Towards Ontology-based Digital Twin Service Construction and Reporting

SIG LLODIA

Languages, Logic, Ontologies for Digital Twin Analysis, Interoperability, and Design

January 21st 2026

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Dr. Bentley Oakes

bentleyoakes.com

Presenter

Bentley Oakes
Assistant Professor at Polytechnique Montréal

bentley.oakes@polymtl.ca
https://bentleyjoakes.github.io/

Assistant Prof
Polytechnique Montréal
2023-present

OAKES

Objective: **A**ccelerating **K**nowledge **E**ngineering for Complex **S**ystems

Tools and techniques: Ontological modelling and analysis, model-based engineering, machine learning, generative AI, co-simulation, 3D game engines

Current Research Focus: *Accelerating and Systematizing Digital Twin Engineering*

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1) OML and openCAESAR
2) Systematic DT Reporting

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OML and openCAESAR

Based on material from:

Maged Elaasar – Modelware, NASA JPL

Eduard Kamburjan – IT University of Copenhagen

and Nicolas Rouquette, David Wagner, Abdelwahab Hamou-Lhadj, Mohammad Hamdaqa

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OML and openCAESAR

Motivation

Context: MBSE

DT engineering is specialization of

model-based systems engineering (MBSE)

MBSE is "**formalized application of modeling** to support system requirements, design, analysis, verification and validation activities beginning in the **conceptual design phase** and continuing throughout **development** and **later life cycle phases**." - INCOSE

See also https://www.mathworks.com/videos/series/systems-engineering.html

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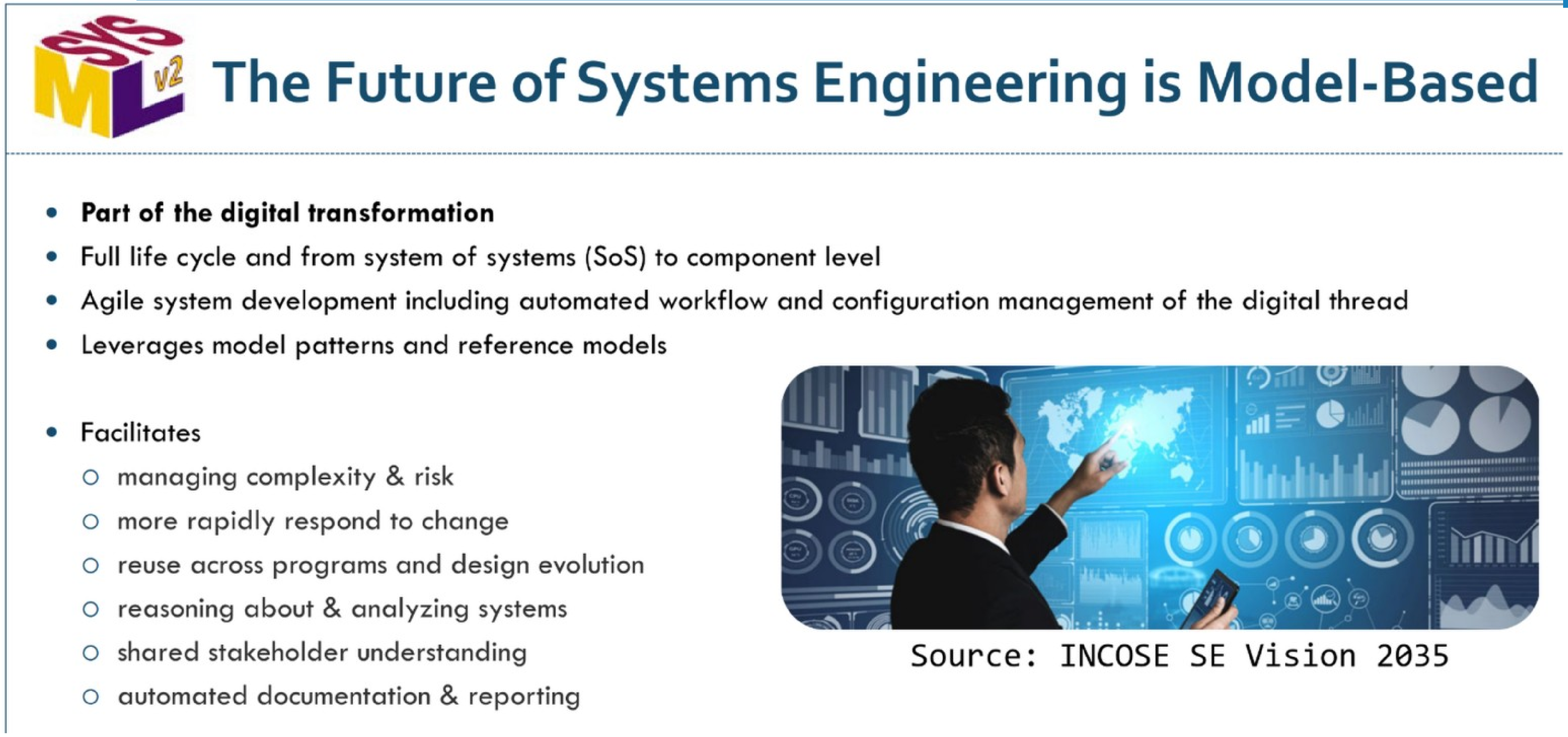
MBSE is the Future



The Future of Systems Engineering is Model-Based

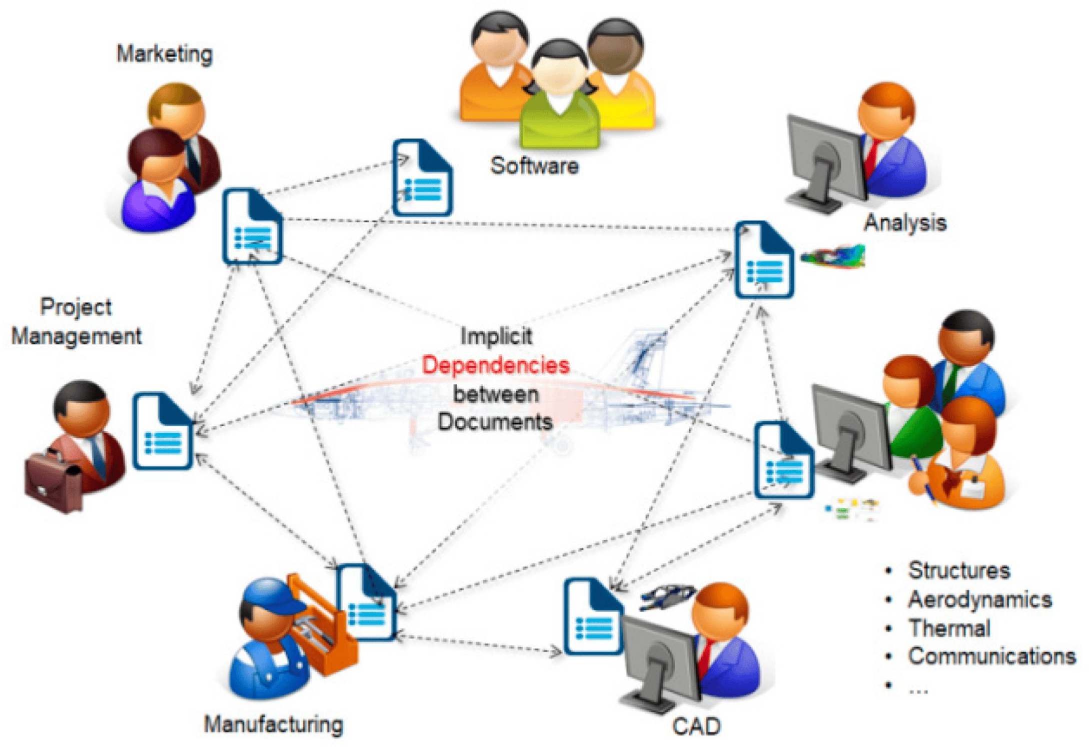
- **Part of the digital transformation**
- Full life cycle and from system of systems (SoS) to component level
- Agile system development including automated workflow and configuration management of the digital thread
- Leverages model patterns and reference models

- Facilitates
  - managing complexity & risk
  - more rapidly respond to change
  - reuse across programs and design evolution
  - reasoning about & analyzing systems
  - shared stakeholder understanding
  - automated documentation & reporting

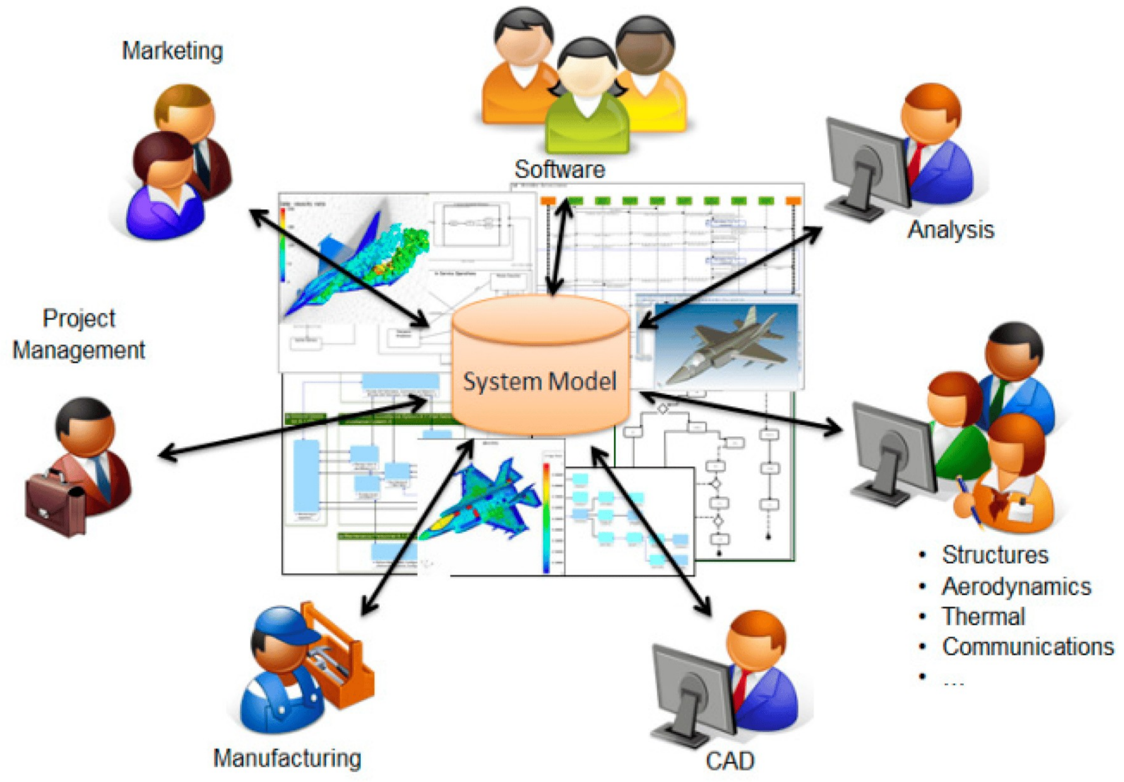
Source: INCOSE SE Vision 2035

https://www.omgwiki.org/MBSE/lib/exe/fetch.php?media=mbse:sysml_v2_transition:sysml_v2_basics-incose_iw-sfriedenthal-2024-01-28.pdf

A Source of Truth



Moving from document-based systems engineering



To model-based systems engineering

Perennial challenges: **Integration and consistency**

Madni AM, Purohit S. Economic Analysis of Model-Based Systems Engineering. Systems. 2019; 7(1):12. https://doi.org/10.3390/systems7010012
Elaasar, M., Hamou-Lhadj, A., Oakes, B., & Hamdaqa, M. (2025).
Model-Based Systems Engineering Perspectives: A Survey of Practitioner Experiences and Challenges. SAM 2025

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Applying Ontologies to MBSE

1) Ontological languages such as OWL are **not the proper level of abstraction for system engineers**
- No background in knowledge engineering
- Want *well-known patterns* (e.g., composition, aggregation) to reason about system in a *closed-world fashion*

2) **lack of robust ontological modeling tools**
- SysMLv2 semantics are expressed through its meta-model
- Hildebrandt et al. "*have identified that there is no suitable tool support to assist domain experts in modeling ontolog[ies]. Existing tools, such as Protégé, require deep ontological knowledge*."

Hildebrandt et al: Ontology building for cyber–physical systems: Application in the manufacturing domain. IEEE Transactions on Automation Science and Engineering 17(3), 1266–1282 (2020). https://doi.org/10.1109/TASE.2020.2991777

Case: Europa Clipper

“Robotic solar-powered spacecraft built to conduct the first detailed investigations of Jupiter's icy moon Europa”

- Have to define power system as connections
- Power system is energy management problem
  - Electrical loads come and go over time
  - Science instruments custom-made, so uncertain power draw

- Tooling was Excel
  - Inconsistent, tedious, error-prone
- And SysML
  - Inconsistent between diagrams, too-large diagrams

Wagner et al. (2023). Semantic Modeling for Power Management Using CAESAR. Handbook of Model-Based Systems Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-93582-5_81
D. Wagner et al., "CAESAR Model-Based Approach to Harness Design," 2020 IEEE Aerospace Conference, Big Sky, MT, USA, 2020, pp. 1-13, doi: 10.1109/AERO47225.2020.9172630.

Solution Methodology

1) Built ontologies as *electrical vocabularies*

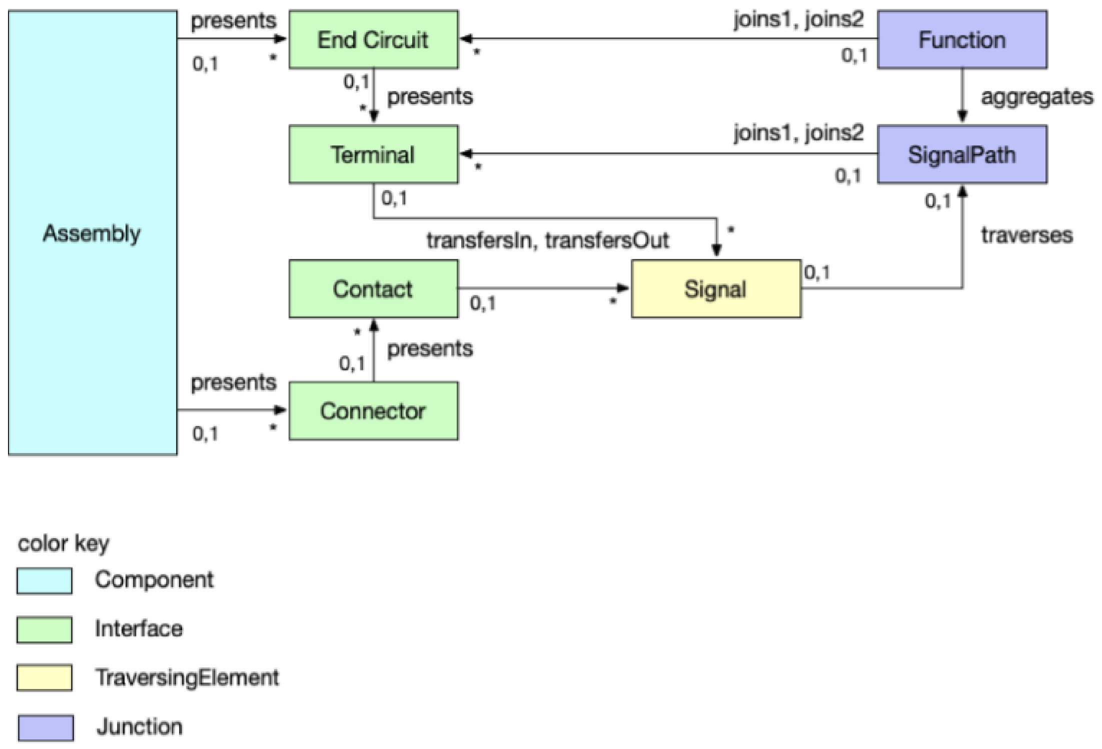
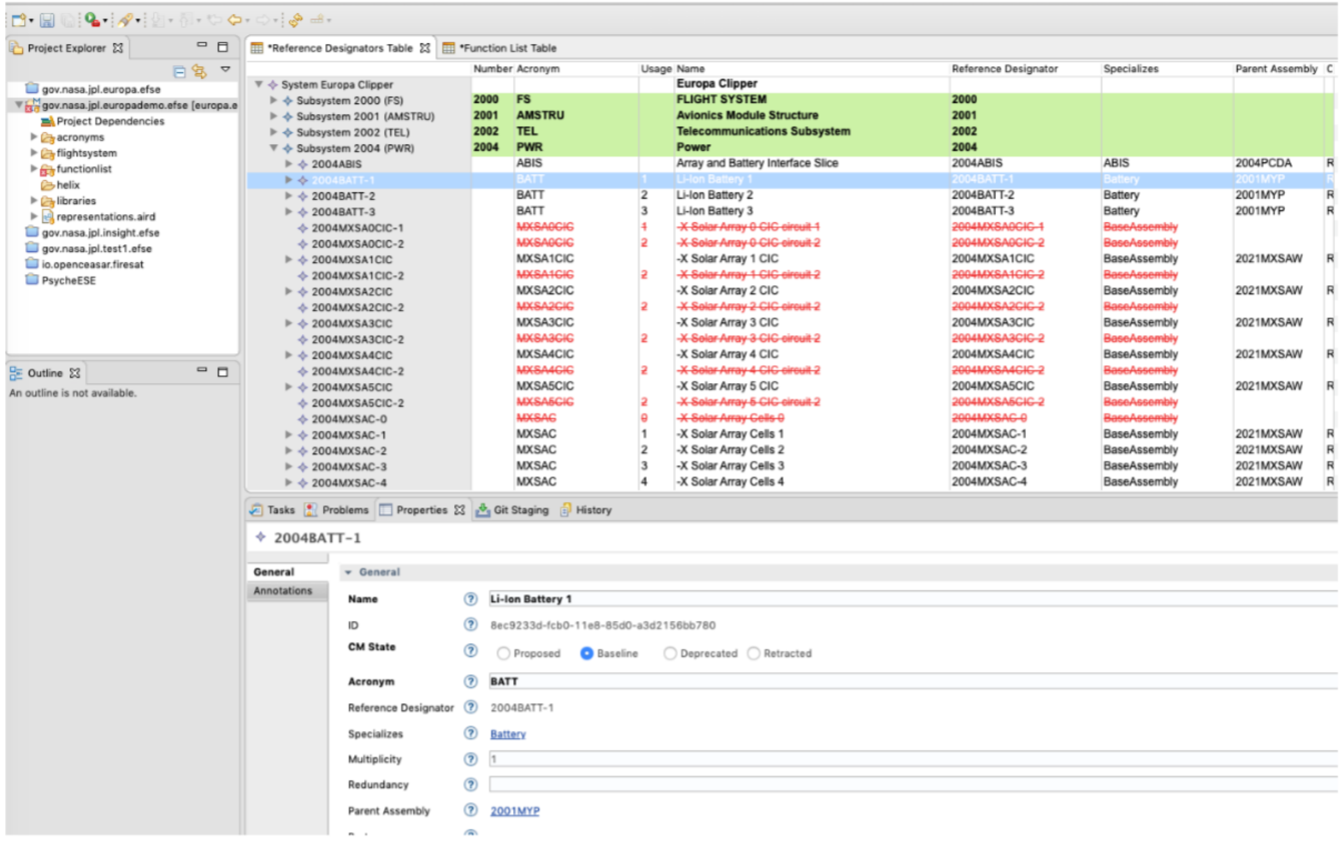


Figure 7 EFSE-2.0 Vocabulary Extensions

2) Built editors and reports aligning with vocabularies


Project Explorer

- gov.nasa.jpl.europa.efse
- gov.nasa.jpl.europademo.efse [europa.e
  - Project Dependencies
  - acronyms
  - flightsystem
  - functionlist
  - helix
  - libraries
  - representations.aird
- gov.nasa.jpl.insight.efse
- gov.nasa.jpl.test1.efse
- io.openceasar.firesat
- PsycheESE

Outline

An outline is not available.

