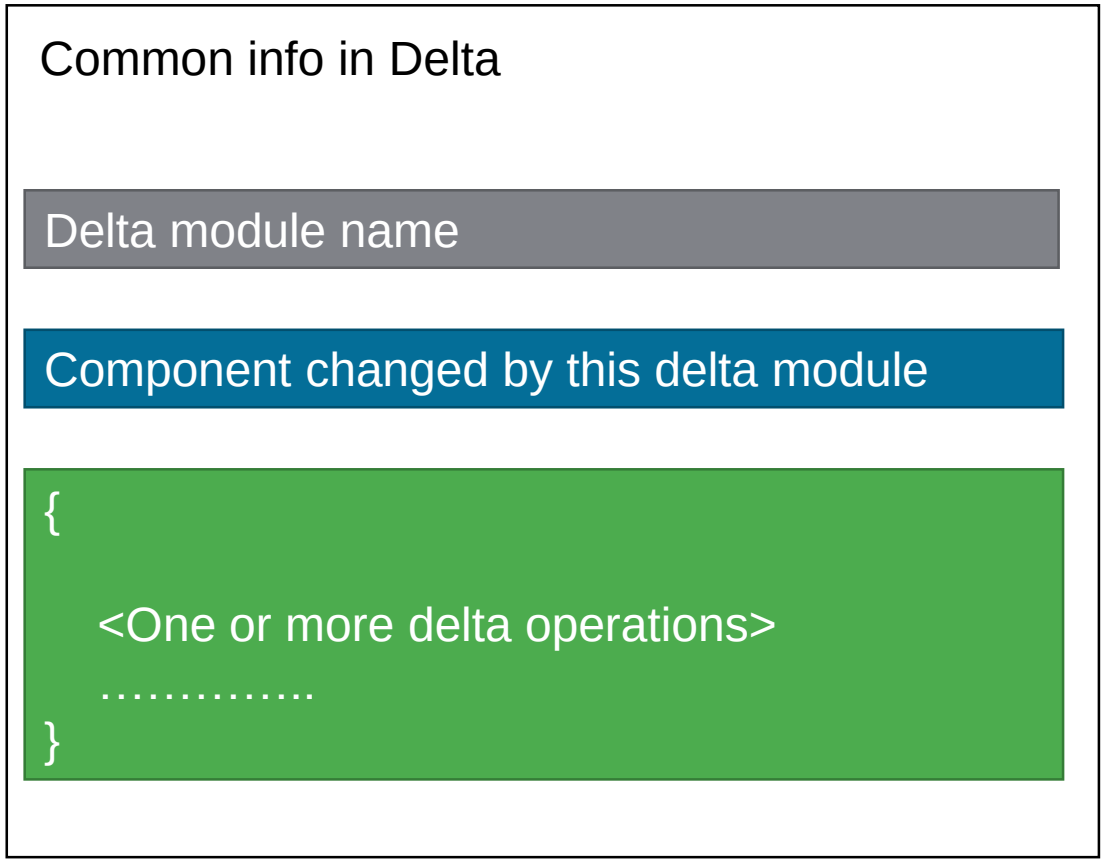
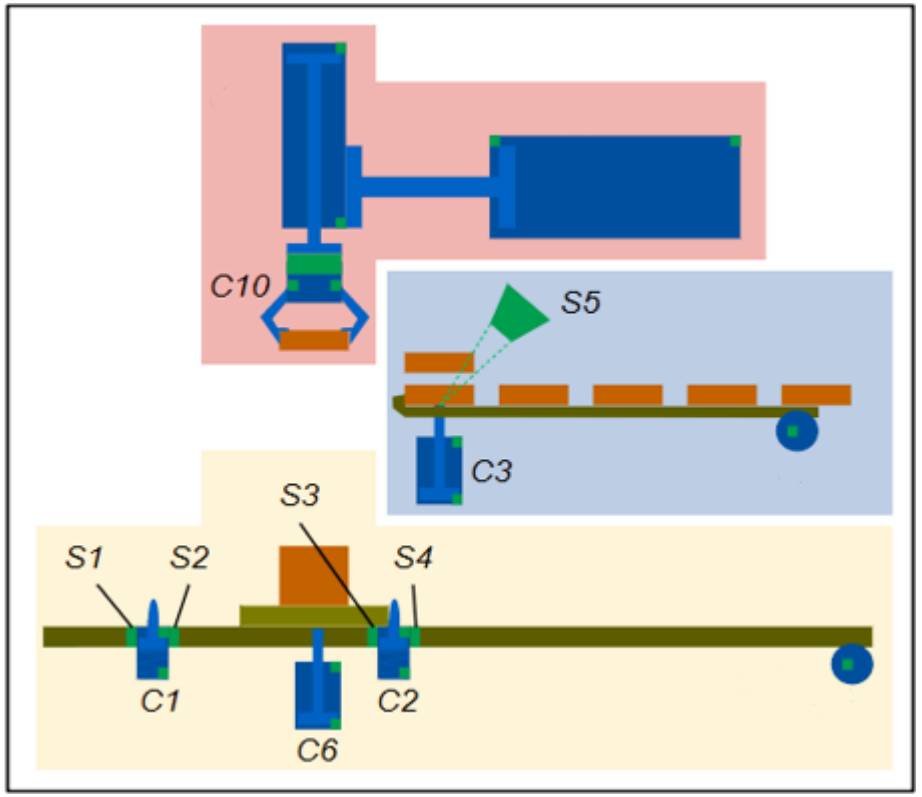
SiCPPS Variability Modeling with Deltas

