

# Checking SysML Models for Co-Simulation

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**Abstract.** Cyber-physical systems (CPSs) are often treated modularly to tackle both complexity and heterogeneity; and their validation may be done modularly by *co-simulation*: the coupling of the individual sub-system simulations. The increasingly important FMI standard embraces this modular approach to modelling and simulation. This paper presents an approach to verify both healthiness and well-formedness of an architectural design, expressed using a profile of SysML, as a prelude to FMI co-simulation. This involves checking the *conformity of connectors* between components and the absence of *algebraic loops*, necessary for co-simulation convergence. Verification of these properties is performed using FRAGMENTA, a formal theory for representing typed visual models, with its mechanisation in the Isabelle/HOL proof assistant together with the CSP process algebra and its FDR3 model-checker. The paper's contributions lie in: a SysML profile for architectural modelling in a setting of multi-modelling and co-simulation; our approach to check the adequacy of a SysML model for co-simulation using theorem proving and model-checking; our verification and transformation workbench for typed visual models based on FRAGMENTA and Isabelle; an approach to detect algebraic loops using CSP and FDR3; and a comparison of approaches to the detection of algebraic loops.

**Keywords:** Co-simulation, FMI, CSP, SysML, algebraic loops

## 1 Introduction

Cyber-physical systems (CPSs) are designed to actively engage with the physical world in which they reside. They tend to be heterogenous: their subsystems tackle a wide variety of domains (such as, mechanical, hydraulic, analogue and a plethora of software domains) that mix phenomena of both continuous and discrete nature, typical of physical and software systems, respectively.

CPSs are often handled modularly to tackle both heterogeneity and complexity. To effectively separate concerns, the global model of the system is decomposed into subsystems, each typically focussed on a particular phenomenon or domain and tackled by the most appropriate modelling technique. Simulation, the most widespread validation mechanism of CPS designs, is often carried out modularly also, using co-simulation [18] – the coupling of subsystem simulations. This constitutes the backdrop of the industrial Functional Mockup Interface (FMI) standard [5,4] for co-simulation of components built using distinct modelling tools.

This paper presents an approach to formally verify the well-formedness and healthiness of SysML CPS architectural designs as a prelude to co-simulation. The designs are described using INTO-SysML [3], a profile for multi-modelling and FMI co-simulation. The well-formedness checks verify that designs comply with all the required constraints of the meta-model, which includes *connector conformity* to validate the connections between SysML blocks (denoting subsystems or components) with respect to the types of the ports being wired. The healthiness checks concern detection of *algebraic loops*, a feedback loop resulting in instantaneous cyclic dependencies, which is relevant because co-simulation, which often reduces to coupling of simulators, may result in an unstable integration if an algebraic loop exists between the subsystems [18]. A desirable property of numerical simulations is *convergence* –whether they approximate the solution – which is dependent on the structure of the subsystems and cannot be guaranteed if this structure contains algebraic loops [18,6]. This demonstrates the capabilities of our verification workbench for modelling languages and engineering theories, which rests on FRAGMENTA [2], a theory to formally represent designs of visual modelling languages, and its accompanying mechanisation in the Isabelle proof assistant [22], and the CSP process algebra [13] with its accompanying FDR3 refinement-checker [12].

**Contributions.** The paper’s contributions are as follows:

- A novel SysML profile for architectural modelling of CPSs that tackles heterogeneity by providing support for multi-modelling and co-simulation in compliance with the FMI standard.
- An approach to statically check the adequacy of a SysML architectural model for co-simulation, supporting connector conformity and algebraic loops detection, by using a theorem prover and a model-checker.
- A prototyping environment for FRAGMENTA [3], a mathematical theory to represent typed visual models, based on Isabelle that enables model verification and transformation.
- A CSP-based solution to the detection of algebraic loops, which is based on a novel approach to represent graphs in CSP.
- An evaluation of approaches to the detection of algebraic loops.

**Outline.** The remainder of the paper gives some background on FRAGMENTA and CSP (Section 2). It presents our approach to represent architectural designs in INTO-SysML, highlighting verification of well-formedness (Section 3), and our approach for representing directed graphs in CSP and detecting algebraic loops through a FDR3 refinement check (Section 4). It evaluates our CSP-based approach (Section 5). Finally, the paper discusses its results (Section 6), compares them against related work (Section 7) and draws the conclusions (Section 8).

## 2 Background

We give some background on two main ingredients underpinning the work presented here: FRAGMENTA and CSP.