*Reference Designators Table | *Function List Table

	Number	Acronym	Usage	Name	Reference Designator	Specializes	Parent Assembly	C
System Europa Clipper				**Europa Clipper**				
Subsystem 2000 (FS)	**2000**	**FS**		**FLIGHT SYSTEM**	**2000**			
Subsystem 2001 (AMSTRU)	**2001**	**AMSTRU**		**Avionics Module Structure**	**2001**			
Subsystem 2002 (TEL)	**2002**	**TEL**		**Telecommunications Subsystem**	**2002**			
Subsystem 2004 (PWR)	**2004**	**PWR**		**Power**	**2004**			
2004ABIS		ABIS		Array and Battery Interface Slice	2004ABIS	ABIS	2004PCDA	R
2004BATT-1		BATT	1	Li-Ion Battery 1	2004BATT-1	Battery	2001MYP	R
2004BATT-2		BATT	2	Li-Ion Battery 2	2004BATT-2	Battery	2001MYP	R
2004BATT-3		BATT	3	Li-Ion Battery 3	2004BATT-3	Battery	2001MYP	R
2004MXSA0CIC-1		~~MXSA0CIC~~	~~1~~	~~-X Solar Array 0 CIC circuit 1~~	~~2004MXSA0CIC-1~~	~~BaseAssembly~~		
2004MXSA0CIC-2		~~MXSA0CIC~~	~~2~~	~~-X Solar Array 0 CIC circuit 2~~	~~2004MXSA0CIC-2~~	~~BaseAssembly~~		
2004MXSA1CIC		MXSA1CIC		-X Solar Array 1 CIC	2004MXSA1CIC	BaseAssembly	2021MXSAW	R
2004MXSA1CIC-2		~~MXSA1CIC~~	~~2~~	~~-X Solar Array 1 CIC circuit 2~~	~~2004MXSA1CIC-2~~	~~BaseAssembly~~		
2004MXSA2CIC		MXSA2CIC		-X Solar Array 2 CIC	2004MXSA2CIC	BaseAssembly	2021MXSAW	R
2004MXSA2CIC-2		~~MXSA2CIC~~	~~2~~	~~-X Solar Array 2 CIC circuit 2~~	~~2004MXSA2CIC-2~~	~~BaseAssembly~~		
2004MXSA3CIC		MXSA3CIC		-X Solar Array 3 CIC	2004MXSA3CIC	BaseAssembly	2021MXSAW	R
2004MXSA3CIC-2		~~MXSA3CIC~~	~~2~~	~~-X Solar Array 3 CIC circuit 2~~	~~2004MXSA3CIC-2~~	~~BaseAssembly~~		
2004MXSA4CIC		MXSA4CIC		-X Solar Array 4 CIC	2004MXSA4CIC	BaseAssembly	2021MXSAW	R
2004MXSA4CIC-2		~~MXSA4CIC~~	~~2~~	~~-X Solar Array 4 CIC circuit 2~~	~~2004MXSA4CIC-2~~	~~BaseAssembly~~		
2004MXSA5CIC		MXSA5CIC		-X Solar Array 5 CIC	2004MXSA5CIC	BaseAssembly	2021MXSAW	R
2004MXSA5CIC-2		~~MXSA5CIC~~	~~2~~	~~-X Solar Array 5 CIC circuit 2~~	~~2004MXSA5CIC-2~~	~~BaseAssembly~~		
2004MXSAC-0		~~MXSAC~~	~~0~~	~~-X Solar Array Cells 0~~	~~2004MXSAC-0~~	~~BaseAssembly~~		
2004MXSAC-1		MXSAC	1	-X Solar Array Cells 1	2004MXSAC-1	BaseAssembly	2021MXSAW	R
2004MXSAC-2		MXSAC	2	-X Solar Array Cells 2	2004MXSAC-2	BaseAssembly	2021MXSAW	R
2004MXSAC-3		MXSAC	3	-X Solar Array Cells 3	2004MXSAC-3	BaseAssembly	2021MXSAW	R
2004MXSAC-4		MXSAC	4	-X Solar Array Cells 4	2004MXSAC-4	BaseAssembly	2021MXSAW	R

Tasks | Problems | Properties | Git Staging | History

2004BATT-1

General | Annotations

General

Name	Li-Ion Battery 1
ID	8ec9233d-fcb0-11e8-85d0-a3d2156bb780
CM State	Proposed [✓ Baseline] Deprecated Retracted
Acronym	BATT
Reference Designator	2004BATT-1
Specializes	Battery
Multiplicity	1
Redundancy	
Parent Assembly	2001MYP

Figure 4 Composition view in CAESAR workbench

Wagner et al. (2023). Semantic Modeling for Power Management Using CAESAR. Handbook of Model-Based Systems Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-93582-5_81

D. Wagner et al., "CAESAR Model-Based Approach to Harness Design," 2020 IEEE Aerospace Conference, Big Sky, MT, USA, 2020, pp. 1-13, doi: 10.1109/AERO47225.2020.9172630.

(open)CAESAR

- *Computer Aided Engineering for Spacecraft System Architectures Tool Suite* (CAESAR) project used for Europa Clipper *et al.*
- Open-sourced at https://www.opencaesar.io/

Elaasar et al. (2023, October). openCAESAR: Balancing agility and rigor in model-based systems engineering. In MODELS-C (pp. 221-230). IEEE.

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OML and openCAESAR

Intro to OML

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Three Core Principles of OML

- *Abstraction*
  - Essentially is a domain-specific language (DSL) over OWL
  - Removes accidental complexity

- *Modularity*
  - Easy definition and federation of vocabulary and description models

- *Extensibility*
  - Can refer to other models and define further concepts/properties/rules/etc.

See tutorials: https://www.opencaesar.io/oml-tutorials/

OML Vocabularies

- Defines concepts and their relations
- Somewhat matches a meta-model
- Promotes modularity and reuse
  - Can refer to concept in another vocabulary to add elements
- Allows addition of description logic (DL) semantics
  - Inference rules allow for a-posteriori typing

OML

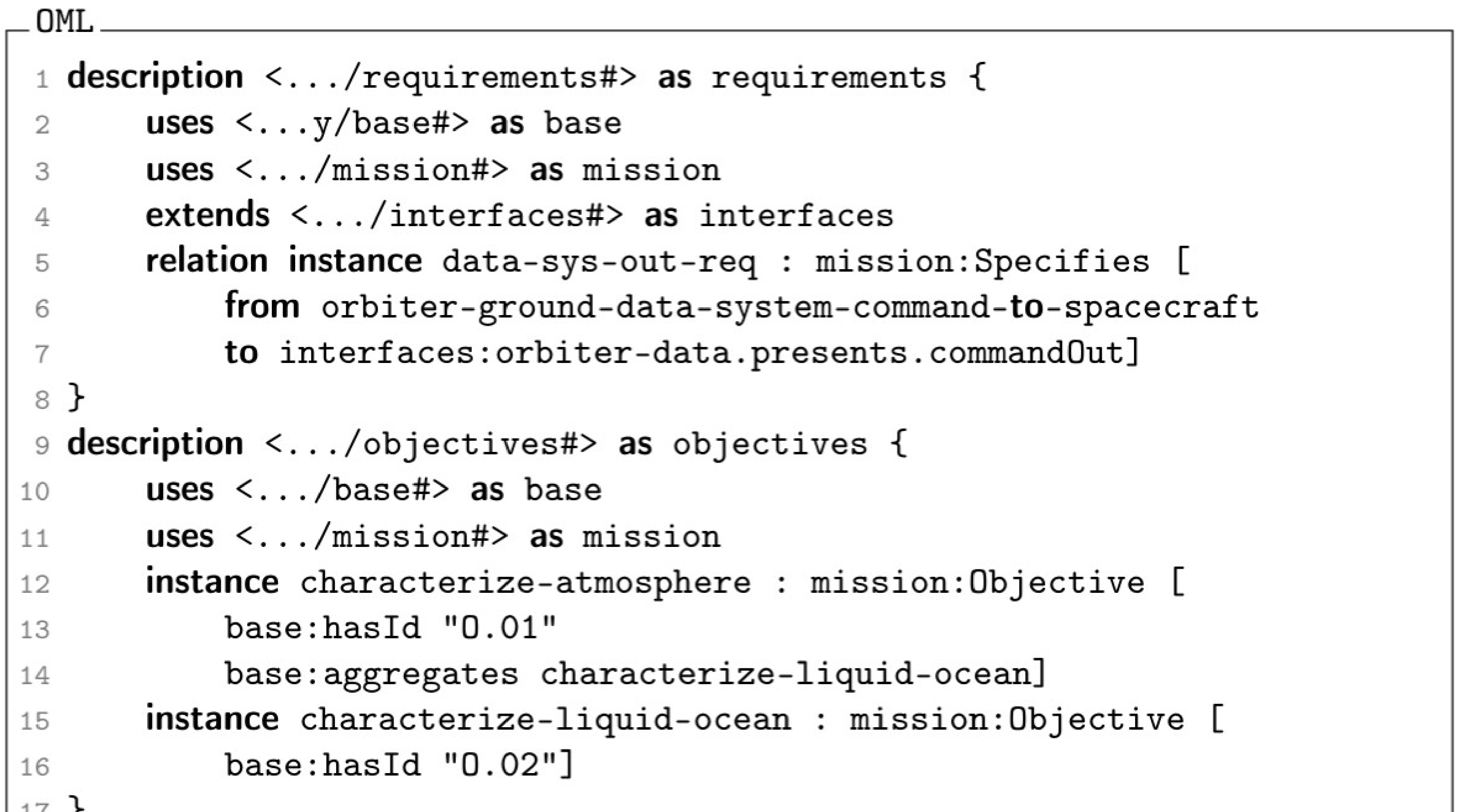
```
vocabulary <.../mission#> as mission {
extends <http://www.w3.org/2000/01/rdf-schema#> as rdfs
extends <.../base#> as base
concept Objective < base:IdentifiedThing, base:AggregatedThing [
    restricts all base:aggregates to Objective
    restricts all base:isAggregatedIn to Objective ]
concept Requirement < base:IdentifiedThing
aspect SpecifiedThing
relation entity Specifies [
    from Requirement  to SpecifiedThing
    forward specifies  reverse isSpecifiedBy functional ]
//Defs for presents, joins, isPresentedBy, and connectsTo omitted
rule Junction-infers-Connection [
    presents(c1, i1) & joins(i1, i2) & isPresentedBy(i2, c2)
    -> connectsTo(c1, c2)]
}
```

OWL

```
Class(Objective)
SubClassOf(Objective base:IdentifiedThing)
SubClassOf(Objective base:AggregatedThing)
SubClassOf(Objective ObjectAllValuesFrom(base:aggregates Objective))
SubClassOf(Objective ObjectAllValuesFrom(base:isAggregatedIn
 Objective))
```

OML Descriptions

- Instances/relations conform to vocabularies
- Essentially a model (in the meta-modelling sense)
- Reasoner can check consistency



OML

```
description <.../requirements#> as requirements {
    uses <...y/base#> as base
    uses <.../mission#> as mission
    extends <.../interfaces#> as interfaces
    relation instance data-sys-out-req : mission:Specifies [
        from orbiter-ground-data-system-command-to-spacecraft
        to interfaces:orbiter-data.presents.commandOut]
}
description <.../objectives#> as objectives {
    uses <.../base#> as base
    uses <.../mission#> as mission
    instance characterize-atmosphere : mission:Objective [
        base:hasId "0.01"
        base:aggregates characterize-liquid-ocean]
    instance characterize-liquid-ocean : mission:Objective [
        base:hasId "0.02"]
}
```

Closing the World

- System engineering depends on *closed-world reasoning*
  - What cannot be proven is *false*

- OML has the *bundle* mechanism to *close the world* when generating the underlying OWL
- A *vocabulary bundle* adds OWL disjointness axioms between all classes that do not have a common subclass
- A *description bundle* adds enumeration axioms that classes contain declared individuals

- Thus
  - Creation of *vocabularies and descriptions* is open-world for flexibility
  - Produced OWL is closed-world for reasoning

Querying

- Produced OWL can be queried with standard SPARQL queries

```
PREFIX base:        <http://example.com/tutorial2/vocabulary/base#>
PREFIX mission:     <http://example.com/tutorial2/vocabulary/mission#>

SELECT DISTINCT ?o1_id ?o1_name ?o2_id ?o2_name
WHERE {
    ?o1 a mission:Objective ;
        base:hasIdentifier ?o1_id ;
        base:hasCanonicalName ?o1_name ;
        base:aggregates [
            base:hasIdentifier ?o2_id ;
            base:hasCanonicalName ?o2_name
        ]
}
ORDER BY ?o1_id ?o2_id
```

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OML and openCAESAR

Intro to openCAESAR

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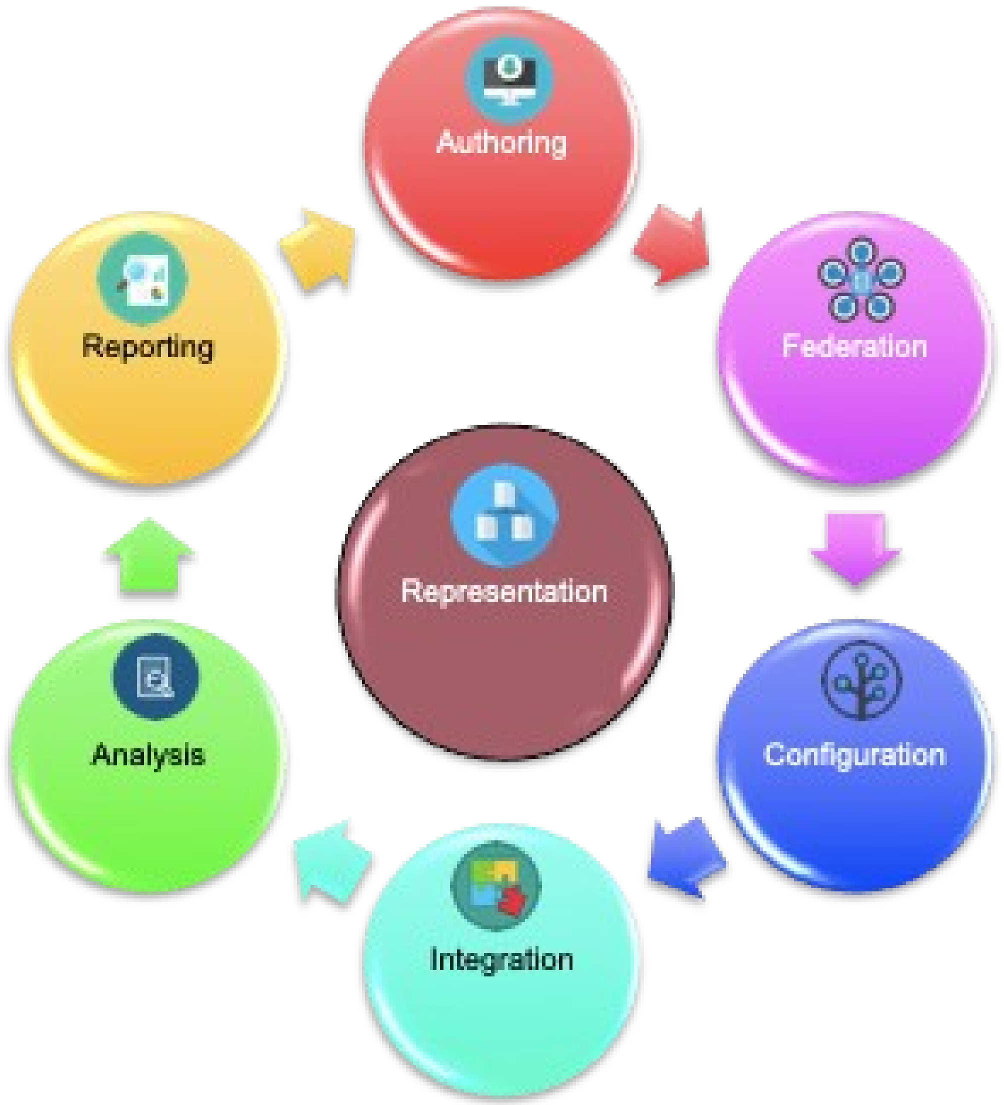
Seven Key SE Functions for JPL



1. **Information Representation**
   Using a formalism with precise syntax and logical semantics
2. **Information Authoring**
   Using a methodology supported by tools
3. **Information Federation**
   Based on concern and authority while preserving provenance
4. **Information Configuration**
   Specifying configurations, versions, and dependencies
5. **Information Integration**
   Continuous and incremental integration of federated datasets
6. **Information Analysis**
   Scalable analysis of consistency, correctness, and completeness
7. **Information Reporting**
   Defining viewpoints framing different stakeholder concerns

D. Wagner et al., "CAESAR Model-Based Approach to Harness Design," 2020 IEEE Aerospace Conference, Big Sky, MT, USA, 2020, pp. 1-13, doi: 10.1109/AERO47225.2020.9172630.

Taken from Elasaar 2022: openCAESAR: a Next Generation Platform for Systems Engineering presentation

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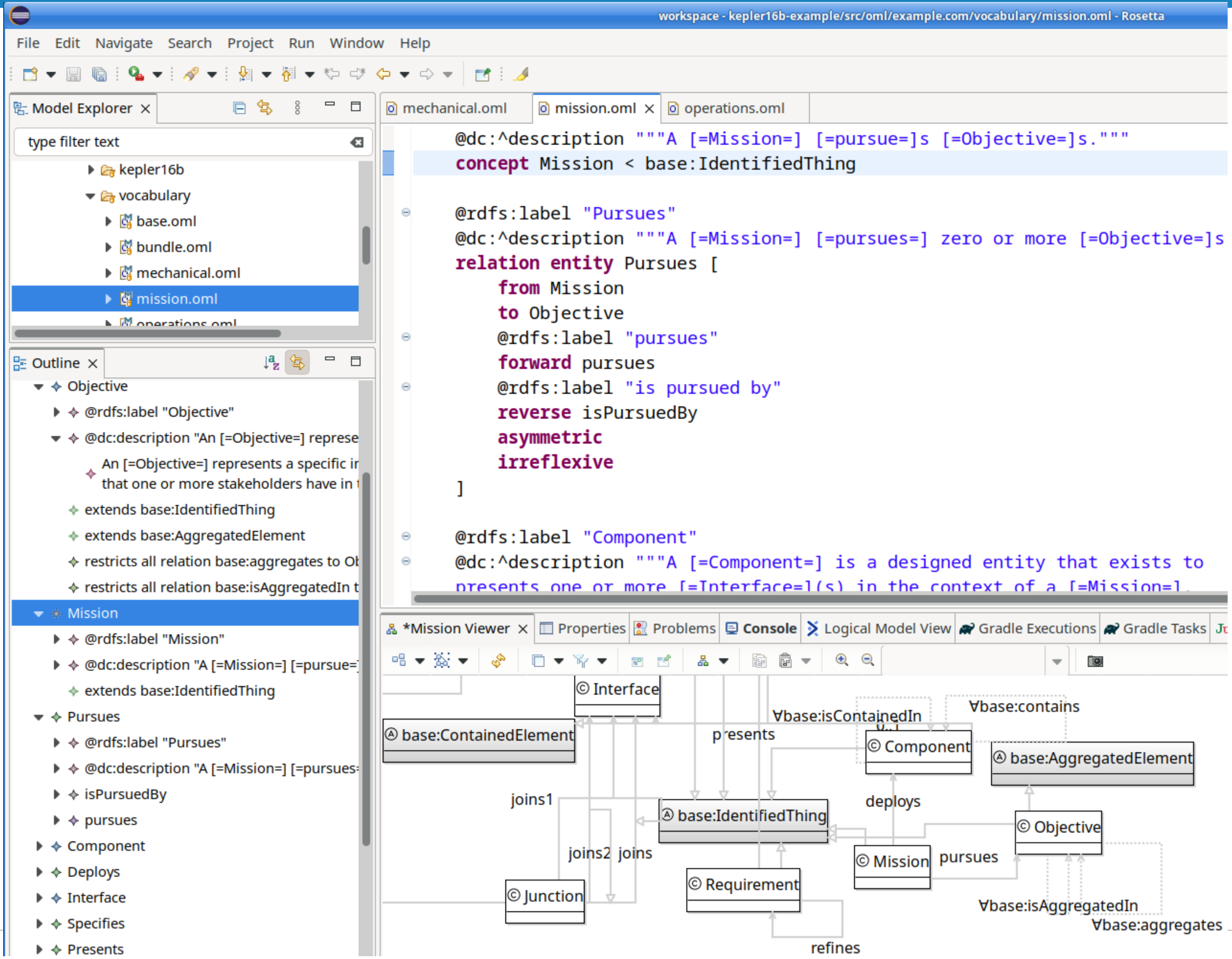
Authoring - Rosetta Editor (Eclipse)