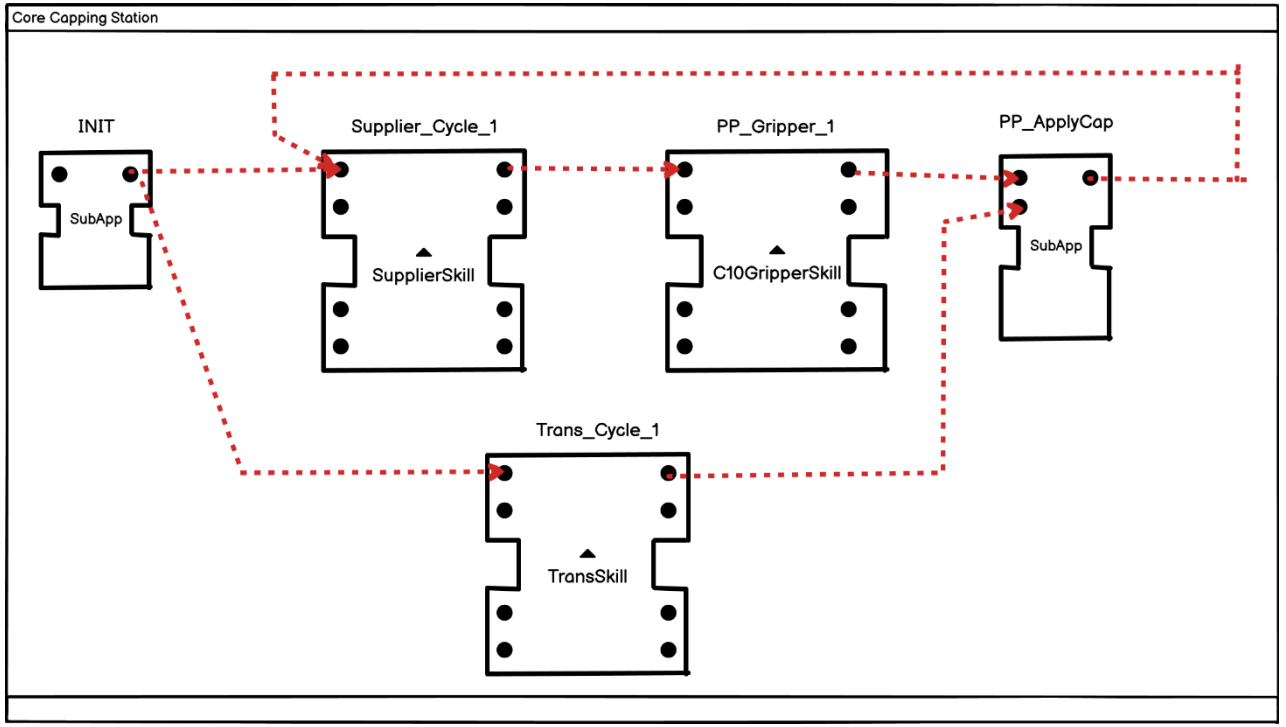
- A *module* describing the changes needed to produce another product variant
- Changes are related to a base or core implementation and always specifically targeted at a certain *component*
- *Delta modules* can contain one or more *delta operations* such as:
  - *Add*
  - *Remove*
  - *Modify*



Hafiyyan Sayyid Fadhlillah, Bianca Wiesmayr, Michael Oberlehner, Rick Rabiser, Alois Zoitl: Towards Delta-Oriented Variability Modeling for IEC 61499. ETFA, IEEE, 2021.

Base Design (Capping 1 Bottle with Finger Gripper)





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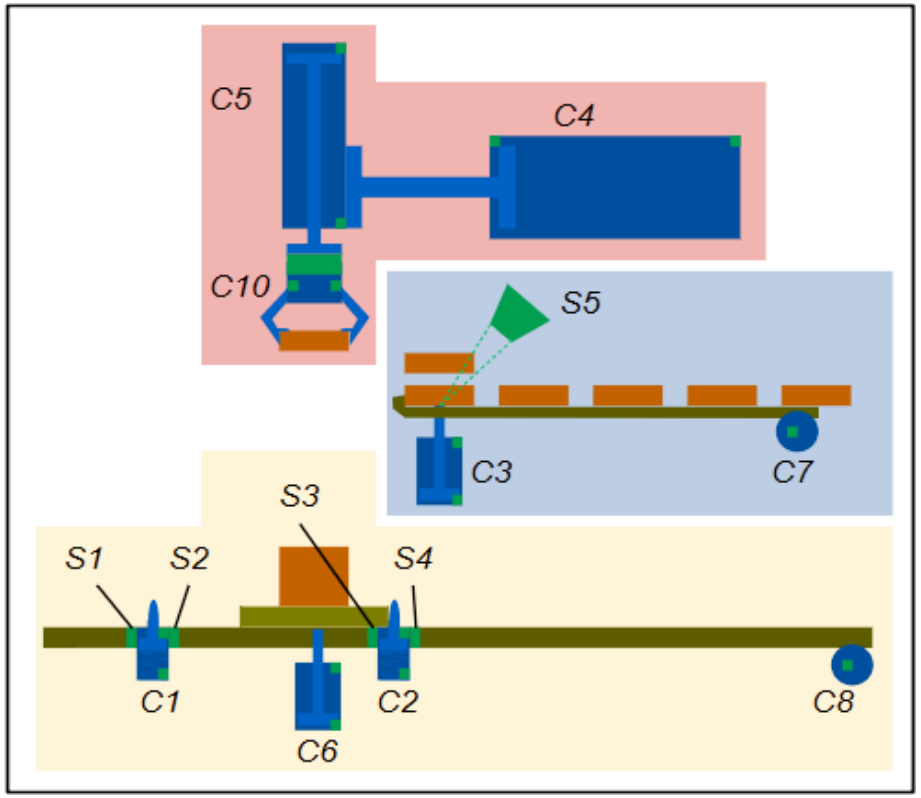
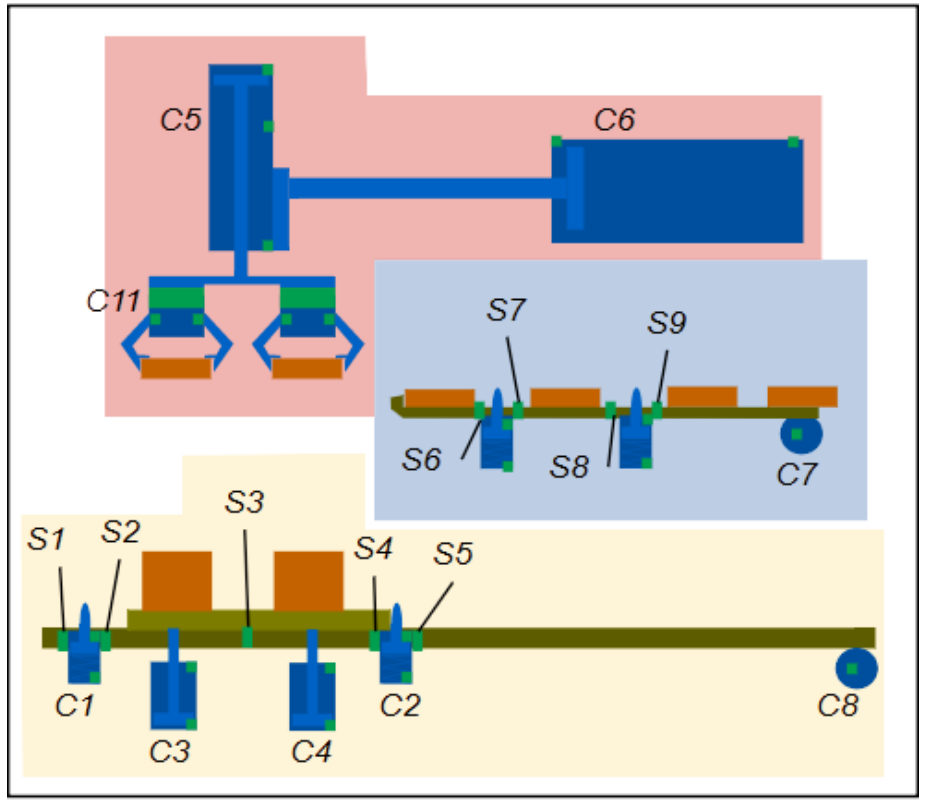
Variation 1 (Capping 2 Bottles w. Finger Gripper)





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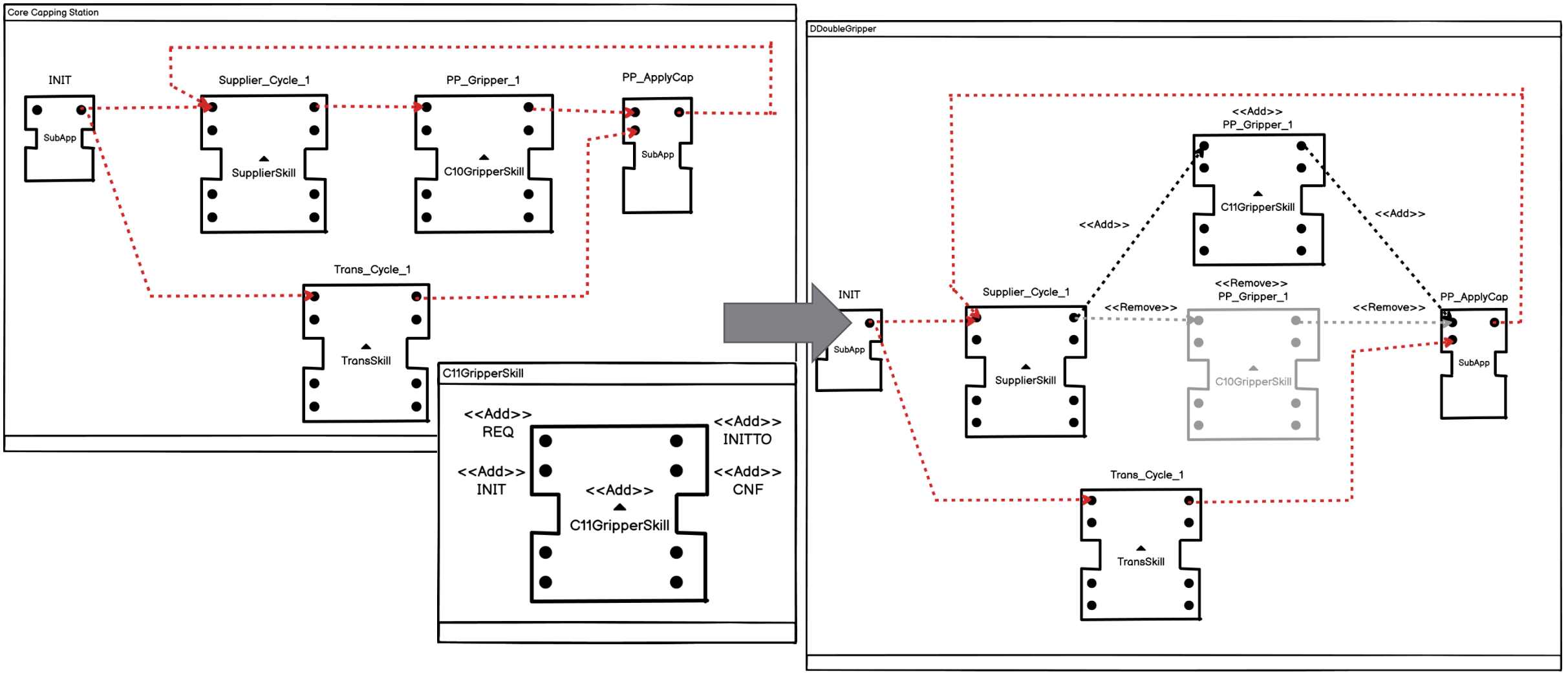
Variation 1 (Capping 2 Bottles with Finger Gripper)