workspace - kepler16b-example/src/oml/example.com/vocabulary/mission.oml - Rosetta

```
Objective
    @rdfs:label "Objective"
    @dc:description "An [=Objective=] represe
        An [=Objective=] represents a specific ir
        that one or more stakeholders have in t
    extends base:IdentifiedThing
    extends base:AggregatedElement
    restricts all relation base:aggregates to Ob
    restricts all relation base:isAggregatedIn t
Mission
    @rdfs:label "Mission"
    @dc:description "A [=Mission=] [=pursue=
    extends base:IdentifiedThing
Pursues
    @rdfs:label "Pursues"
    @dc:description "A [=Mission=] [=pursues=
    isPursuedBy
    pursues
Component
Deploys
Interface
Specifies
Presents
```

```
@dc:^description """A [=Mission=] [=pursue=]s [=Objective=]s."""
concept Mission < base:IdentifiedThing

@rdfs:label "Pursues"
@dc:^description """A [=Mission=] [=pursues=] zero or more [=Objective=]s
relation entity Pursues [
    from Mission
    to Objective
    @rdfs:label "pursues"
    forward pursues
    @rdfs:label "is pursued by"
    reverse isPursuedBy
    asymmetric
    irreflexive
]

@rdfs:label "Component"
@dc:^description """A [=Component=] is a designed entity that exists to
presents one or more [=Interface=](s) in the context of a [=Mission=]
```

https://github.com/opencaesar/oml-rosetta

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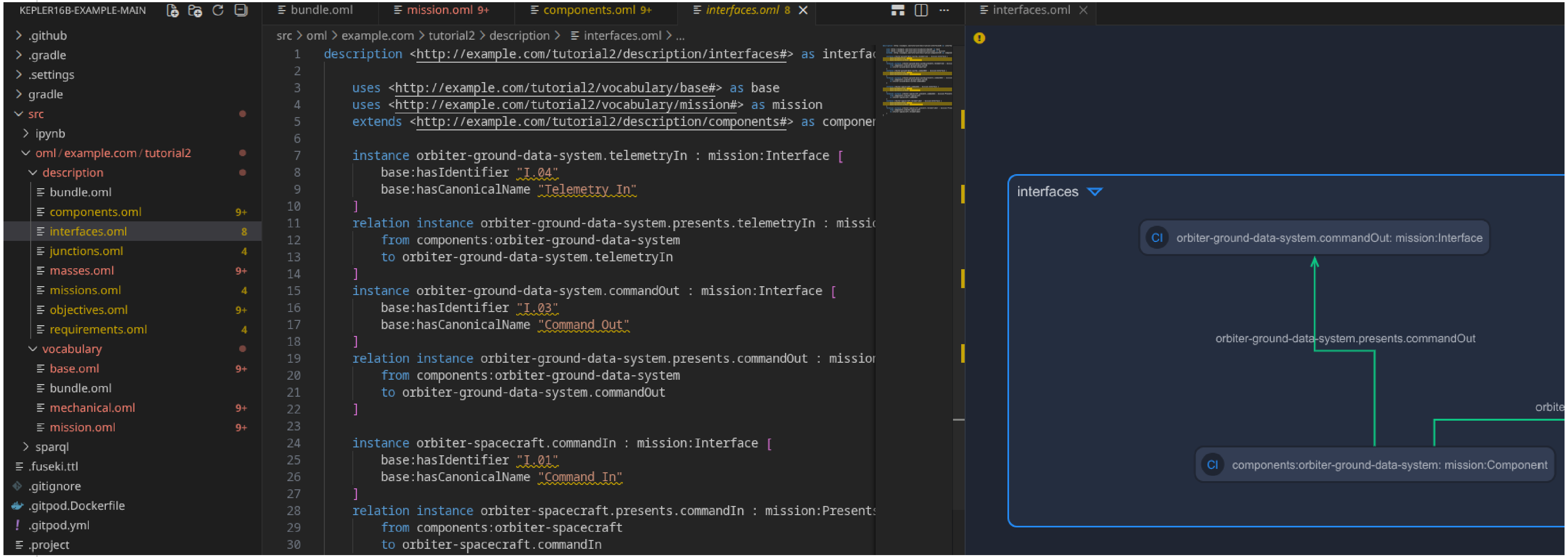
Authoring - Luxor Editor (VSCode)



KEPLER16B-EXAMPLE-MAIN

```
> .github
> .gradle
> .settings
> gradle
v src
  > ipynb
  v oml / example.com / tutorial2
    v description
        bundle.oml
        components.oml        9+
        interfaces.oml        8
        junctions.oml         4
        masses.oml            9+
        missions.oml          4
        objectives.oml        9+
        requirements.oml      4
    v vocabulary
        base.oml              9+
        bundle.oml
        mechanical.oml        9+
        mission.oml           9+
  > sparql
.fuseki.ttl
.gitignore
.gitpod.Dockerfile
.gitpod.yml
.project
```

bundle.oml | mission.oml 9+ | components.oml 9+ | *interfaces.oml* 8 | interfaces.oml

src > oml > example.com > tutorial2 > description > interfaces.oml > ...

```
description <http://example.com/tutorial2/description/interfaces#> as interfac

    uses <http://example.com/tutorial2/vocabulary/base#> as base
    uses <http://example.com/tutorial2/vocabulary/mission#> as mission
    extends <http://example.com/tutorial2/description/components#> as componen

    instance orbiter-ground-data-system.telemetryIn : mission:Interface [
        base:hasIdentifier "I.04"
        base:hasCanonicalName "Telemetry In"
    ]
    relation instance orbiter-ground-data-system.presents.telemetryIn : missio
        from components:orbiter-ground-data-system
        to orbiter-ground-data-system.telemetryIn
    ]
    instance orbiter-ground-data-system.commandOut : mission:Interface [
        base:hasIdentifier "I.03"
        base:hasCanonicalName "Command Out"
    ]
    relation instance orbiter-ground-data-system.presents.commandOut : missio
        from components:orbiter-ground-data-system
        to orbiter-ground-data-system.commandOut
    ]

    instance orbiter-spacecraft.commandIn : mission:Interface [
        base:hasIdentifier "I.01"
        base:hasCanonicalName "Command In"
    ]
    relation instance orbiter-spacecraft.presents.commandIn : mission:Presents
        from components:orbiter-spacecraft
        to orbiter-spacecraft.commandIn
```

interfaces
CI orbiter-ground-data-system.commandOut: mission:Interface
orbiter-ground-data-system.presents.commandOut
orbite
CI components:orbiter-ground-data-system: mission:Component

https://github.com/opencaesar/oml-luxor

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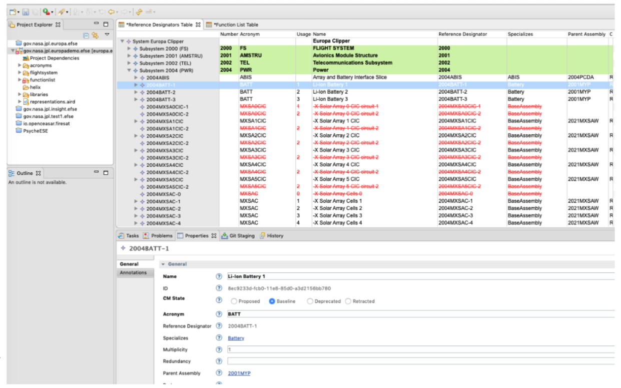
Authoring - Adaptors

Adapters needed to import from and export to other tools
- Excel, MagicDraw, SysML, DOORS
- Also custom editors
- Based on defined vocabularies



Project Explorer
- gov.nasa.jpl.europa.efse
- gov.nasa.jpl.europademo.efse [europa.e
  - Project Dependencies
  - acronyms
  - flightsystem
  - functionlist
  - helix
  - libraries
  - representations.aird
- gov.nasa.jpl.insight.efse
- gov.nasa.jpl.test1.efse
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2004BATT-1		BATT	1	Li-Ion Battery 1	2004BATT-1	Battery	2001MYP	R
2004BATT-2		BATT	2	Li-Ion Battery 2	2004BATT-2	Battery	2001MYP	R
2004BATT-3		BATT	3	Li-Ion Battery 3	2004BATT-3	Battery	2001MYP	R
2004MXSA0CIC-1		~~MXSA0CIC~~	~~1~~	~~-X Solar Array 0 CIC circuit 1~~	~~2004MXSA0CIC-1~~	~~BaseAssembly~~		
2004MXSA0CIC-2		~~MXSA0CIC~~	~~2~~	~~-X Solar Array 0 CIC circuit 2~~	~~2004MXSA0CIC-2~~	~~BaseAssembly~~		
2004MXSA1CIC		MXSA1CIC		-X Solar Array 1 CIC	2004MXSA1CIC	BaseAssembly	2021MXSAW	R
2004MXSA1CIC-2		~~MXSA1CIC~~	~~2~~	~~-X Solar Array 1 CIC circuit 2~~	~~2004MXSA1CIC-2~~	~~BaseAssembly~~		
2004MXSA2CIC		MXSA2CIC		-X Solar Array 2 CIC	2004MXSA2CIC	BaseAssembly	2021MXSAW	R
2004MXSA2CIC-2		~~MXSA2CIC~~	~~2~~	~~-X Solar Array 2 CIC circuit 2~~	~~2004MXSA2CIC-2~~	~~BaseAssembly~~		
2004MXSA3CIC		MXSA3CIC		-X Solar Array 3 CIC	2004MXSA3CIC	BaseAssembly	2021MXSAW	R
2004MXSA3CIC-2		~~MXSA3CIC~~	~~2~~	~~-X Solar Array 3 CIC circuit 2~~	~~2004MXSA3CIC-2~~	~~BaseAssembly~~		
2004MXSA4CIC		MXSA4CIC		-X Solar Array 4 CIC	2004MXSA4CIC	BaseAssembly	2021MXSAW	R
2004MXSA4CIC-2		~~MXSA4CIC~~	~~2~~	~~-X Solar Array 4 CIC circuit 2~~	~~2004MXSA4CIC-2~~	~~BaseAssembly~~		
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2004MXSA5CIC-2		~~MXSA5CIC~~	~~2~~	~~-X Solar Array 5 CIC circuit 2~~	~~2004MXSA5CIC-2~~	~~BaseAssembly~~		
2004MXSAC-0		~~MXSAC~~	~~0~~	~~-X Solar Array Cells 0~~	~~2004MXSAC-0~~	~~BaseAssembly~~		
2004MXSAC-1		MXSAC	1	-X Solar Array Cells 1	2004MXSAC-1	BaseAssembly	2021MXSAW	R
2004MXSAC-2		MXSAC	2	-X Solar Array Cells 2	2004MXSAC-2	BaseAssembly	2021MXSAW	R
2004MXSAC-3		MXSAC	3	-X Solar Array Cells 3	2004MXSAC-3	BaseAssembly	2021MXSAW	R
2004MXSAC-4		MXSAC	4	-X Solar Array Cells 4	2004MXSAC-4	BaseAssembly	2021MXSAW	R

Tasks | Problems | Properties | Git Staging | History

2004BATT-1

General | Annotations

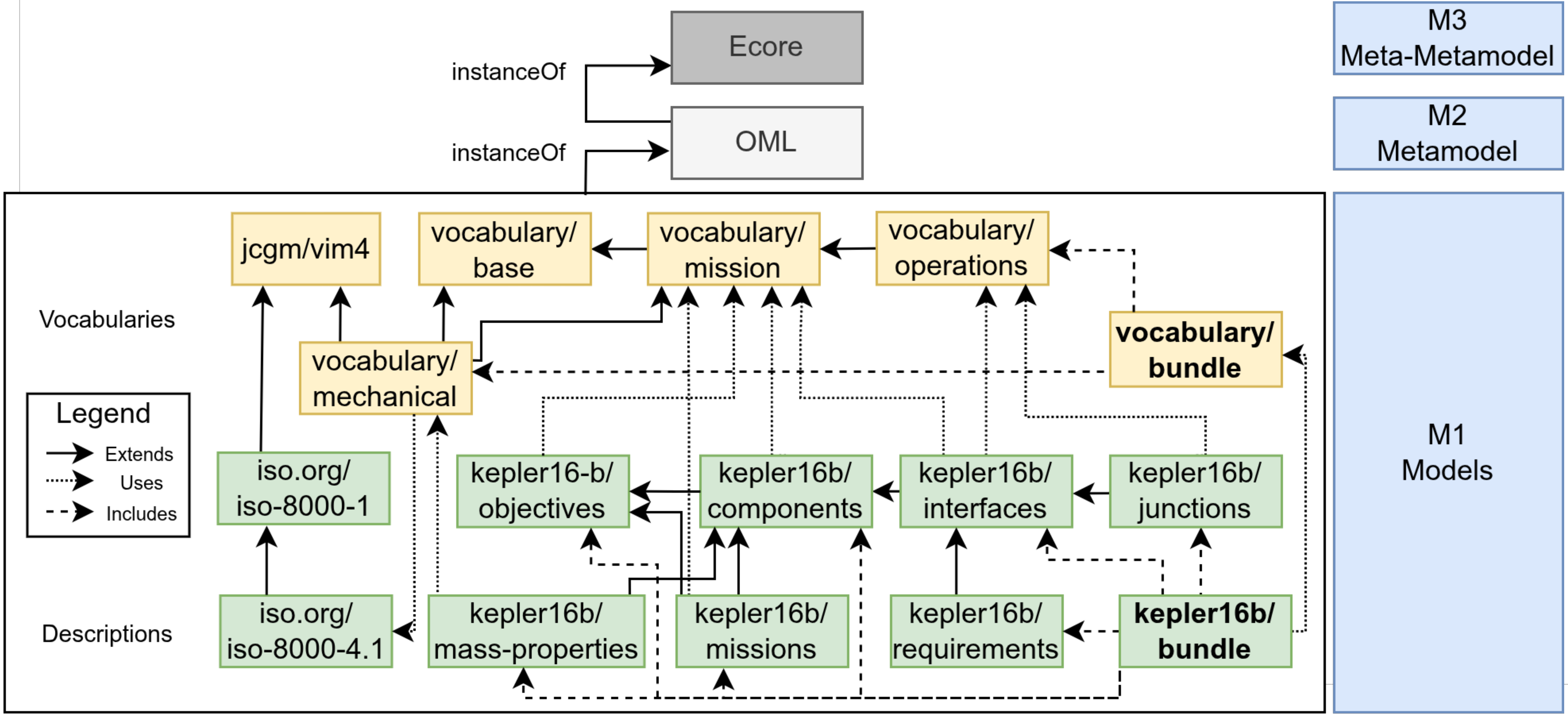
General

Name	Li-Ion Battery 1
ID	8ec9233d-fcb0-11e8-85d0-a3d2156bb780
CM State	( ) Proposed [✓ Baseline] ( ) Deprecated ( ) Retracted
Acronym	BATT
Reference Designator	2004BATT-1
Specializes	Battery
Multiplicity	1
Redundancy	
Parent Assembly	2001MYP

Figure 4 Composition view in CAESAR workbench

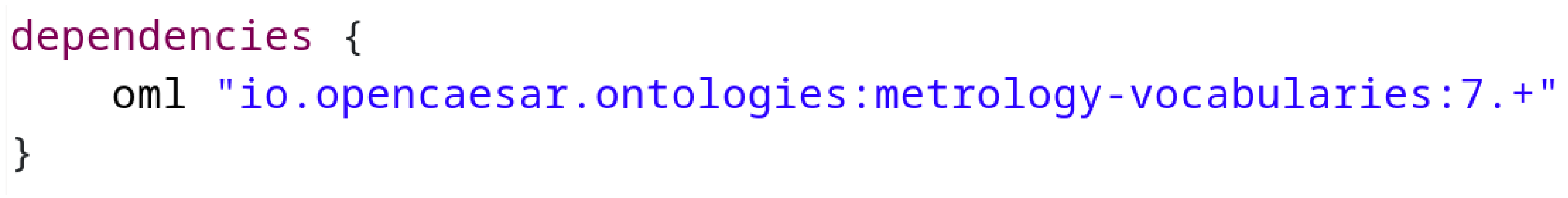
Federation - OML Modelling Levels

Federation achieved by placing models in different Git repositories

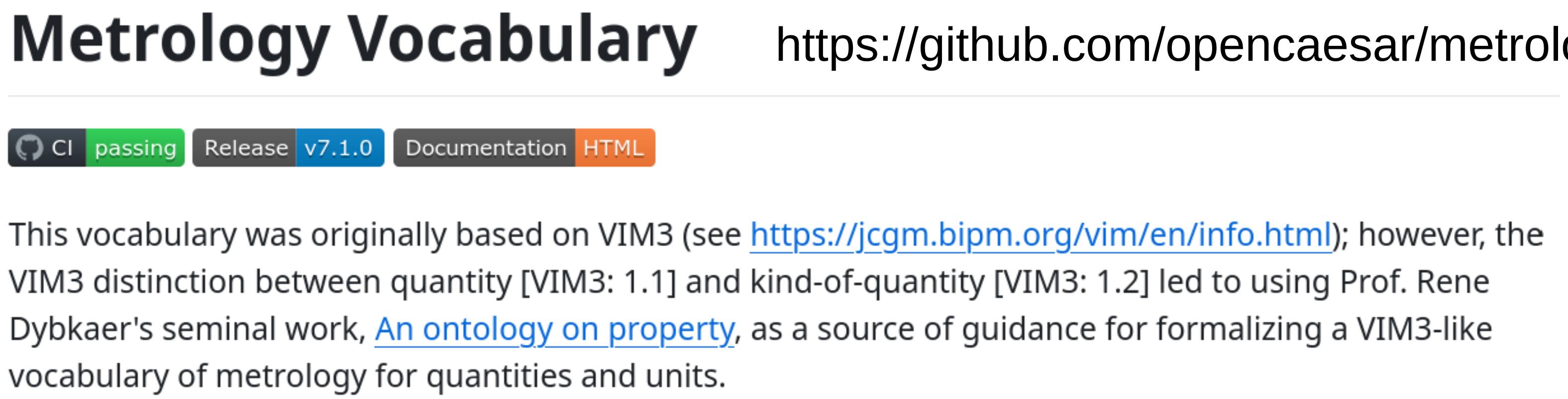


Configuration/Integration

OML projects can define dependencies



```
dependencies {
    oml "io.opencaesar.ontologies:metrology-vocabularies:7.+"
}
```

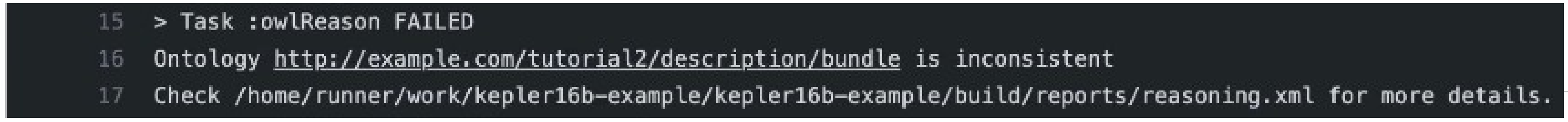


Metrology Vocabulary

https://github.com/opencaesar/metrology-vocabularies

This vocabulary was originally based on VIM3 (see https://jcgm.bipm.org/vim/en/info.html); however, the VIM3 distinction between quantity [VIM3: 1.1] and kind-of-quantity [VIM3: 1.2] led to using Prof. Rene Dybkaer's seminal work, An ontology on property, as a source of guidance for formalizing a VIM3-like vocabulary of metrology for quantities and units.