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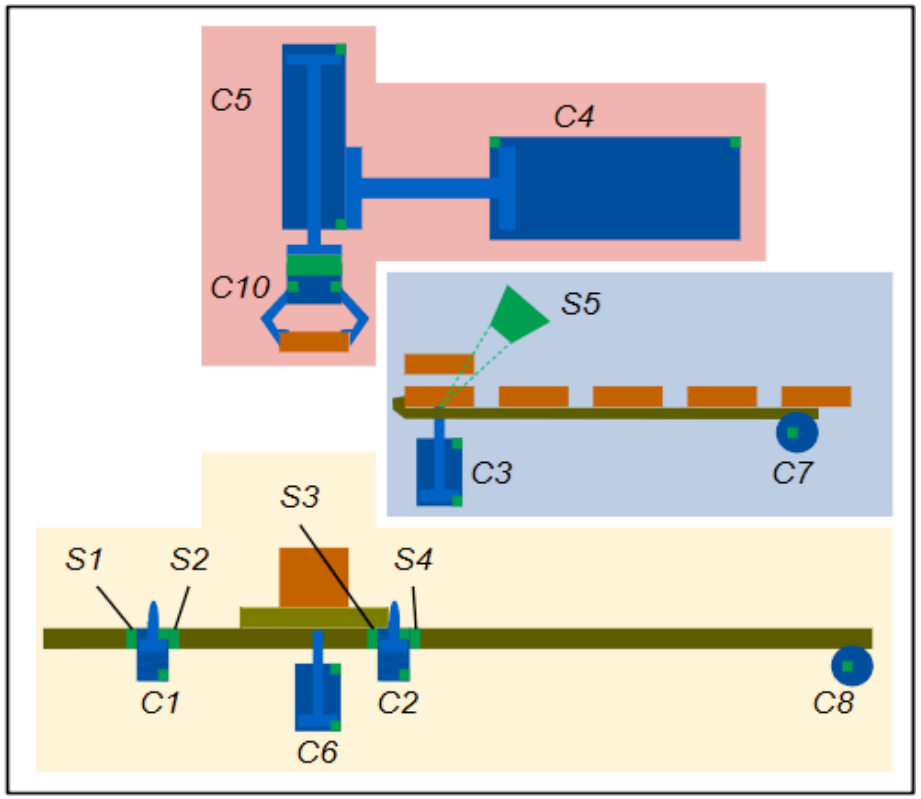
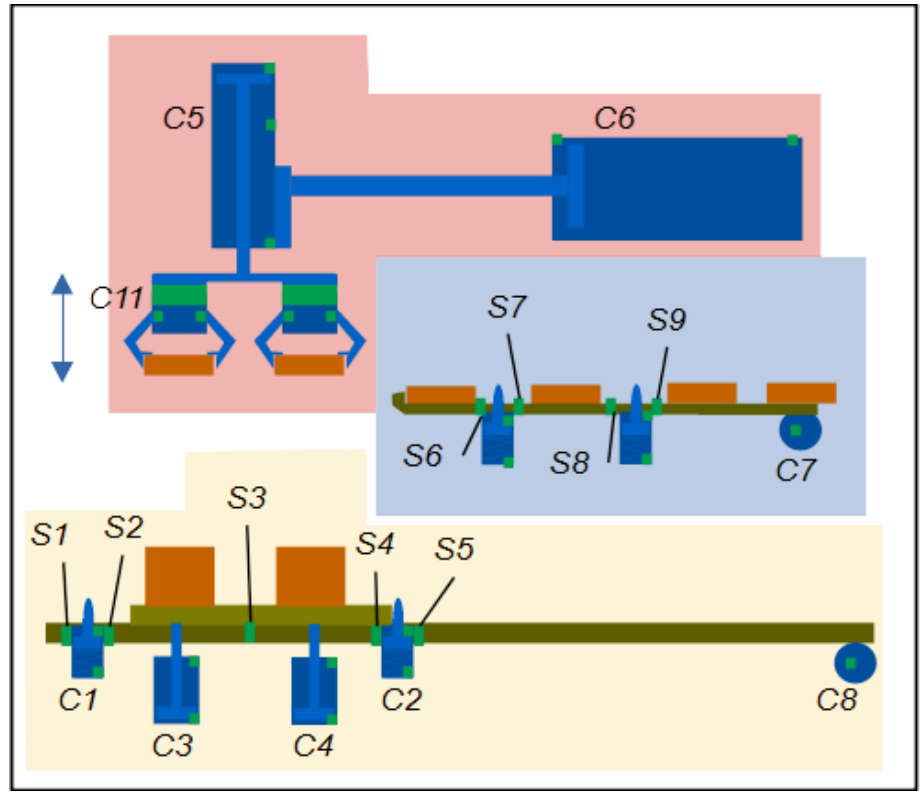
Variation 2 (Capping 2 Bottles with Finger Gripper with Re-grip Functionality)





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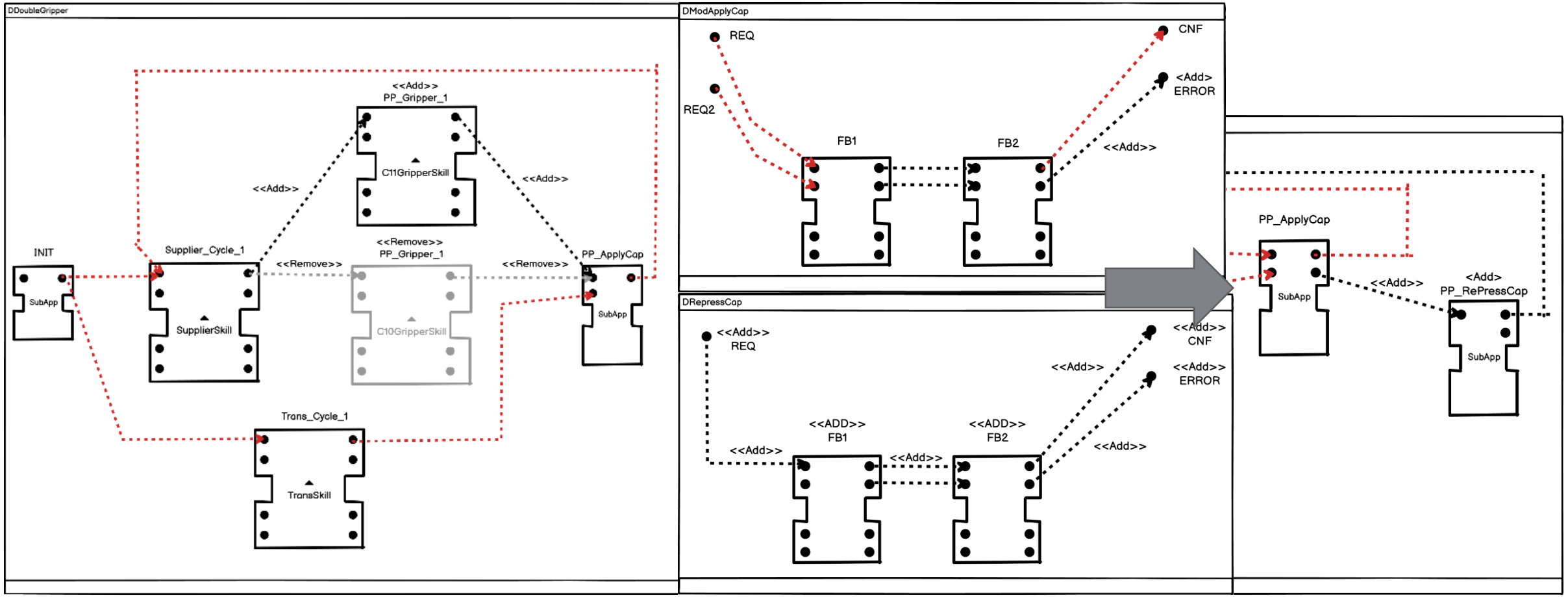

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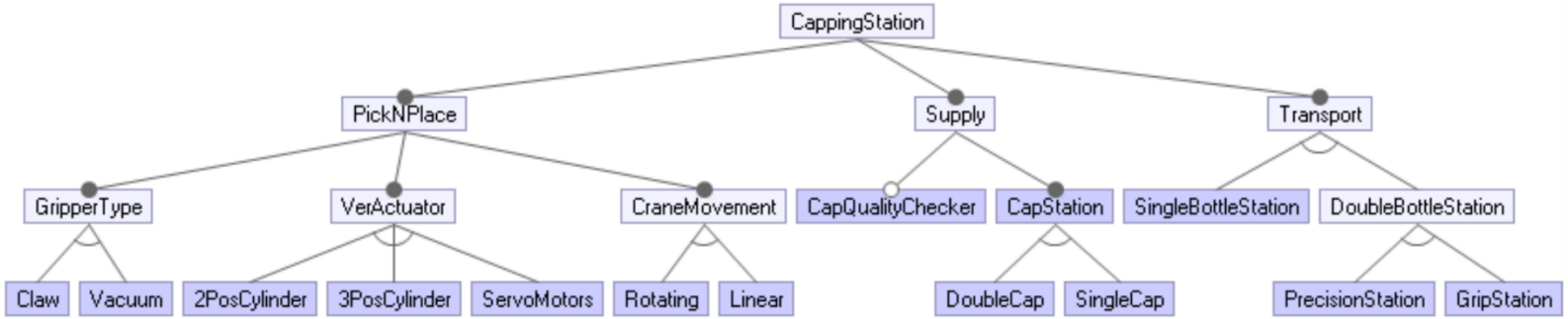
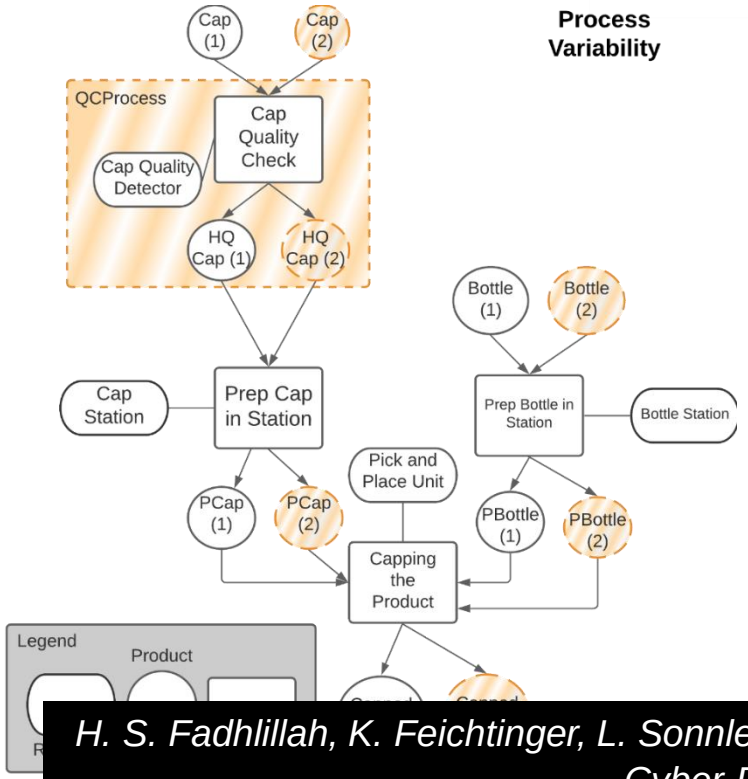
CPPS Var: Multiple Views



Mechatronics Variability



Process Variability

SingleCap ∧ DoubleBottleStation ⇔ Rotating

Cross-Dimensional Constraints

Business Variability

Q1. What is your planned production capacity? (Positive Integer)

Q2. What is your planned return of investment? (Positive Integer)

Q3. Area of your factory (approximately in m^2)? (Positive Integer)

Legend: BV: Business Variability | PV: Process Variability | MV: Mechatronics Variability

$(C1.)\ BV.Q1 > 100 \Leftrightarrow \neg\, MV.SingleBottleStation \wedge PV.Cap(2) \wedge PV.HQCap(2) \wedge PV.PCap(2) \wedge PV.Bottle(2) \wedge PV.PBottle(2) \wedge PV.CappedBottle(2)$

$(C2.)\ BV.Q1 \leq 100 \Leftrightarrow \neg\, (MV.DoubleCap \vee MV.Rotating \vee MV.DoubleBottleStation \vee (PV.Cap(2) \wedge PV.HQCap(2) \wedge PV.PCap(2) \wedge PV.Bottle(2) \wedge PV.PBottle(2) \wedge PV.CappedBottle(2)))$