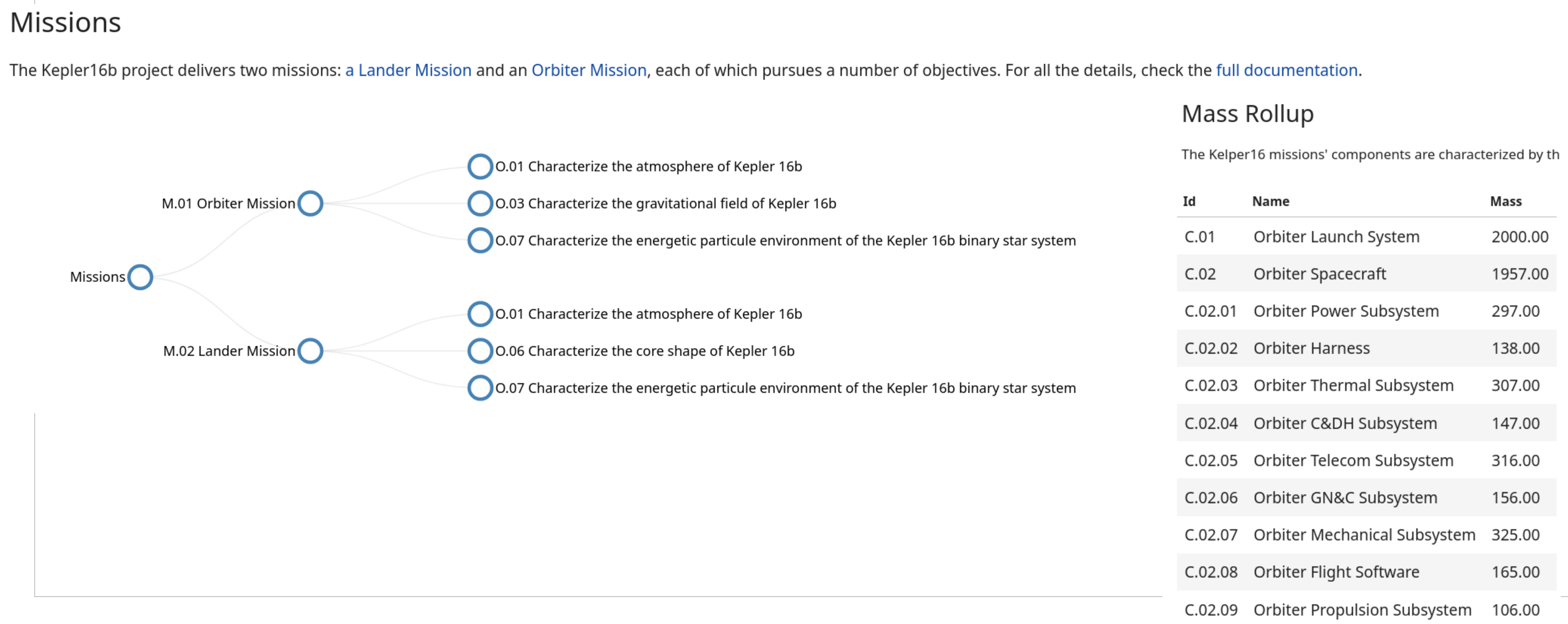
- Ontologies are stored in Git repositories
- Versioned through Git and Maven
- CI/CD can be used to check consistency



```
> Task :owlReason FAILED
Ontology http://example.com/tutorial2/description/bundle is inconsistent
Check /home/runner/work/kepler16b-example/kepler16b-example/build/reports/reasoning.xml for more details.
```

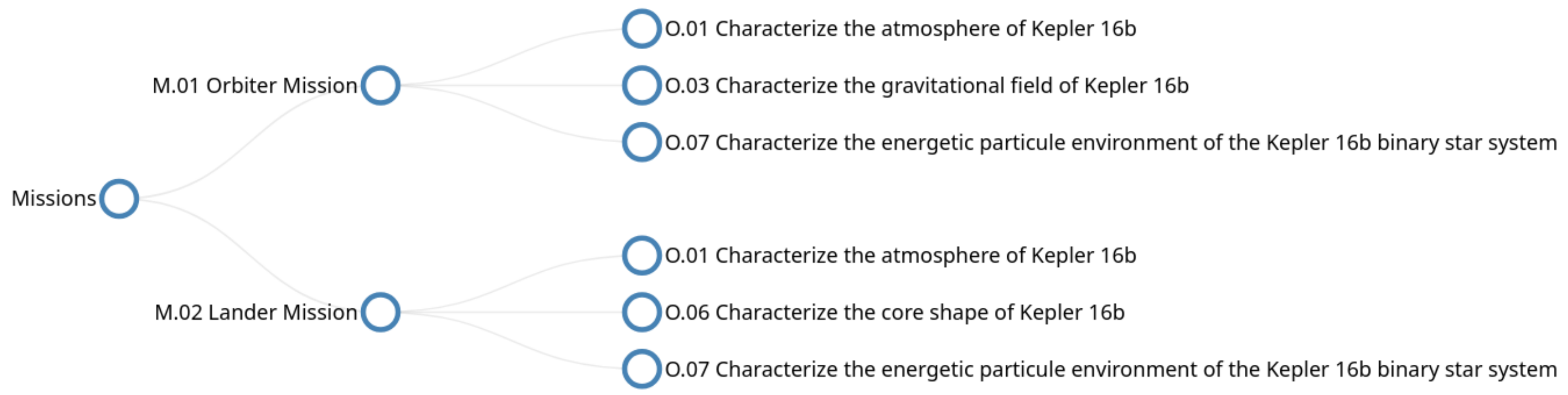
Analysis/Reporting

- Analysis can be federated for each repository
- CI/CD used to automate analysis
- Analysis produces results, combined with query results to produce reports



Missions

The Kepler16b project delivers two missions: a Lander Mission and an Orbiter Mission, each of which pursues a number of objectives. For all the details, check the full documentation.

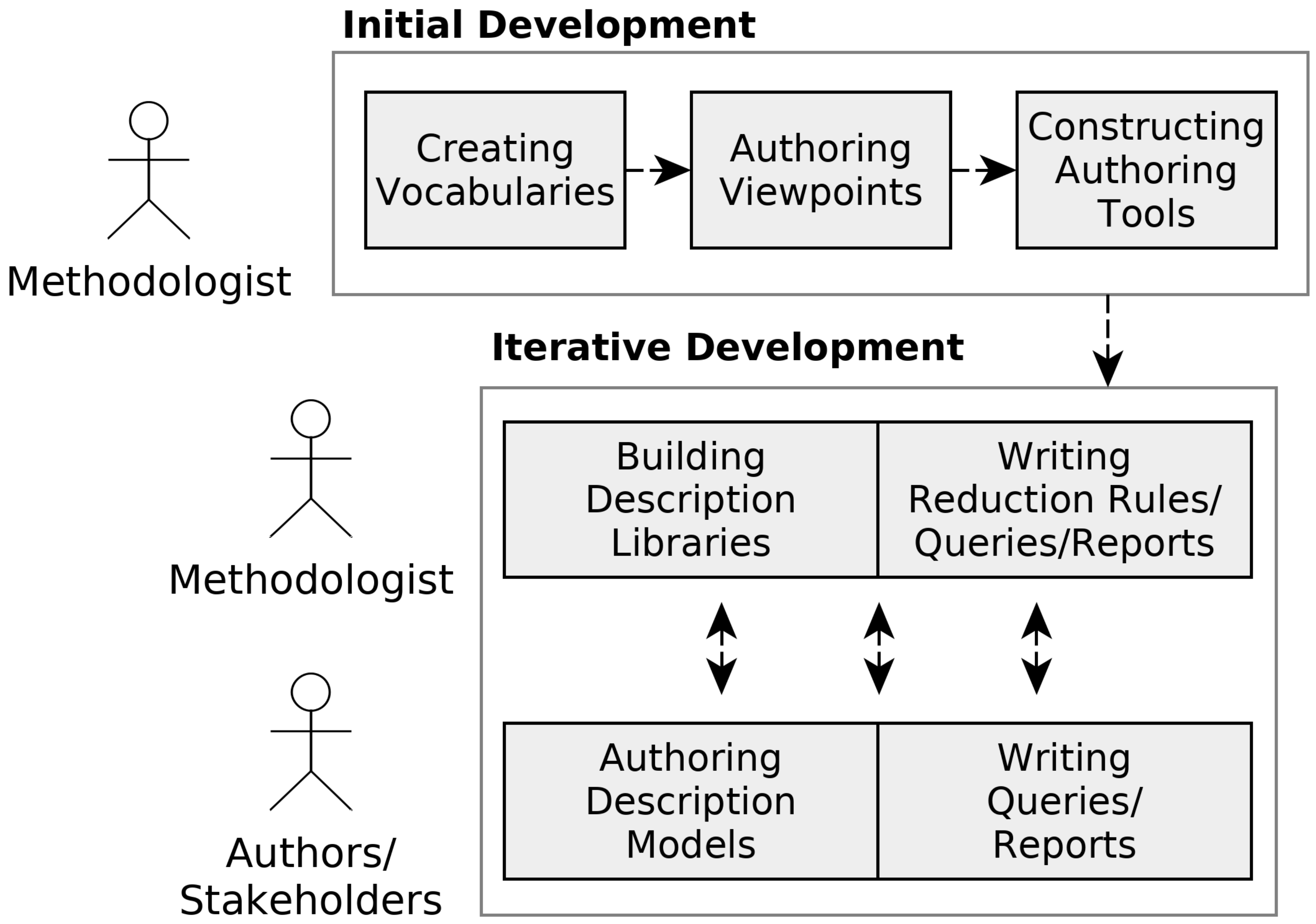

Missions
M.01 Orbiter Mission
O.01 Characterize the atmosphere of Kepler 16b
O.03 Characterize the gravitational field of Kepler 16b
O.07 Characterize the energetic particule environment of the Kepler 16b binary star system
M.02 Lander Mission
O.01 Characterize the atmosphere of Kepler 16b
O.06 Characterize the core shape of Kepler 16b
O.07 Characterize the energetic particule environment of the Kepler 16b binary star system

Mass Rollup

The Kelper16 missions' components are characterized by th

Id	Name	Mass
C.01	Orbiter Launch System	2000.00
C.02	Orbiter Spacecraft	1957.00
C.02.01	Orbiter Power Subsystem	297.00
C.02.02	Orbiter Harness	138.00
C.02.03	Orbiter Thermal Subsystem	307.00
C.02.04	Orbiter C&DH Subsystem	147.00
C.02.05	Orbiter Telecom Subsystem	316.00
C.02.06	Orbiter GN&C Subsystem	156.00
C.02.07	Orbiter Mechanical Subsystem	325.00
C.02.08	Orbiter Flight Software	165.00
C.02.09	Orbiter Propulsion Subsystem	106.00

openCAESAR Methodology



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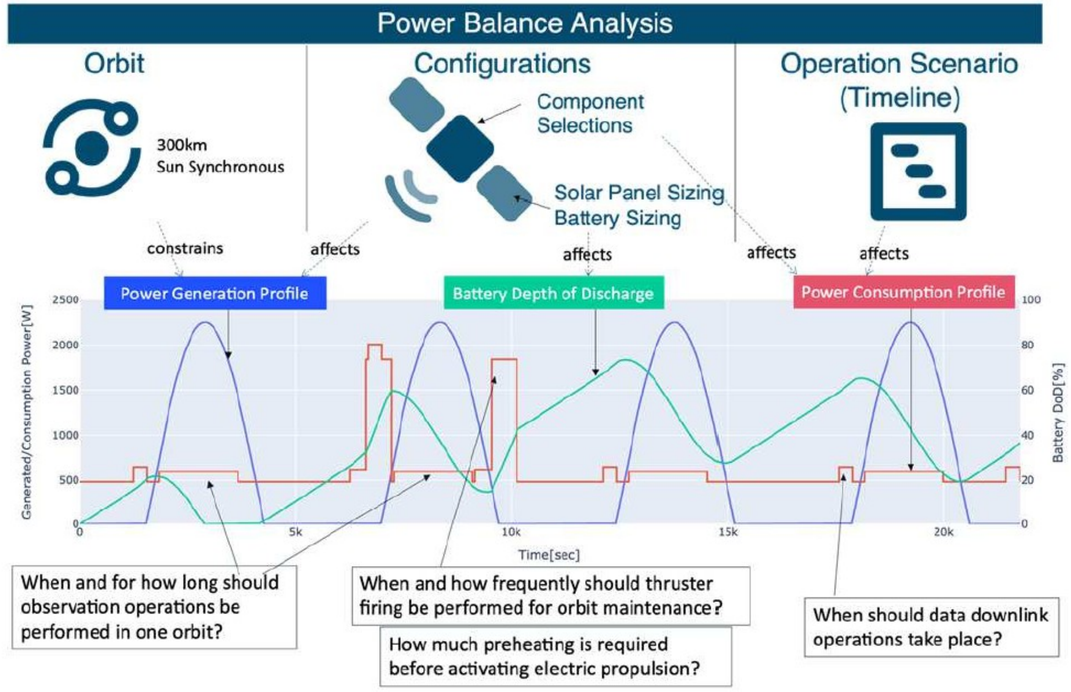
Onto:Nexus workshop at MODELS

onto:Nexus
Workshop 2025

https://www.opencaesar.io/events/onto-Nexus-Workshop-2025

- Keynote: Software Quality for the Semantic Web– Eduard Kamburjan
- Integrated Knowledge Centric Engineering: Delivering Next-Generation Aircraft Projects at Pace – Lewis Humphries et al.
- **openCAESAR Application to Power Balance Analysis in Early Space Mission Formulation – Yuta Nakajima et al.**
- Power of a Reasoner: Model Validation for SysML Model using openCAESAR – Yuta Nakajima et al.
- Towards bridging ontological and closed-world modelling with synchronised EMF views of RDF models – Owen Reynolds et al.
- An Ontological Representation of the UML Testing Profile – Joe Gregory et al.

openCAESAR Application to Power Balance Analysis in Early Space Mission Formulation



Power Balance Analysis
Orbit
Configurations
Operation Scenario (Timeline)
300km Sun Synchronous
Component Selections
Solar Panel Sizing Battery Sizing
constrains
affects
affects
affects
affects
Power Generation Profile
Battery Depth of Discharge
Power Consumption Profile
Generated/Consumption Power[W]
Battery DoD[%]
Time[sec]
When and for how long should observation operations be performed in one orbit?
When and how frequently should thruster firing be performed for orbit maintenance?
How much preheating is required before activating electric propulsion?
When should data downlink operations take place?

Fig. 1. Power Balance Analysis in early space mission formulation

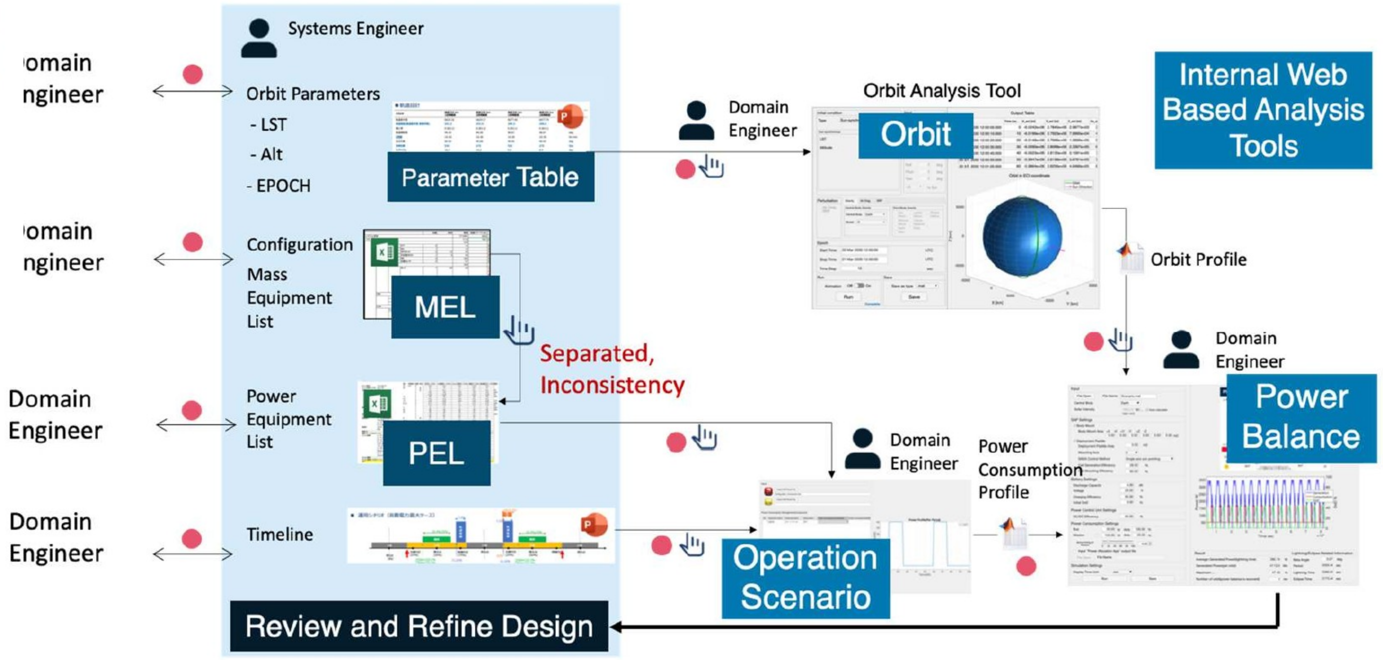


Fig. 2. Current Power Balance Analysis Workflow in early space mission formulation. The red circle highlights manual data entry activity.

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openCAESAR Application to Power Balance Analysis in Early Space Mission Formulation

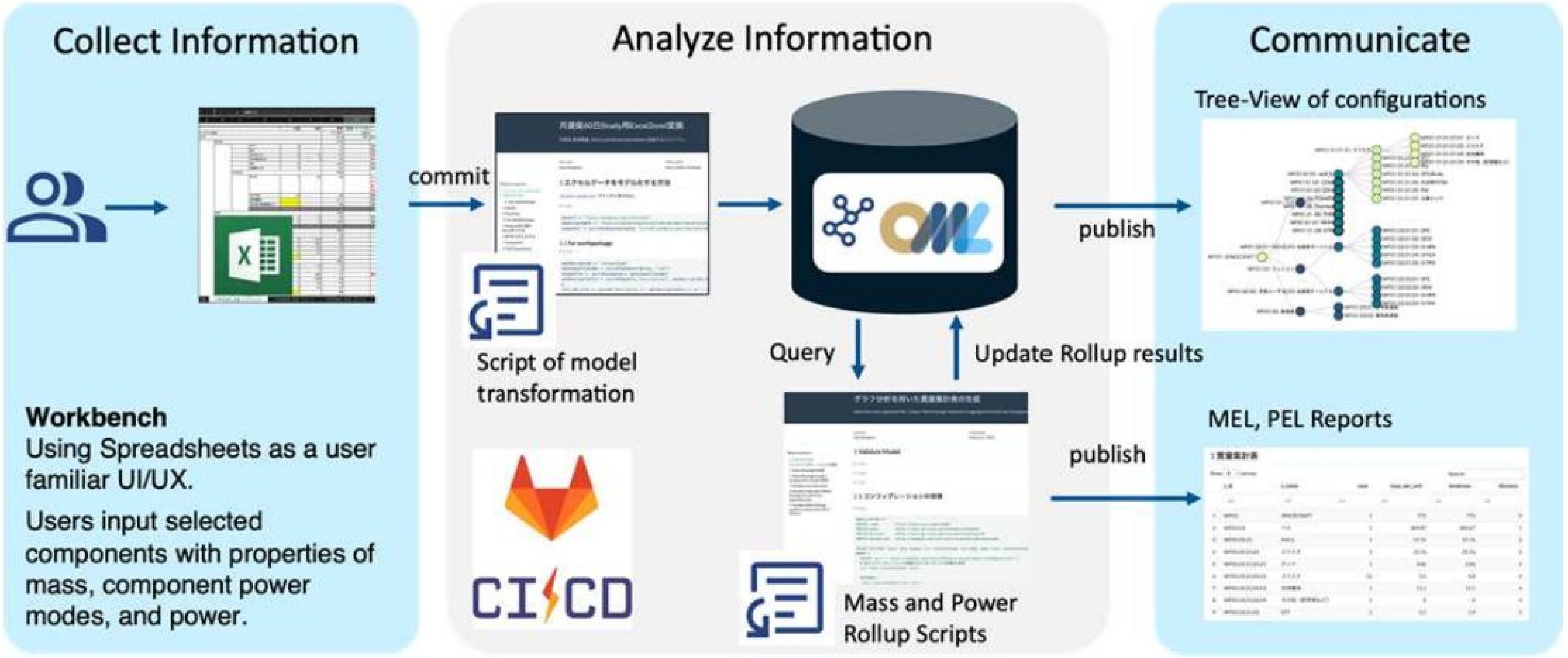
Collect Information
Analyze Information
Communicate
commit
Script of model transformation
Query
Update Rollup results
publish
Tree-View of configurations
MEL, PEL Reports
publish
Workbench
Using Spreadsheets as a user familiar UI/UX.
Users input selected components with properties of mass, component power modes, and power.
CI/CD
Mass and Power Rollup Scripts

Fig.4. Workflow for System Configurations, MELs, and PELs.

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openCAESAR Application to Power Balance Analysis in Early Space Mission Formulation

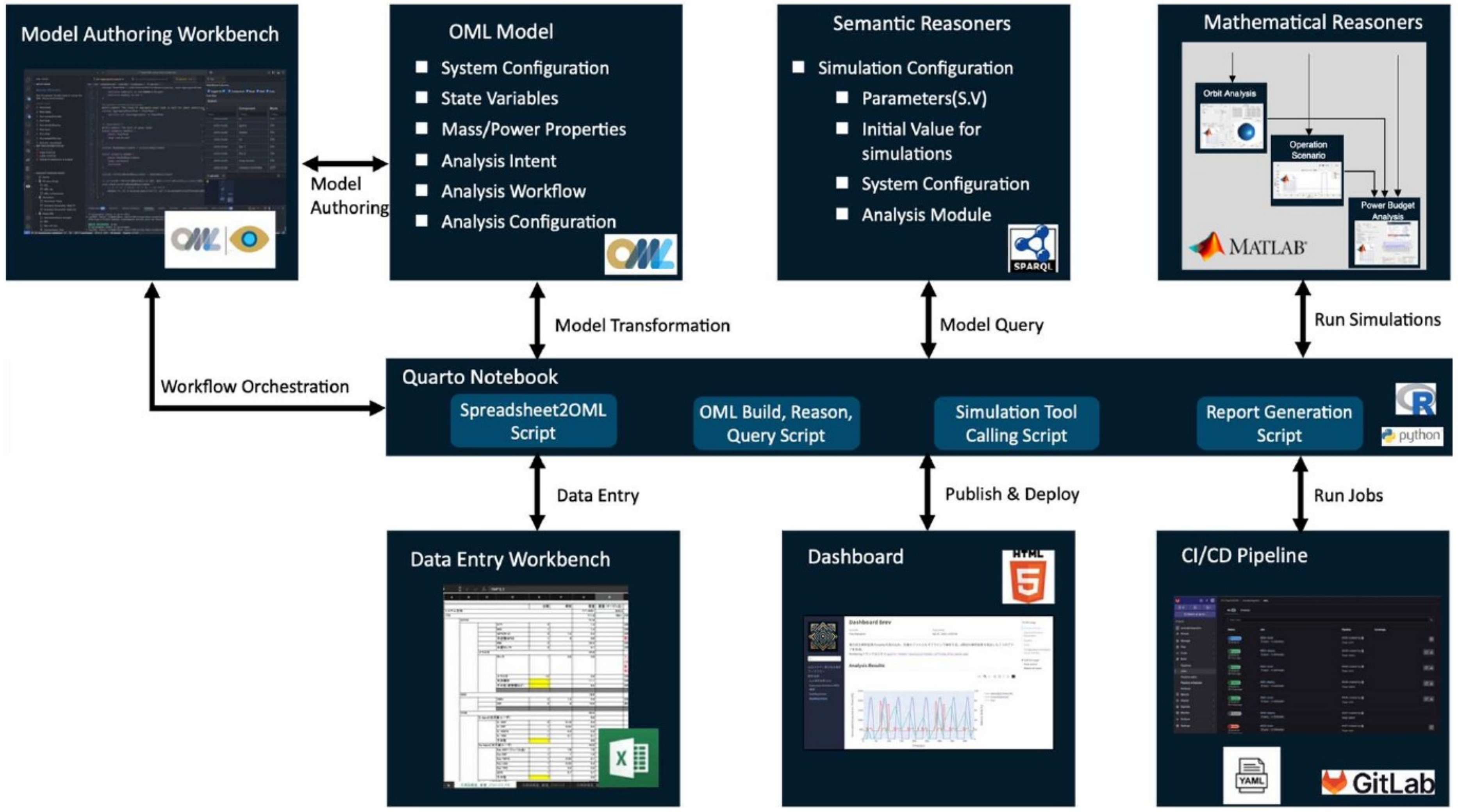

Fig. 3. Integrated Workflow for 60-day studies using openCAESAR.

OML and openCAESAR Conclusion

- Rigorous and flexible framework
- OML addresses level of abstraction issue
- OpenCAESAR addresses tooling issue

- Why I like them
  - Feels more model-based, engineer-minded
  - Brings software engineering principles to systems engineering

- Used in practice
  - NASA JPL, JAXA, Leonardo
  - U Arizona, U Antwerp, Polytechnique Montreal
- Supported by NASA JPL and JAXA

https://www.opencaesar.io/oml-tutorials/

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Systematic DT Reporting

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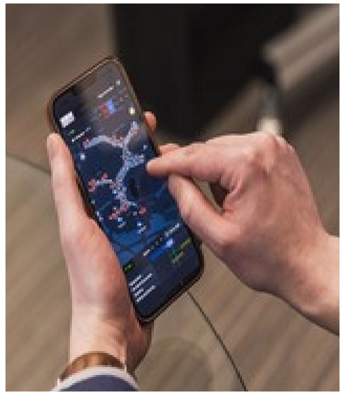
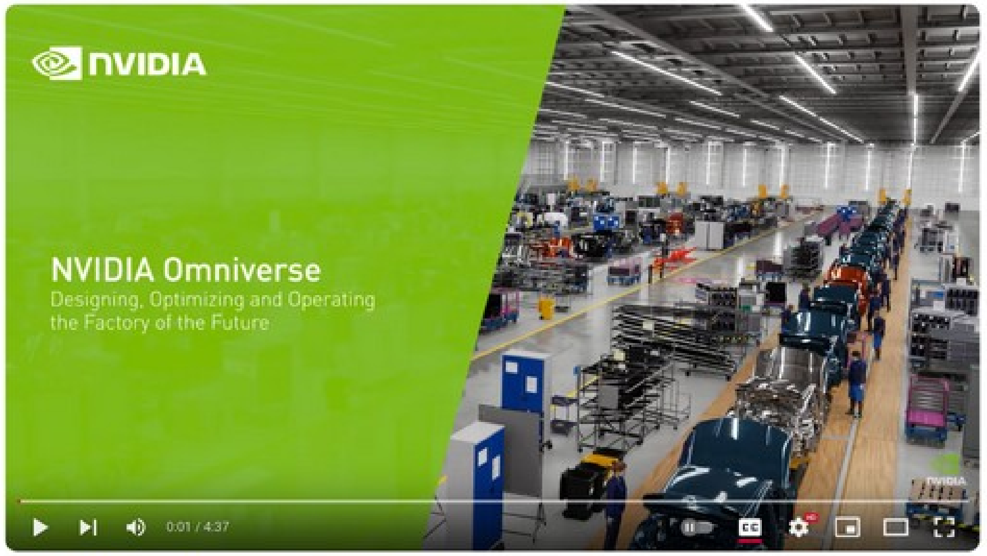
Systematic DT Reporting

Motivation

DT Diversity




NVIDIA
NVIDIA Omniverse
Designing, Optimizing and Operating the Factory of the Future
0:01 / 4:37

NVIDIA Omniverse - Designing, Optimizing and Operating the Factory of the Future

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“What Does Your DT Do?”

Instead of arguing about definitions...

Let’s discuss what your DT **is** and **does**

My questions: Is it **real-time**? What are the **services** it provides? How did you **engineer** it?

Unclear Info in Reports

We argue that due to the lack of standardization in Digital Twins, **essential information is not being adequately reported**

Oakes et al.. (2021). *Improving digital twin experience reports*. MODELSWARD (pp. 179-190).

Digital (Model vs Shadow vs Twin)

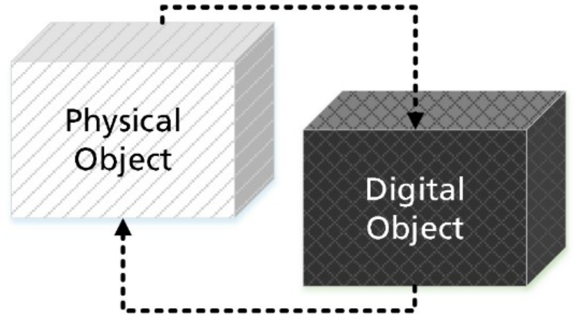


Fig. 1. Data Flow in a Digital Model

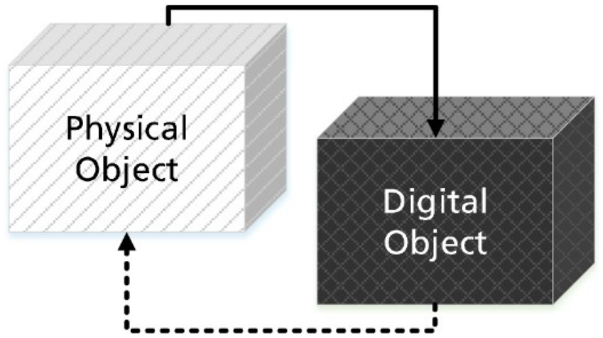


Fig. 2. Data Flow in a Digital Shadow

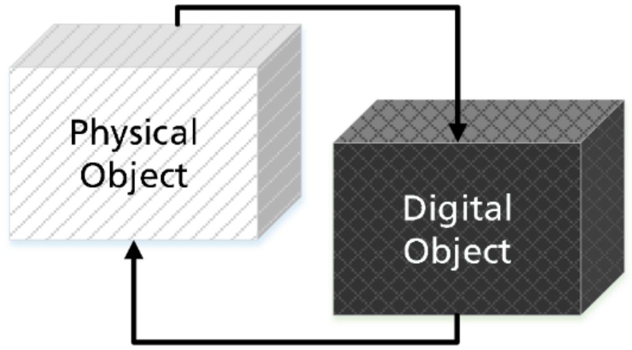
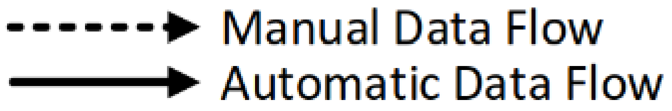
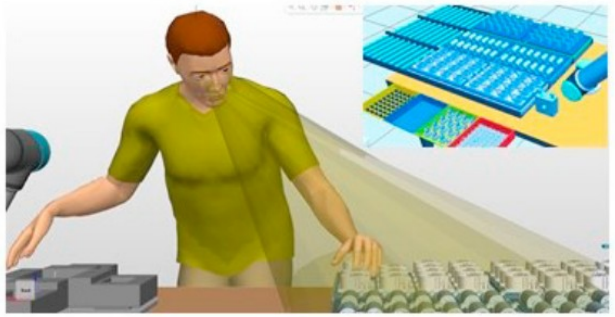


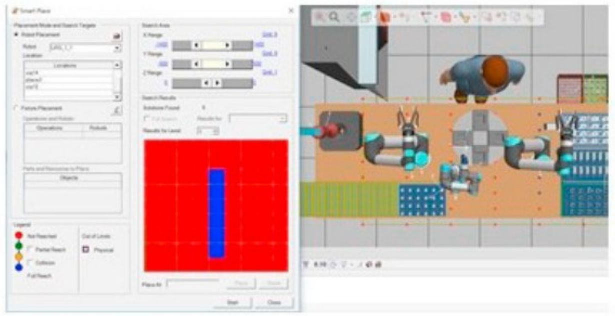
Fig. 3. Data Flow in a Digital Twin



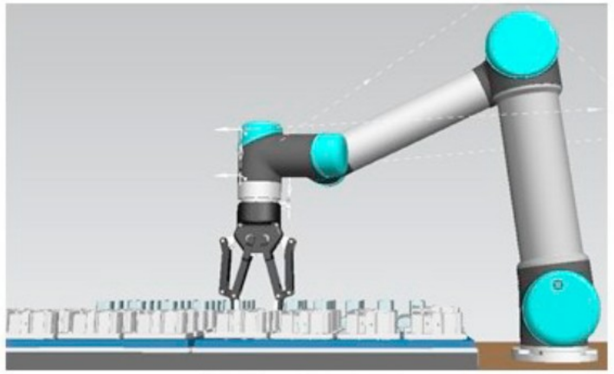
Kritzinger et al. (2018).
Digital Twin in manufacturing: A categorical literature review and classification.
Ifac-PapersOnline, 51(11), 1016-1022.

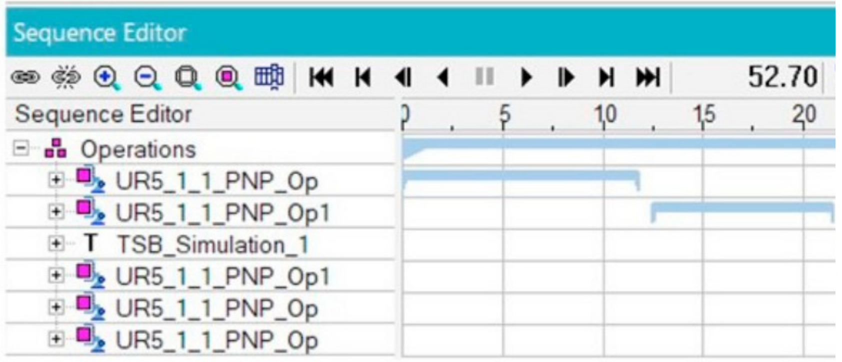
Unclear Info Example


Vision Analysis


Robot Reach Analysis

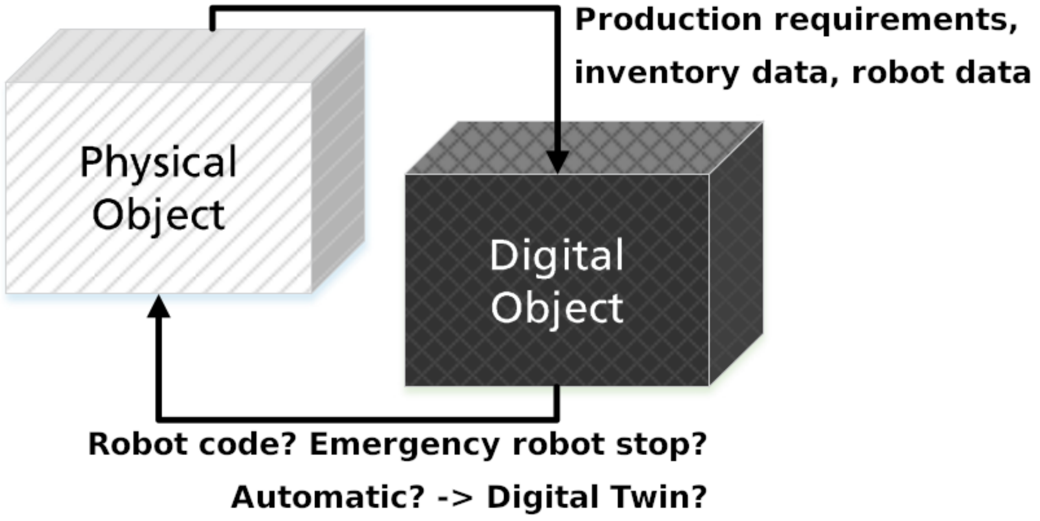
Grasp Analysis


Robot Program



```
Sequence Editor
⊟ Operations
  ⊞ UR5_1_1_PNP_Op
  ⊞ UR5_1_1_PNP_Op1
  ⊞ T TSB_Simulation_1
  ⊞ UR5_1_1_PNP_Op1
  ⊞ UR5_1_1_PNP_Op
  ⊞ UR5_1_1_PNP_Op
```

Operation Times


Production requirements,
inventory data, robot data
Physical Object
Digital Object
Robot code? Emergency robot stop?
Automatic? -> Digital Twin?

Bilberg & Malik (2019). Digital twin driven human–robot collaborative assembly. CIRP annals, 68(1), 499-502.

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Hindering Empirical Research?

Returning to my questions:

What exact **services** are there? What **technology**? What **models**? What were the **engineering milestones** of the DT? Etc.

- Important for both **researchers** and **practitioners** (to know best practices)

- Having all details **explicitly reported** would allow for more detailed empirical research

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Systematic DT Reporting

Reporting Framework

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Reporting Framework Goal

- Define **DT characteristics** to be reported/discussed
- Move towards **common language** (textual and graphical)

- Not to be **enforced** on authors, simply guidance
- Characteristics must be **flexible** and change as needed

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Constructive Intention

Reporting framework is intended to **support** improvement, **not criticize** DT researchers or their papers

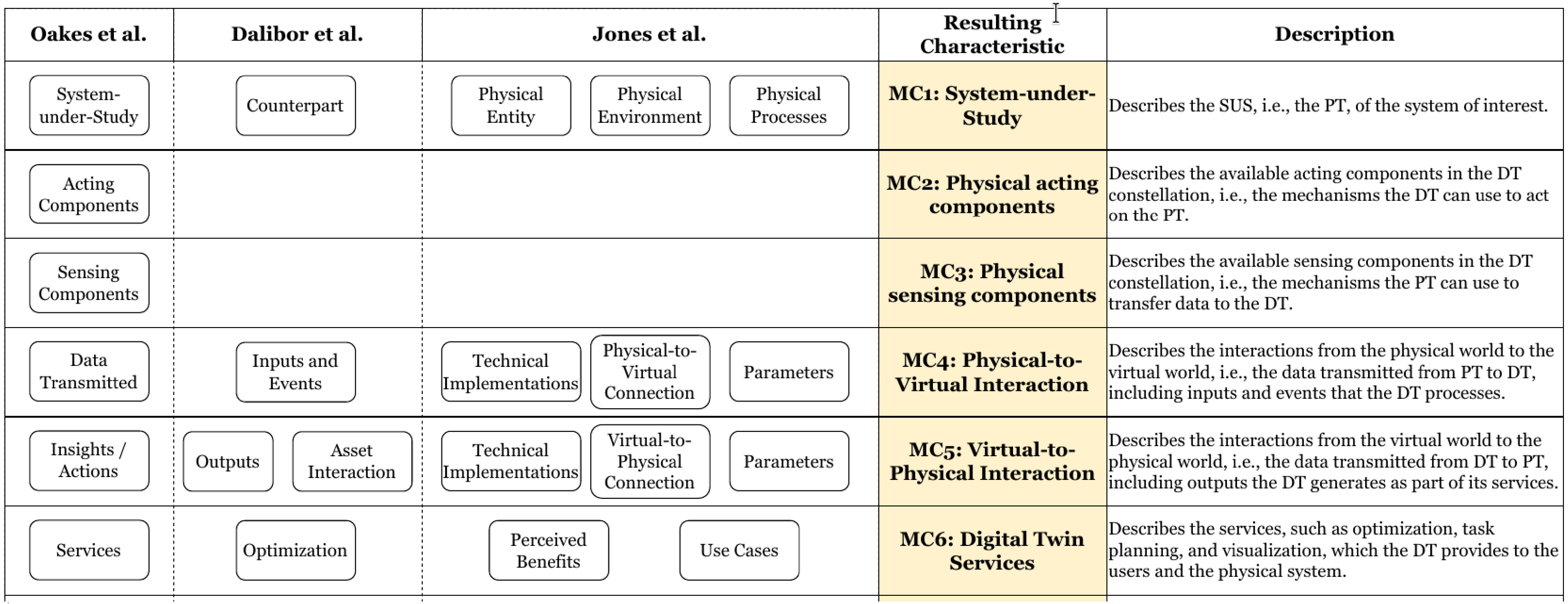
DT Systematic Reporting Framework

Gil, Oakes, et al. (2024). *Toward a systematic reporting framework for digital twins: a cooperative robotics case study*. Simulation.