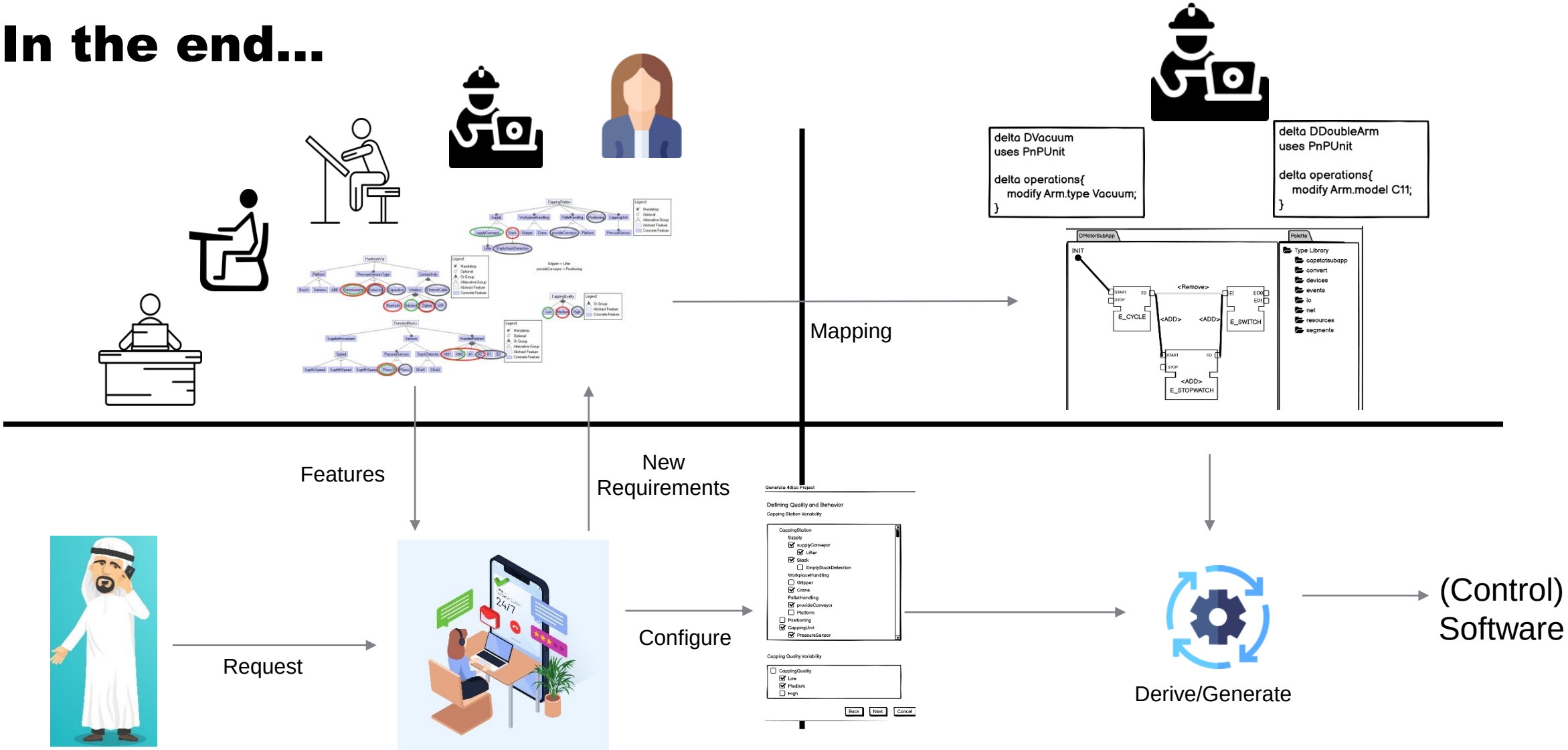
$(C3.)\ BV.Q2 \leq 150 \Leftrightarrow \neg\, (MV.Rotating \vee MV.ServoMotors \vee MV.CapQualityChecker)$

$(C4.)\ BV.Q2 \leq 150 \wedge BV.Q1 > 100 \Leftrightarrow \neg\, MV.SingleCap$

$(C5.)\ BV.Q3 \leq 50 \Leftrightarrow \neg\, MV.Rotating$

H. S. Fadhlillah, K. Feichtinger, L. Sonnleithner, R. Rabiser, and A. Zoitl: Towards Heterogeneous Multi-Dimensional Variability Modeling in Cyber-Physical Production Systems. VariVolution at SPLC, ACM, 2021.

In the end...


delta DVacuum
uses PnPUnit

delta operations{
modify Arm.type Vacuum;
}
delta DDoubleArm
uses PnPUnit

delta operations{
modify Arm.model C11;
}
Mapping
Features
New
Requirements
Request
Configure
Derive/Generate
(Control)
Software

LINZ INSTITUTE OF TECHNOLOGY

Other current work (Selection)