- **18 fundamental characteristics** and **three cross-cutting characteristics** for reporting DT case studies
- Formed by systematically **merging three frameworks** from Oakes, Dalibor, and Jones
- Reports **robotics, mobile robotics, and incubator case studies**

Merging Detail

Table 4. Merge of the reporting frameworks by Oakes et al.[7], Dalibor et al.[14], and Jones et al.[18]. *In bold*: Fundamental characteristics. *In italics*: cross-cutting characteristics.



Oakes et al.	Dalibor et al.	Jones et al.	Resulting Characteristic	Description
System-under-Study	Counterpart	Physical Entity Physical Environment Physical Processes	**MC1: System-under-Study**	Describes the SUS, i.e., the PT, of the system of interest.
Acting Components			**MC2: Physical acting components**	Describes the available acting components in the DT constellation, i.e., the mechanisms the DT can use to act on the PT.
Sensing Components			**MC3: Physical sensing components**	Describes the available sensing components in the DT constellation, i.e., the mechanisms the PT can use to transfer data to the DT.
Data Transmitted	Inputs and Events	Technical Implementations Physical-to-Virtual Connection Parameters	**MC4: Physical-to-Virtual Interaction**	Describes the interactions from the physical world to the virtual world, i.e., the data transmitted from PT to DT, including inputs and events that the DT processes.
Insights / Actions	Outputs Asset Interaction	Technical Implementations Virtual-to-Physical Connection Parameters	**MC5: Virtual-to-Physical Interaction**	Describes the interactions from the virtual world to the physical world, i.e., the data transmitted from DT to PT, including outputs the DT generates as part of its services.
Services	Optimization	Perceived Benefits Use Cases	**MC6: Digital Twin Services**	Describes the services, such as optimization, task planning, and visualization, which the DT provides to the users and the physical system.

...

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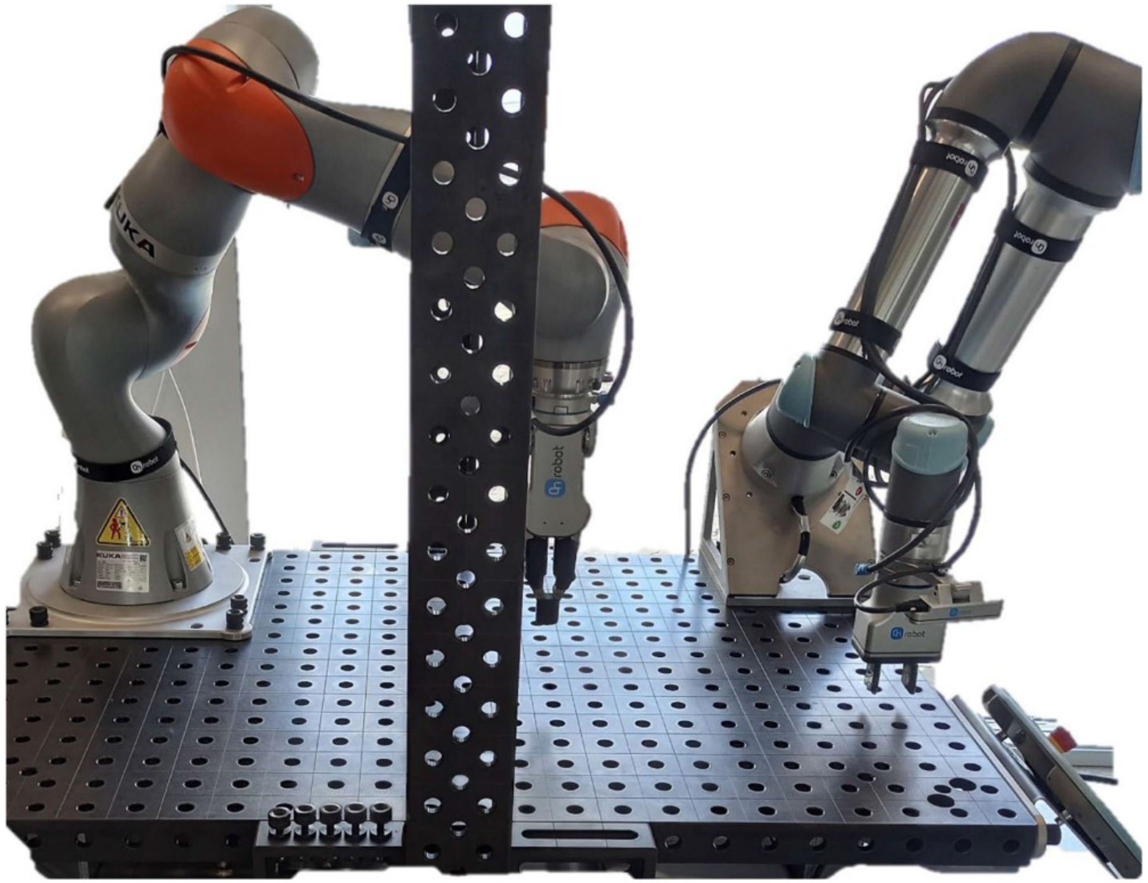
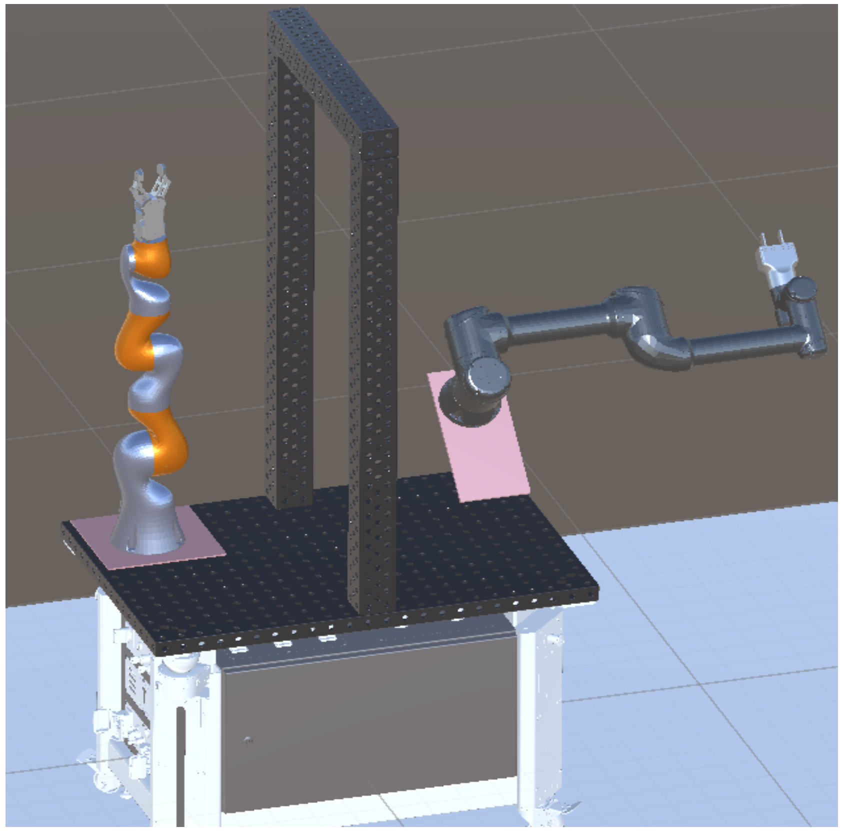
Main Idea: DT Constellation

- DTs:
  - connected in loop with PT
  - provide **services** (top)
  - operate on **models/data** (bottom)
  - Have **enablers** (in-between)
  - Data flows through DT

Robotics Case Study



PT: Manufacturing cell with independent assets
(2 robotic arms, 2 grippers)



DT: what-if simulation, trajectory visualization, discrete working space commands, and deviation checking

Robotics Constellation

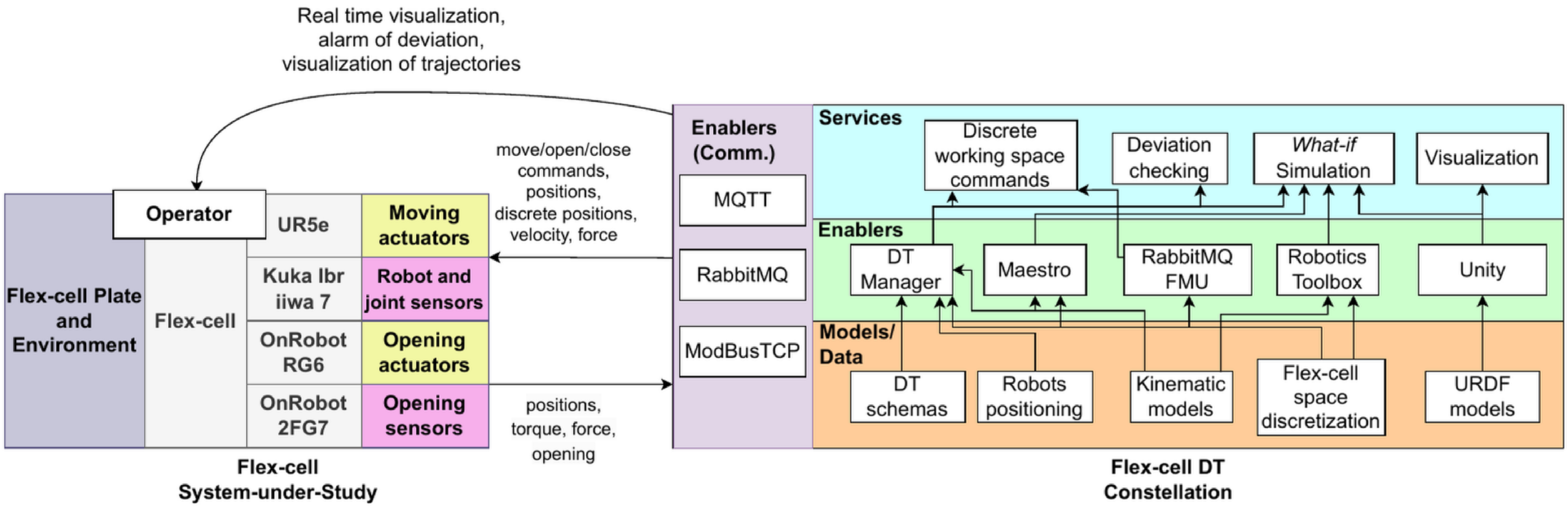
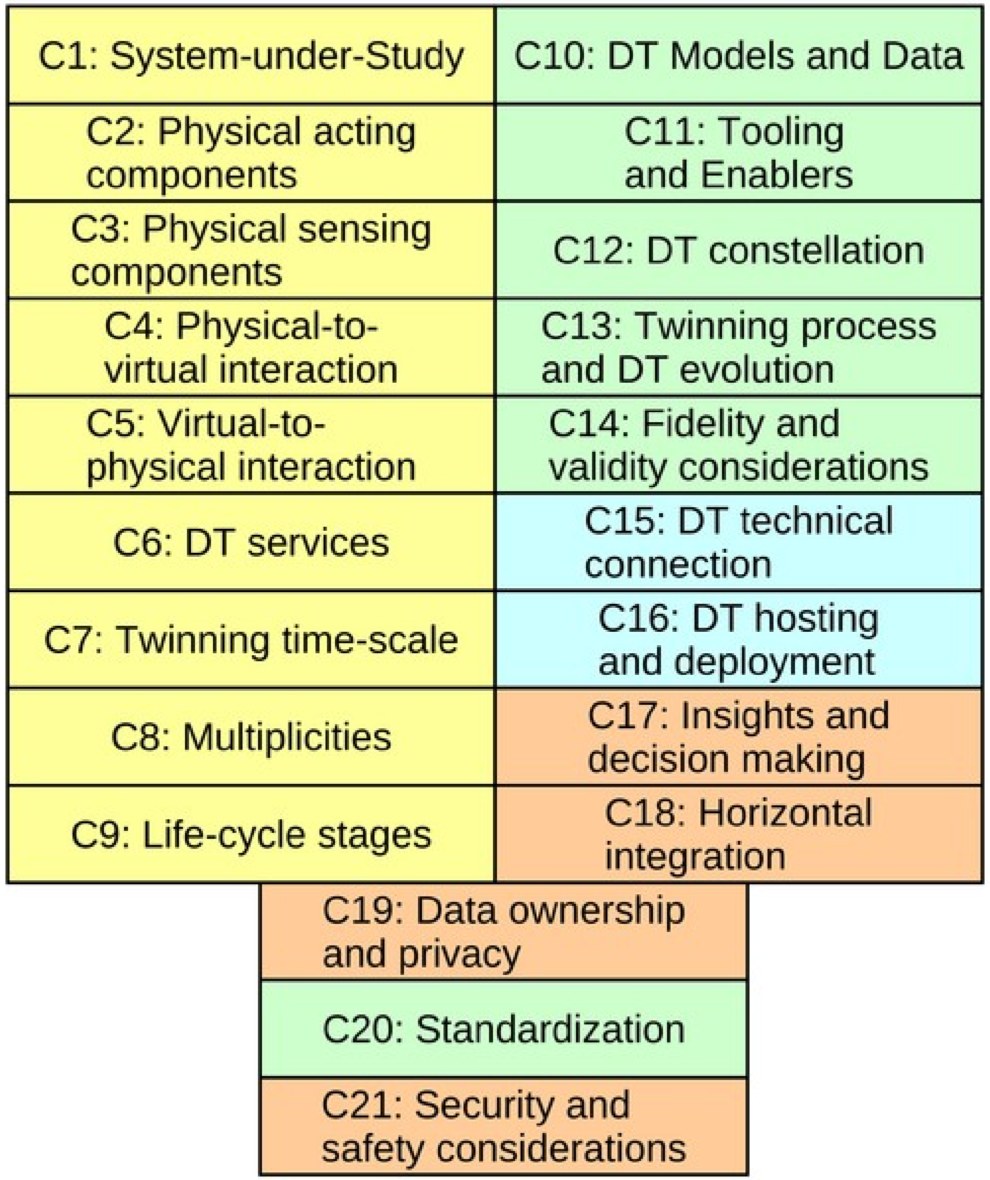


Figure 5. Constellation[7] of the flex-cell DT, detailing the composition of the DT and the data flow.

DT Characteristics



🟨 C1: System-under-Study	🟩 C10: DT Models and Data
🟨 C2: Physical acting components	🟩 C11: Tooling and Enablers
🟨 C3: Physical sensing components	🟩 C12: DT constellation
🟨 C4: Physical-to-virtual interaction	🟩 C13: Twinning process and DT evolution
🟨 C5: Virtual-to-physical interaction	🟩 C14: Fidelity and validity considerations
🟨 C6: DT services	🟦 C15: DT technical connection
🟨 C7: Twinning time-scale	🟦 C16: DT hosting and deployment
🟨 C8: Multiplicities	🟧 C17: Insights and decision making
🟨 C9: Life-cycle stages	🟧 C18: Horizontal integration

🟧 C19: Data ownership and privacy
🟩 C20: Standardization
🟧 C21: Security and safety considerations

Legend:

🟨	Reqs/Concept/Design
🟩	Realization
🟦	Deployment
🟧	Operation

- 18 characteristics are "essential"
- 3 characteristics are "cross-cutting"

- Characteristics are (multi-) labelled with four system life-cycle stages

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Robotics Table Summary

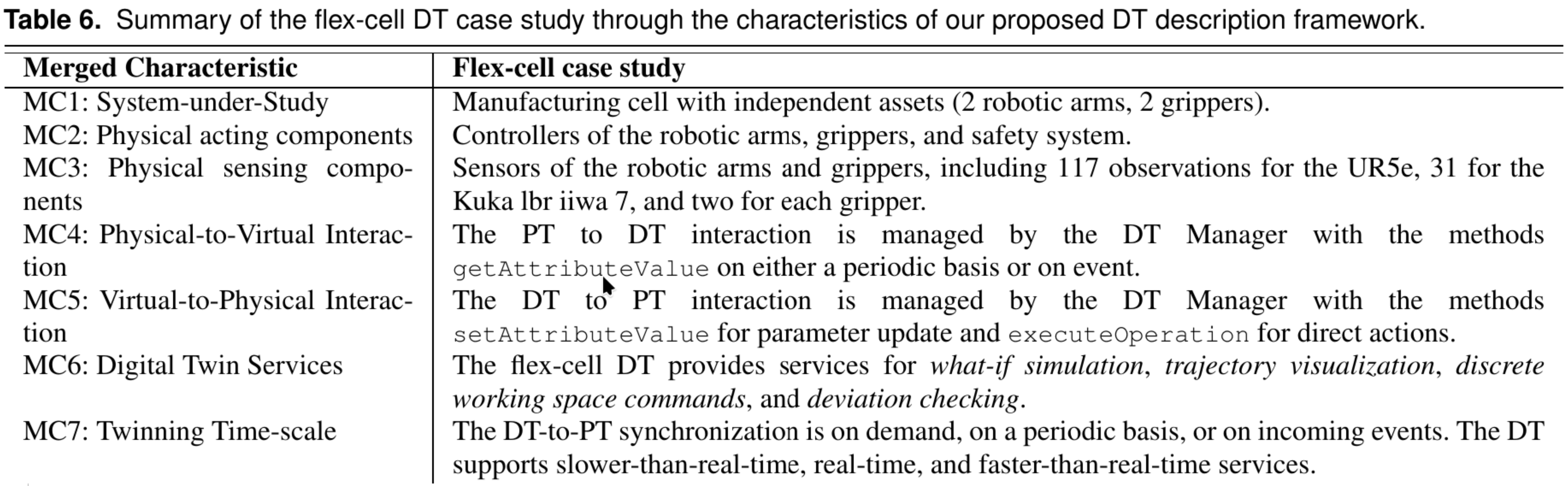
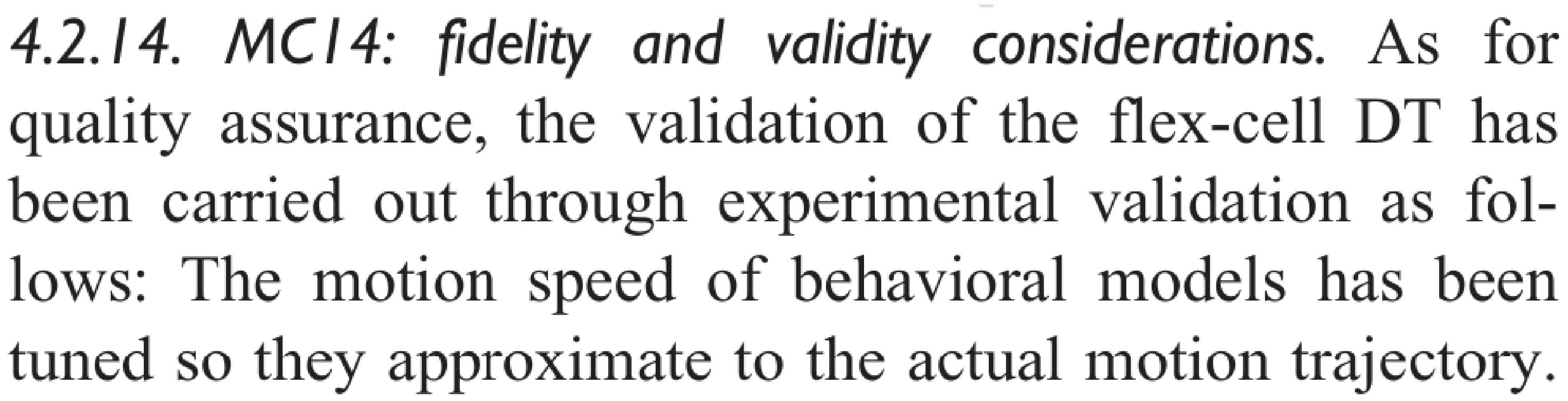