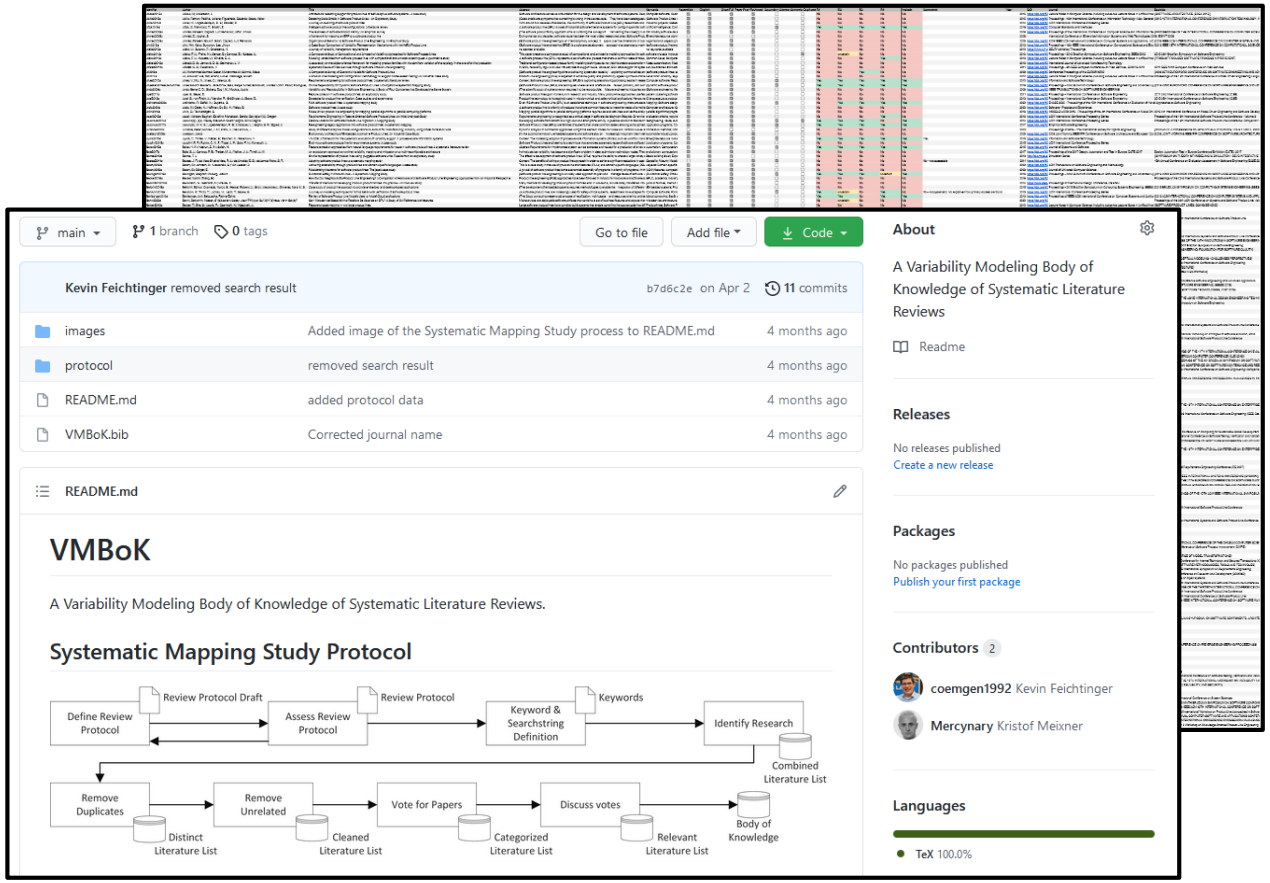
https://www.jku.at/en/lit-cyber-physical-systems-lab/research/current-work

LIT | Cyber-Physical Systems Lab
Johannes Kepler University Linz

A Variability Modeling Body of Knowledge

- https://github.com/SECPS/VMBoK
- Collection of 78 Secondary Studies + Meta-Info (e.g., spreadsheet with infos on 454 publications voted on)
- Coop. with TU Vienna

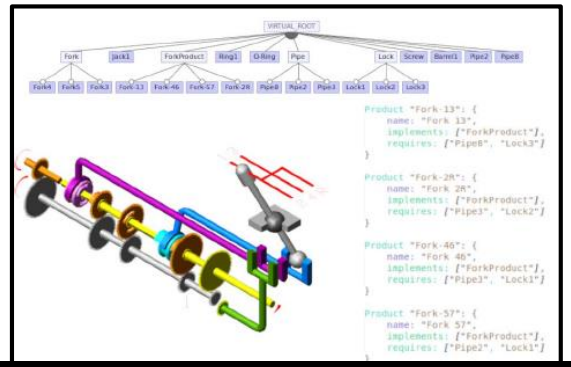
- Current Work: Systematic Studies of three PhD students (Kevin Feichtinger, Kristof Meixner, Hafiyyan Sayyid Fadhlillah) focusing on different yet related research questions based on the BoK