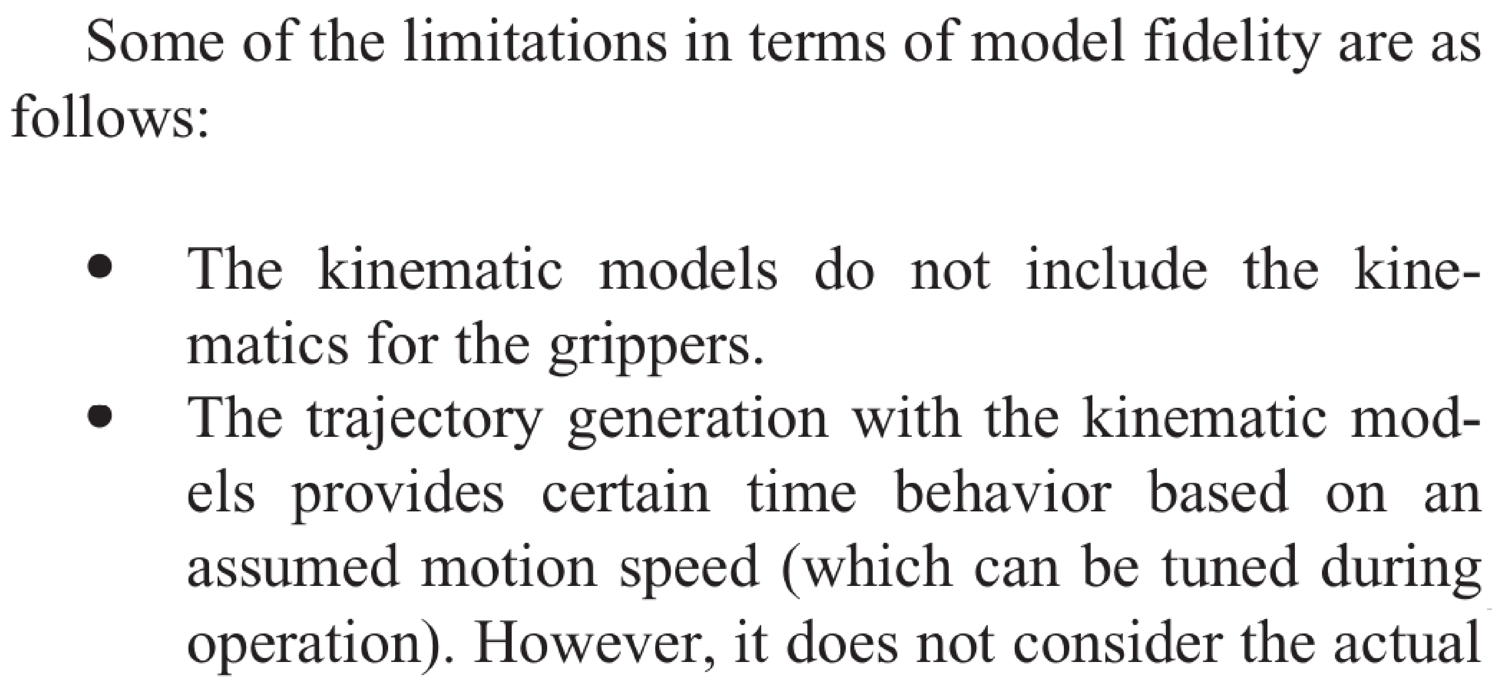
Table 6. Summary of the flex-cell DT case study through the characteristics of our proposed DT description framework.

Merged Characteristic	**Flex-cell case study**
MC1: System-under-Study	Manufacturing cell with independent assets (2 robotic arms, 2 grippers).
MC2: Physical acting components	Controllers of the robotic arms, grippers, and safety system.
MC3: Physical sensing components	Sensors of the robotic arms and grippers, including 117 observations for the UR5e, 31 for the Kuka lbr iiwa 7, and two for each gripper.
MC4: Physical-to-Virtual Interaction	The PT to DT interaction is managed by the DT Manager with the methods `getAttributeValue` on either a periodic basis or on event.
MC5: Virtual-to-Physical Interaction	The DT to PT interaction is managed by the DT Manager with the methods `setAttributeValue` for parameter update and `executeOperation` for direct actions.
MC6: Digital Twin Services	The flex-cell DT provides services for *what-if simulation*, *trajectory visualization*, *discrete working space commands*, and *deviation checking*.
MC7: Twinning Time-scale	The DT-to-PT synchronization is on demand, on a periodic basis, or on incoming events. The DT supports slower-than-real-time, real-time, and faster-than-real-time services.

Robotics Prose


4.2.14. MC14: fidelity and validity considerations. As for quality assurance, the validation of the flex-cell DT has been carried out through experimental validation as follows: The motion speed of behavioral models has been tuned so they approximate to the actual motion trajectory.

...


Some of the limitations in terms of model fidelity are as follows:

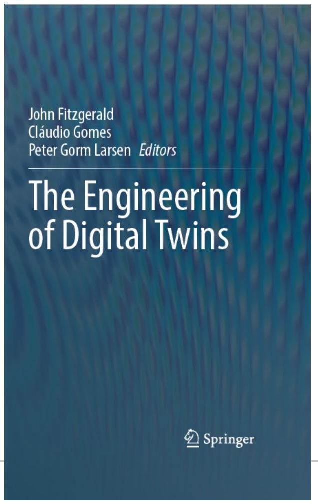
- The kinematic models do not include the kinematics for the grippers.
- The trajectory generation with the kinematic models provides certain time behavior based on an assumed motion speed (which can be tuned during operation). However, it does not consider the actual

Suggested Framework Usage

- Report on these characteristics as precisely as possible
  - In detail and/or tabular form
- Draw the constellation figure

- Nothing set in stone, make changes if needed
- Out of room? Place table in appendix or online

- For guidance, paper offers three DT reports
  - **Flex cell**
    - In detail and in table
  - **Robotti mobile robotics**
    - In table form
  - **Tempeh incubator**
    - In table form
- DT book also provides *Gunnerus* ship DT (in older framework version)



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Systematic DT Reporting

DTInsight

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DTInsight: A Tool for Explicit, Interactive, and Continuous Digital Twin Reporting

Kérian Fiter, Louis Malassigné-Onfroy, Bentley Oakes

EDTconf
International Conference on Engineering Digital Twins

Grand Rapids, MI, USA - 2025-10-07

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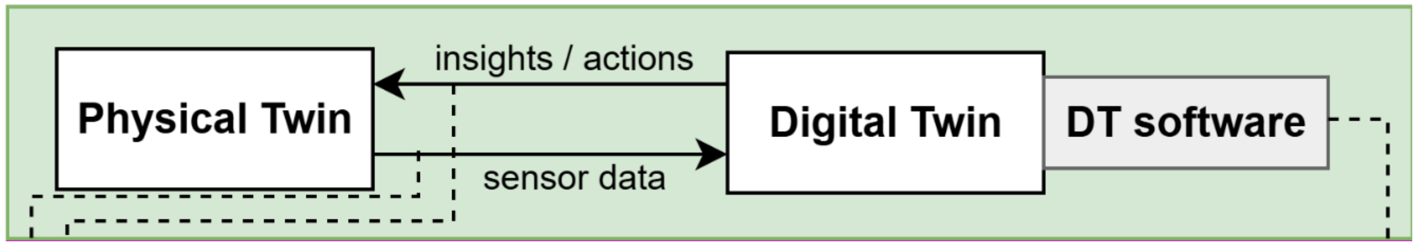
Research Questions

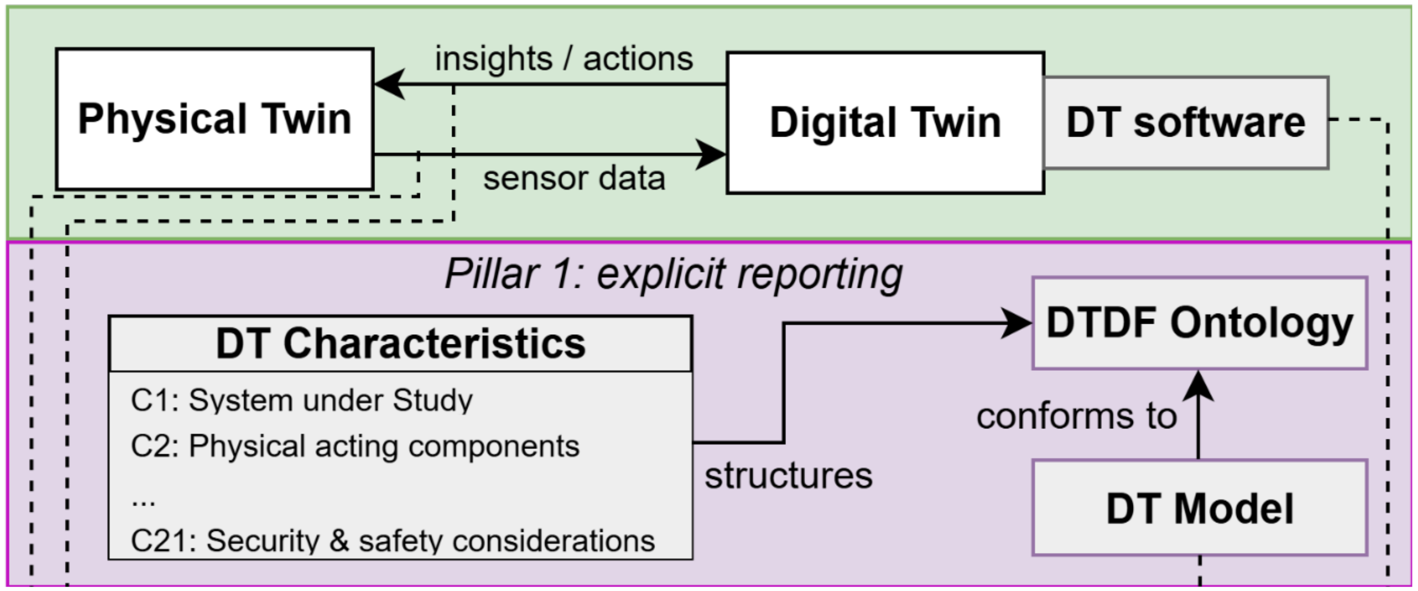
(1) How to make DT reporting **more formal & systematic**?

(2) How to easily explain a DT to **different stakeholders**?

(3) How to provide **continuous reports** of evolving DTs?

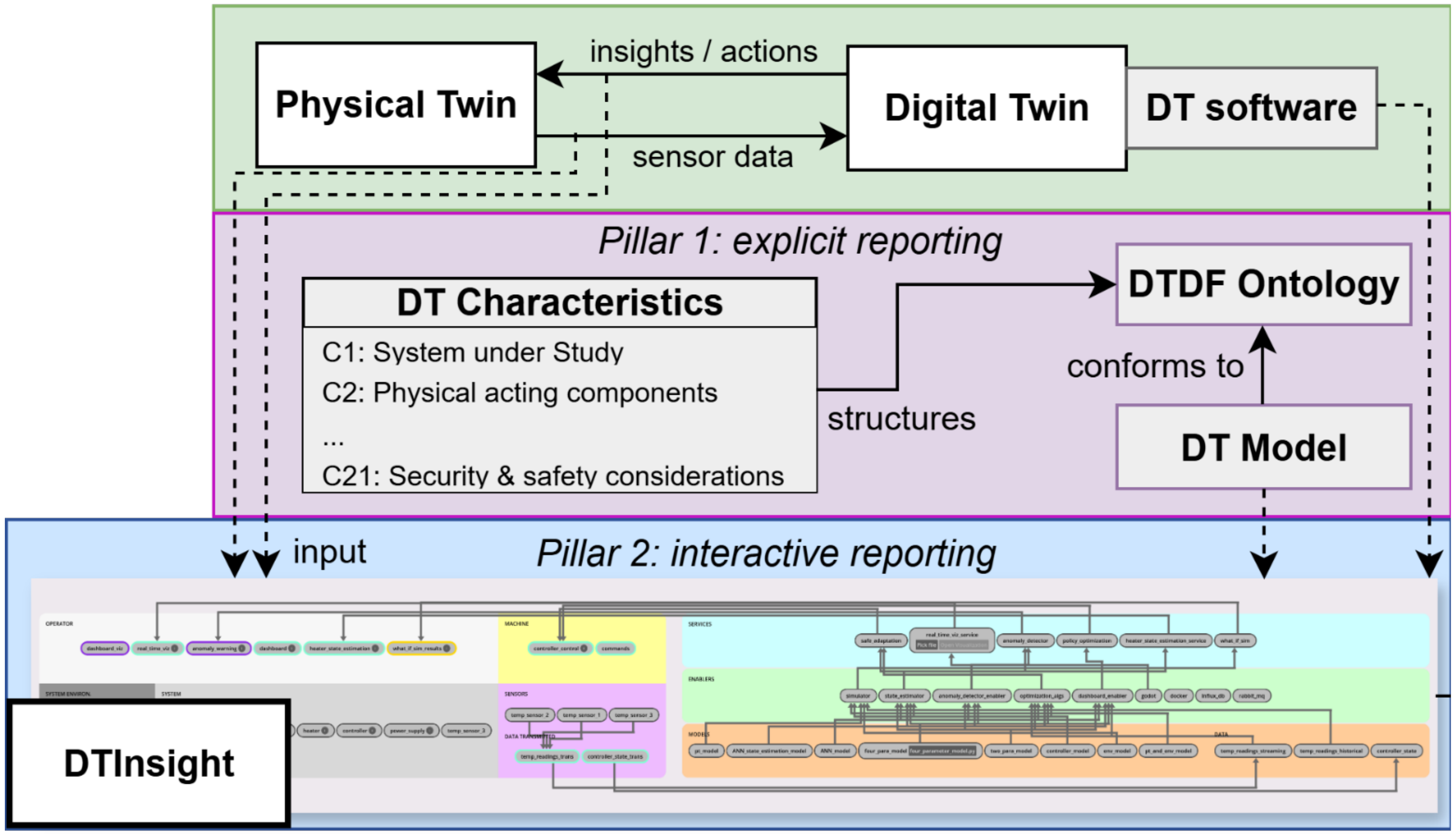

insights / actions
Physical Twin
Digital Twin
DT software
sensor data

(1) Explicit



Physical Twin
insights / actions
sensor data
Digital Twin
DT software
Pillar 1: explicit reporting
DT Characteristics
C1: System under Study
C2: Physical acting components
...
C21: Security & safety considerations
structures
DTDF Ontology
conforms to
DT Model

(1) Explicit (2) Interactive



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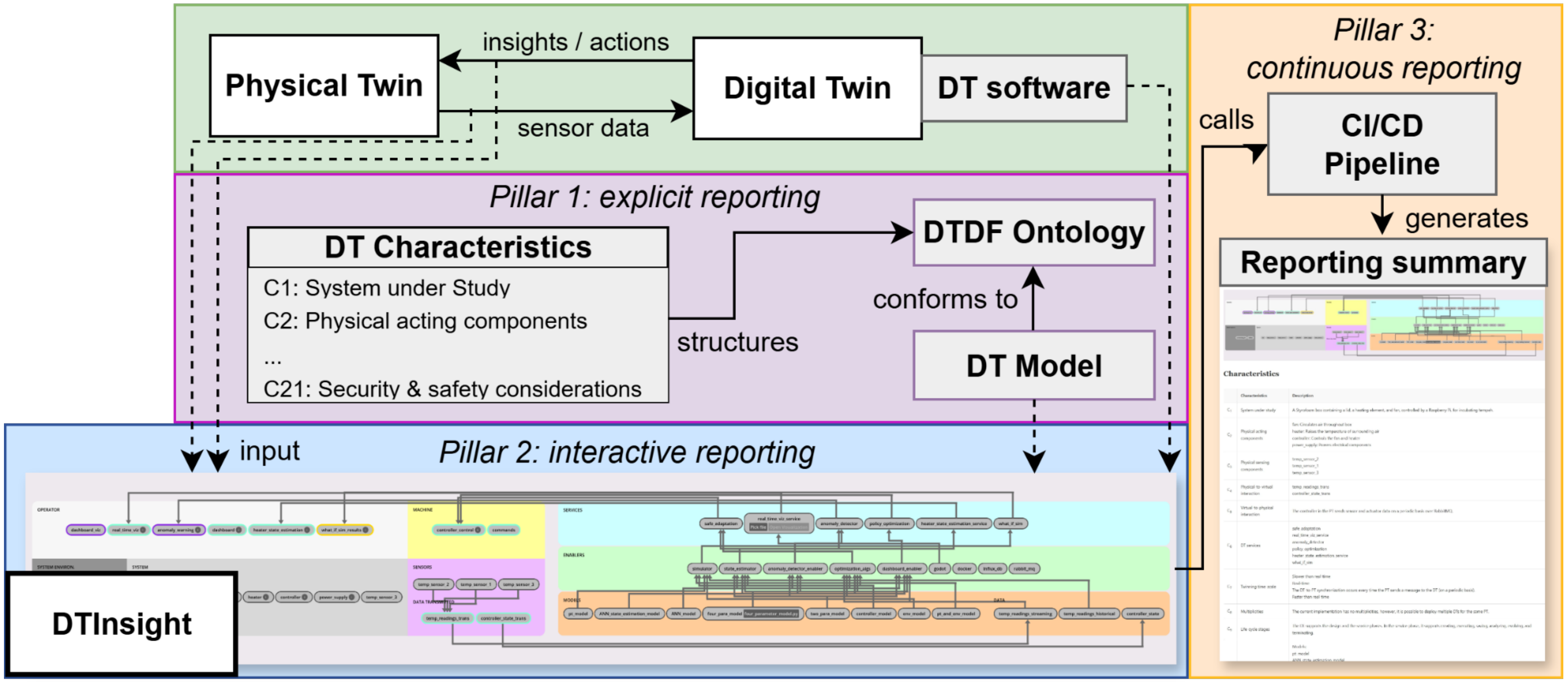
(1) Explicit (2) Interactive (3) Continuous



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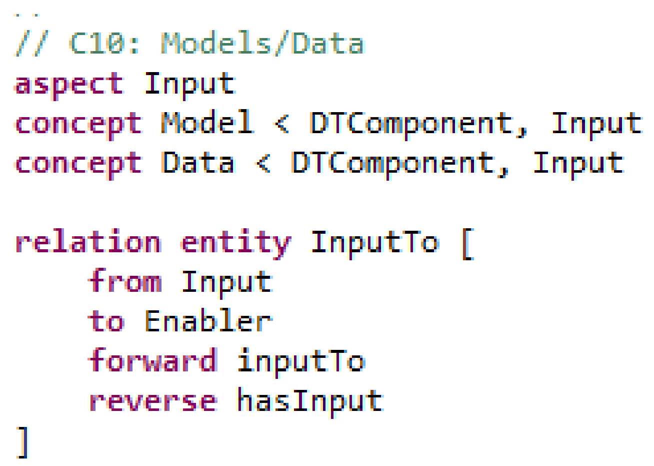
21 characteristics to describe a DT

- **C1.** System under study
- **C2.** Physical acting components
- ...
- **C21.** Security and safety considerations

(1) Explicit representation

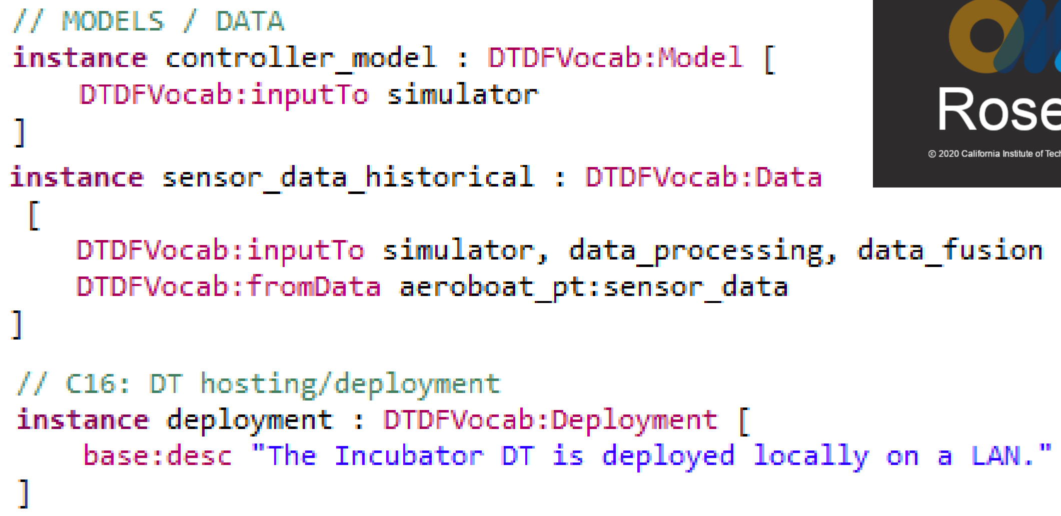
in **O**ntology **M**odeling **L**anguage



```
// C10: Models/Data
aspect Input
concept Model < DTComponent, Input
concept Data < DTComponent, Input

relation entity InputTo [
    from Input
    to Enabler
    forward inputTo
    reverse hasInput
]
```

OML vocabulary (concepts)



```
// MODELS / DATA
instance controller_model : DTDFVocab:Model [
    DTDFVocab:inputTo simulator
]
instance sensor_data_historical : DTDFVocab:Data
 [
    DTDFVocab:inputTo simulator, data_processing, data_fusion
    DTDFVocab:fromData aeroboat_pt:sensor_data
]

// C16: DT hosting/deployment
instance deployment : DTDFVocab:Deployment [
    base:desc "The Incubator DT is deployed locally on a LAN."
]
```

OML description (instances)

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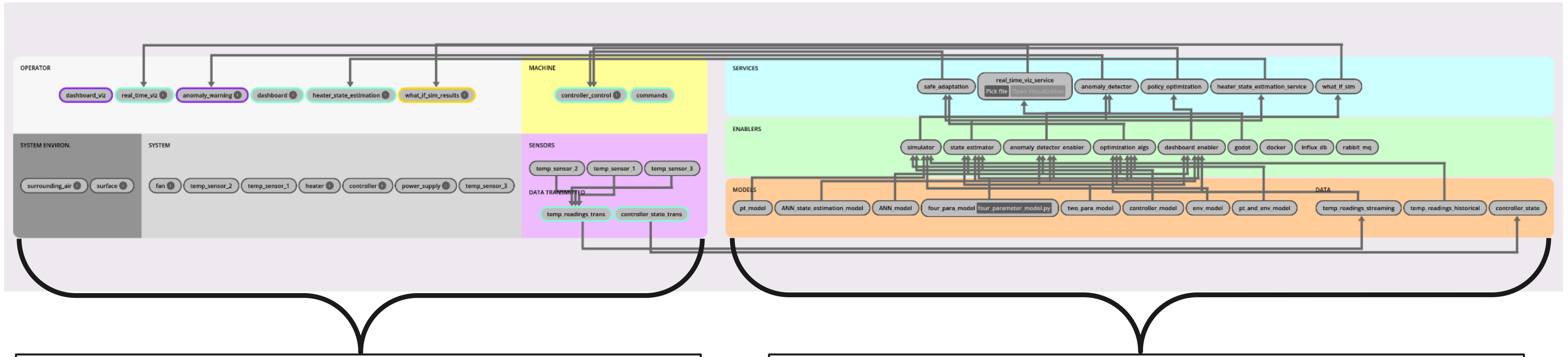
(2) Interactive DT Conceptual Architecture Visualization

DT constellation for reporting both **structure** and **behaviour**

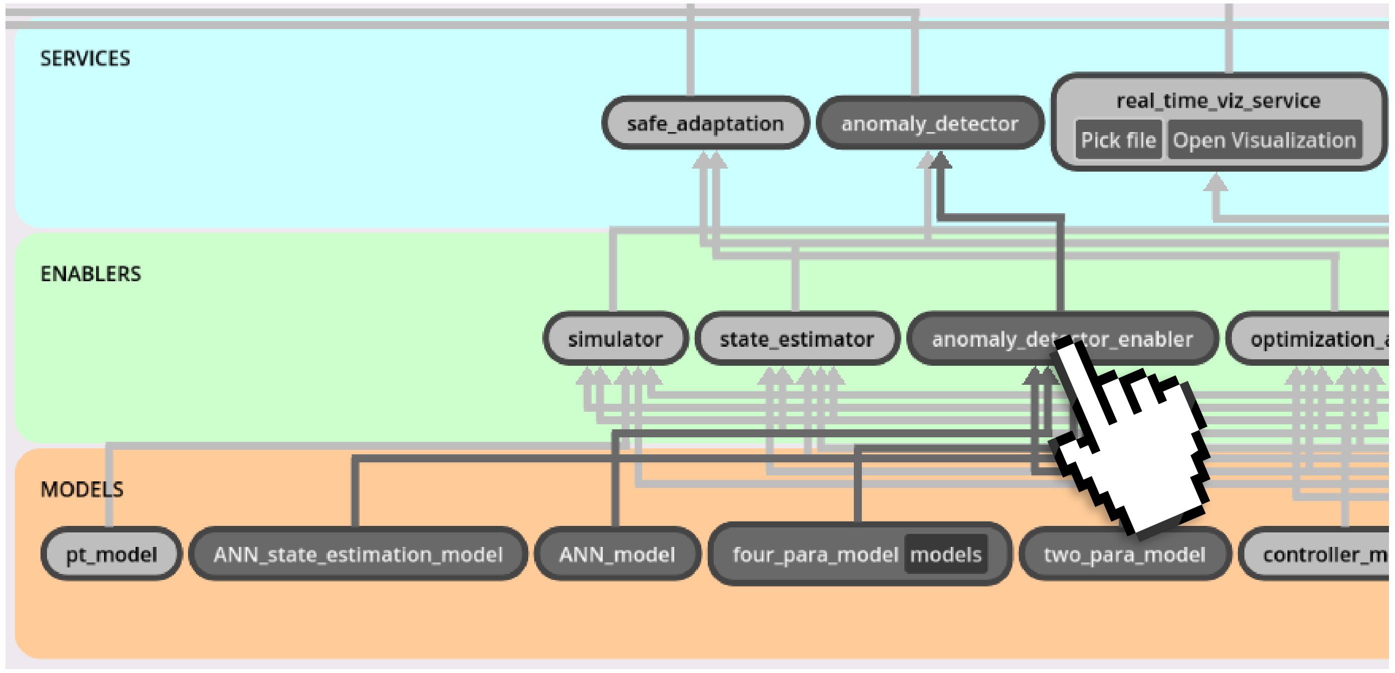


Physical Twin (left part): *Operator, Machine, System Environment, System, and Sensors/Data Transmission*

Digital Twin (right part): *Models/Data, Enablers, and Services*

(2) Interactive DT Conceptual Architecture Visualization

- Viz built in **open-source game engine** (Godot)
- Uses **SPARQL queries** to fetch the DT characteristics
- Example constellation is of the **incubator DT**



Feng H *et al.* "The incubator case study for digital twin engineering", arXiv:2102.10390

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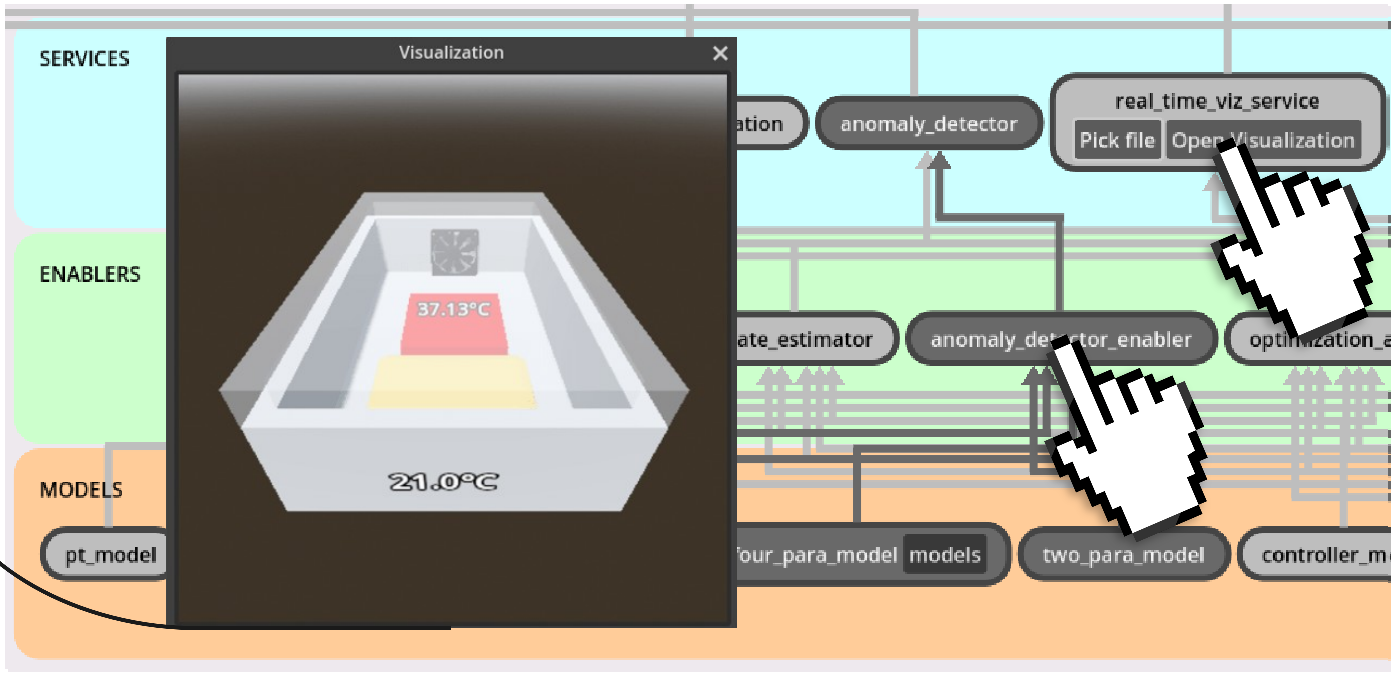
(2) Interactive DT Conceptual Architecture Visualization

- Three main capabilities:
  - Hover to **explore data flows** between DT components
  - View DT component **scripts**
  - Visualize **real-time sensor data** (graphs or 3D)

Goal: Relating DT **structure** and **behaviour**



Interactive monitoring with RabbitMQ message broker

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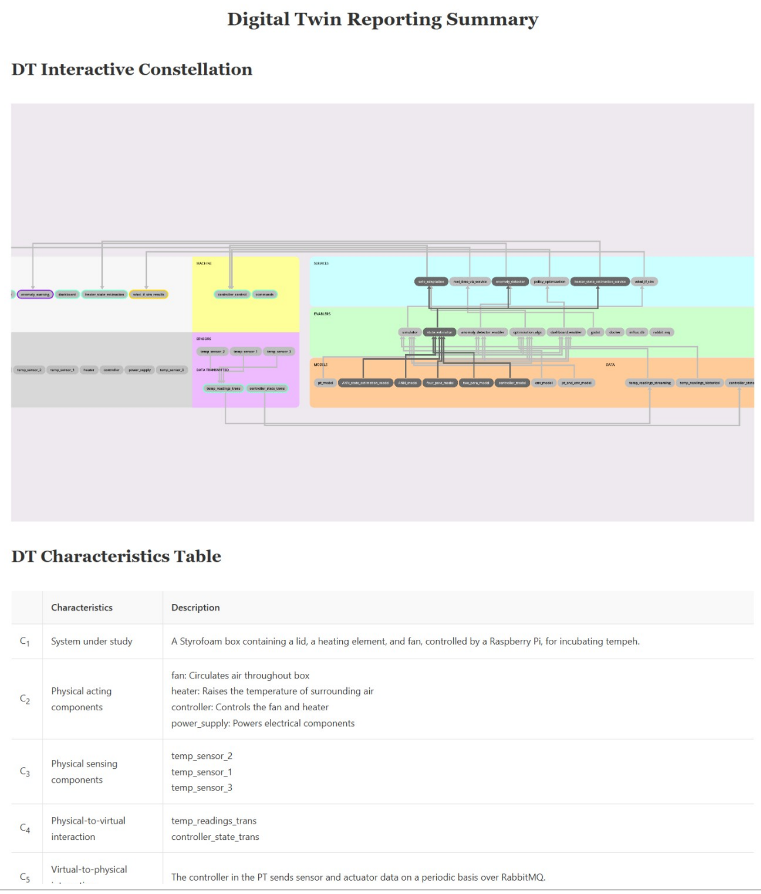
(3) **Continuous** Integration into a **live reporting page**

- **Continually** generated by a CI/CD pipeline to generate a reporting page website
- When the ontology representing the system changes, the **reporting page is re-generated**

(C6) DT services: *safe_adaptation, real_time_viz_service, anomaly_detector, policy_optimization, heater_state_estimation_service, what_if_sim*

(C20) Standardization: *Communication is carried out using AMQP standard via RabbitMQ. Behavioral models have been produced following the FMI standard version 2.*

GitHub Actions



Digital Twin Reporting Summary

DT Interactive Constellation

DT Characteristics Table

	Characteristics	Description
C_1	System under study	A Styrofoam box containing a lid, a heating element, and fan, controlled by a Raspberry Pi, for incubating tempeh.
C_2	Physical acting components	fan: Circulates air throughout box heater: Raises the temperature of surrounding air controller: Controls the fan and heater power_supply: Powers electrical components
C_3	Physical sensing components	temp_sensor_2 temp_sensor_1 temp_sensor_3
C_4	Physical-to-virtual interaction	temp_readings_trans controller_state_trans
C_5	Virtual-to-physical	The controller in the PT sends sensor and actuator data on a periodic basis over RabbitMQ.

https://oakeslabmtl.github.io/DTDF/

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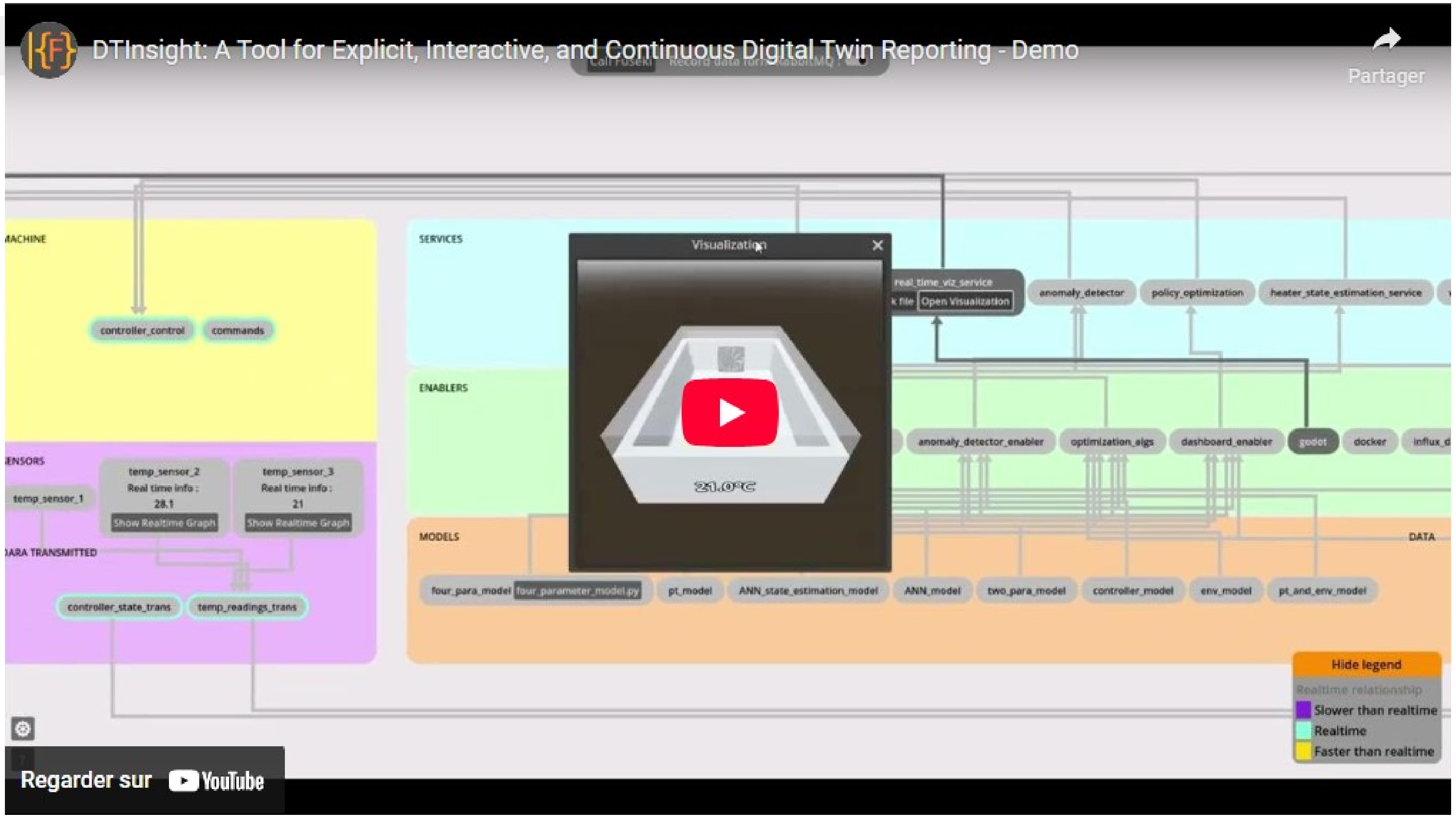
Demo



https://www.youtube.com/watch?v=CD0pdK-eGXY

https://oakeslabmtl.github.io/DTDF/

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Conclusion & Future Work

DTInsight improves stakeholder communication by making DT reporting:

1. **Explicit**: ontology-based modeling
2. **Interactive**: structural + behavioral architecture viz
3. **Continuous**: automated reporting page generation

Paper: https://arxiv.org/abs/2508.18431
Tool: https://github.com/oakeslabmtl/DTInsight

Future work:

- LLMs for ontology modeling
- Drag-and-drop reporting
- Expose further DT behaviour

DTInsight: A Tool for Explicit, Interactive, and Continuous Digital Twin Reporting,
Fiter, Malassigné-Onfroy, and Oakes

Any questions?

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Conclusion

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Oakes Lab Members and Topics

PhDs

Kérian Fiter
- DT reporting
- DT engineering using LLMs

Adil Lagrou
- Consistency framework

Master's

Angelica Portocarrero
- DT engineering using LLMs

Gabrielle Gallant
- DT model evolution

Contact me about collaborations:
https://bentleyjoakes.github.io/

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Winter 2026 - Digital Twin Eng. Course

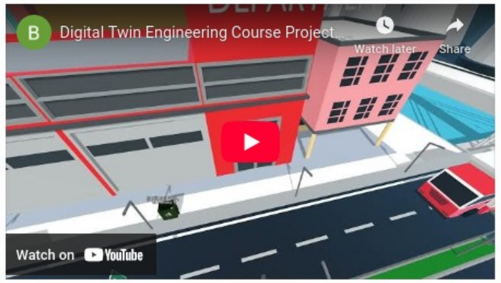
“Digital Twins are an emerging topic in both industry and academia. But what are Digital Twins (DTs), and how can we engineer them?”

Beer Fermentation DT

Presentation
Report

Smart City DT

Presentation
Report



STM Bus Visualization

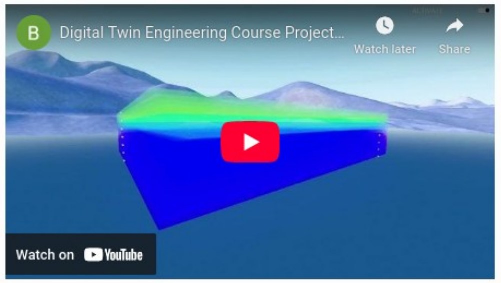
Presentation
Report

Robotics

Presentation
Report

Permafrost DT

Presentation
Report



Database Optimization

Presentation
Report

https://bentleyjoakes.github.io/dte_course/

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Takeaways

1) OML and openCAESAR: enable **new generation of ontology creation and usage**
2) DT engineering and reporting must become **more systematic**
3) Many opportunities for model-/ontology-based techniques to **structure DTs and their tooling and guide users**

bentley.oakes@polymtl.ca
bentleyoakes.com

Thank you!