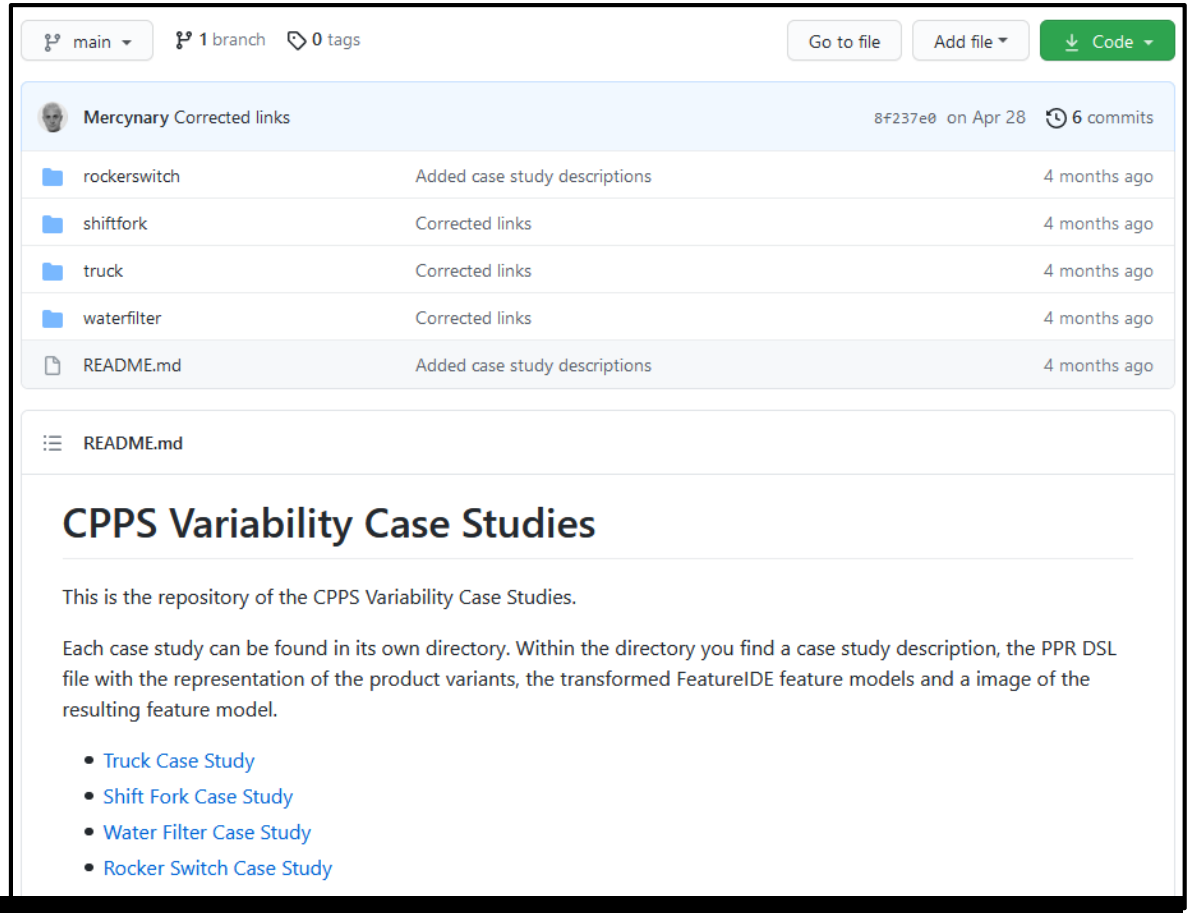


K. Feichtinger, K. Meixner, R. Rabiser, and S. Biffl, "A Systematic Study as Foundation for a Variability Modeling Body of Knowledge, Euromicro SEAA, IEEE, 2021.

Reusable Set of Real-World Product Line Case Studies

- https://github.com/tuw-qse/cpps-var-case-studies
- Coop. with TU Vienna
- Case Study Description, Product-Process-Resource DSL Files representing product variants, and FeatureIDE feature models
- Lego Truck
- Shift Fork
- Water Filter
- Rocker Switch



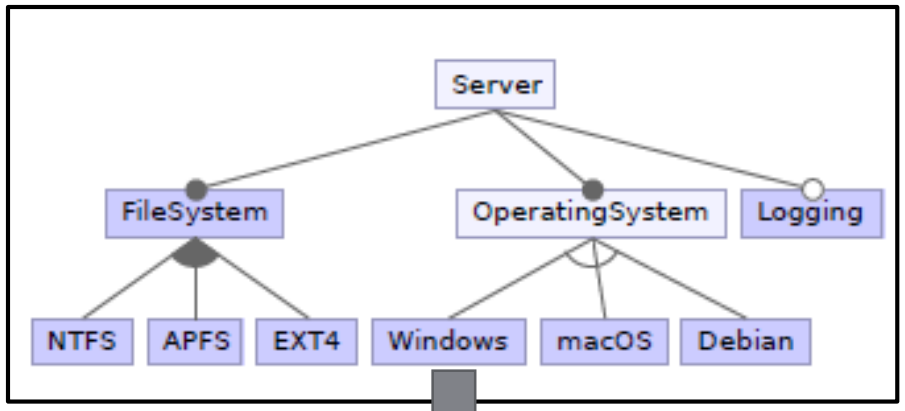


K. Meixner, K. Feichtinger, R. Rabiser, and S. Biffl, "A Reusable Set of Real-World Product Line Case Studies for Comparing Variability Models in Research and Practice, WEESR at SPLC, ACM, 2021.

Univ.-Prof. Dr. Rick Rabiser
(rick.rabiser@jku.at)

MODEVAR / UVL

- Goal: **standard variability modelling language developed by academia for academia and practice**
- Coop. with ~20+ universities, initiated by David Benavides
- https://modevar.github.io/
- Workshop series since 2018, collocated with VaMoS and SPLC
- Key result: **UVL – Proposal for a Universal Variability Language**
  - Uni Ulm with JKU and Uni Sevilla
  - https://github.com/Universal-Variability-Language




```
features
  Server {abstract}
    mandatory
      FileSystem
        or // with cardinality: [1..*]
          NTFS
          APFS
          EXT4
      OperatingSystem {abstract}
        alternative
          Windows
          macOS
          Debian
    optional
      Logging {
      default,
      log_level "warn" // Feature Attribute
    }
constraints
  Windows => NTFS
  macOS => APFS
```

C. Sundermann, K. Feichtinger, D. Engelhardt, R. Rabiser, and T. Thüm, "Yet Another Textual Variability Language? A Community Effort Towards a Unified Language, SPLC 2021, ACM, 2021.

Other Current Projects/Work at LIT CPS Lab

- **TraVarT: Transforming Variability Models**
  - with TU Vienna, Uni Ulm, SE/WIN JKU
- **Testing of Highly Configurable Cyber-Physical Systems**
  - with SCCH
- **Relation of academia and industry in Software Engineering**
  - with Uni Hildesheim, SE WIN JKU, Fraunhofer IESE, Canterbury University NZ, KU Leuven, Lero/Trinity College Dublin
- **Usability Studies of (Software) Engineering Tools**
- **SECPPS (Software Engineering in Cyber-Physical Production Systems) Workshop Series**
  - with TU Munich, SE WIN JKU, Uni Stuttgart
- **JKU/Dynatrace Co-Innovation Lab**
  - distributed data systems, real-time data analytics
- **EU Project 1-SWARM**
  - framework to standardize design of cyber-physical systems of systems
- **FFG Project BrAIN**
  - interaction patterns among individual process steps in manufacturing and production industry

Conclusion: Close Cooperation between Industry and Academia is needed

"I have the impression that industry is often stuck/has problems with concepts we already introduced decades ago"

"It seems to me that many of the academic papers are exploring areas that industry has already solved in practice"

Rabiser, R., Schmid, K., Becker, M., Botterweck, G., Galster, M., Groher, I., Weyns, D.: Industrial and Academic Software Product Line Research at SPLC: Perceptions of the Community, SPLC, ACM, 2019, pp. 189-194.

Thank you!

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Christian Doppler Lab VaSiCS
LIT | Cyber-Physical Systems Lab
Johannes Kepler University Linz

PRIMETALS TECHNOLOGIES
ober österreich
Federal Ministry
Republic of Austria
Digital and
Economic Affairs