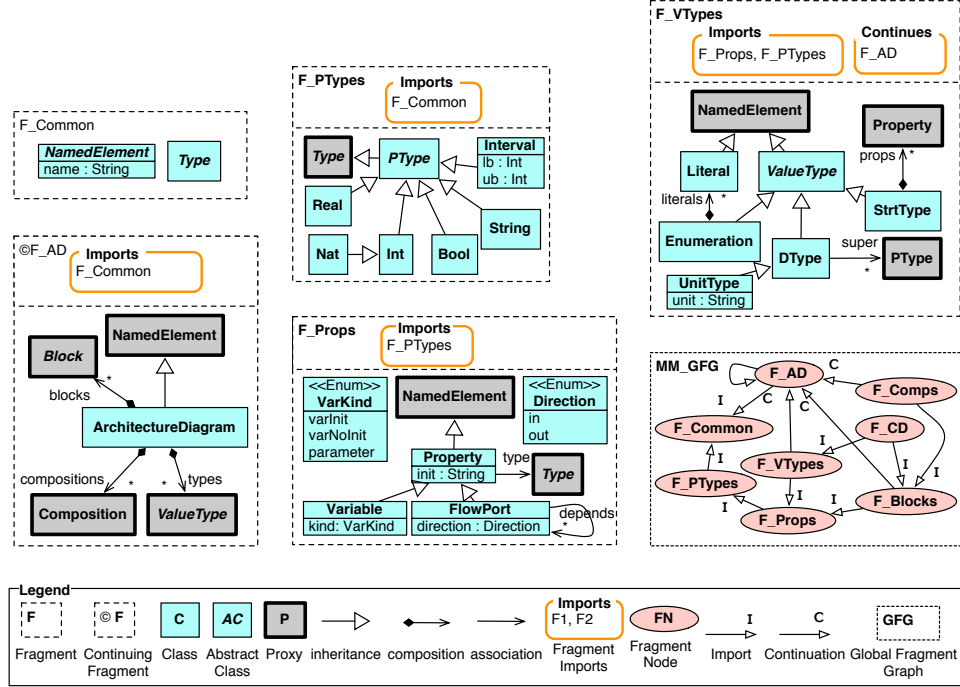


Fig. 1: Some fragments of metamodel of INTO-SysML.

## 2.1 Fragmenta and its Isabelle Mechanisation

FRAGMENTA [2] is a graph-based theory to represent modularised (or fragmented) typed class models. It is based on the algebraic theory of graphs and their morphisms [8]. FRAGMENTA represents designs of visual modelling languages whose structure is defined by class metamodels – domain-specific languages (DSLs) – and their resulting instance models. Its overall models are a collection of sub-models called *fragments*. Type and instance models are related through typing morphisms. A major novelty lies in FRAGMENTA’s *proxies* – representatives of other nodes. A fragment is as a graph that supports proxies.

Figure 1 portrays five fragments and one global fragment graph (GFG) from INTO-SysML’s metamodel. It highlights how fragments build up on other fragments either in a bottom-up (through imports) or top-down (through continues) fashion and the use of proxies to reference elements from other fragments. Fragment importing is bottom-up because the bigger fragments are built from smaller ones. Fragment continuation is top-down because it starts by specifying a summary model (or a skeleton) with points of continuation, represented as proxies, to be continued by other fragments. Fragment **F\_PTypes** is an increment to **F\_Common**; node **Type** from **F\_Common** is referenced through the proxy with same name; likewise in **F\_Props** with proxy **NamedElement**. Fragment **F\_AD**,

which summarises metamodel of INTO-SysML architecture diagrams (ADs), is a continuing fragment;  $F\_VTypes$  continues  $F\_AD$ . The GFG ( $MM\_GFG$ ) describes how fragments are related with each other through *imports* and *continues*.

FRAGMENTA proposes two composition operators: (a) union composition ( $\cup_F$ ) merges fragments without resolving the proxies, and (b) colimit composition (based on category theory) joins fragments by resolving the proxies.

The theory introduces the following sets (see [2] for details):

- $Fr$ , of well-formed fragments, requires that: (a) the underlying graph is well-formed, (b) the inheritance hierarchy is acyclic, (c) the source of composition relations has multiplicity 1 or  $0 \dots 1$  and (d) proxies do not inherit<sup>3</sup>. All fragments in Fig. 1 are members of  $Fr$ .
- $GFGr$ , of GFGs, requires that the graph is acyclic.  $MM\_GFG$  in Fig. 1 is a member of  $GFGr$ .
- $Mdl$ , of all well-formed models, requires, among other things, that the model's fragments are disjoint. A model  $M$  is a tuple  $(GFG, fd)$ , made up of a  $GFG \in GFGr$  and a total function  $fd : Ns_{GFG} \rightarrow Fr$  mapping nodes of  $GFG$  to local fragments. The metamodel of INTO-SysML, partially described in Fig. 1, is a member of  $Mdl$ .
- $F_1 \rightarrow_F F_2$ , of all well-formed fragment morphisms, which impose the required graph commuting constraints in the setting of fragments.
- $FrTy$ , of well-formed typed fragments  $FT = (F, TF, ty)$ , where  $F$  and  $TF$  are instance and type fragments, respectively, such that  $F, TF \in Fr$ , and  $ty \in F \rightarrow_F TF$ .
- $FrTyConf$ , of conformant fragments, a subset of  $FrTy$ , requires that an instance conforms to the following constraints: abstract nodes may not have direct instances, containments are not shared, instance relations satisfy metamodel multiplicities, and instances of containments form a forest.
- $MdlTy$ , of all well-formed typed models  $MT = (M, TM, ty)$ , where  $M$  and  $TM$  are instance and type models –  $M, TM \in Mdl$  –, and the type morphism is conformant –  $(UFs M, UFs TM, ty) \in FrTyConf$ , where  $UFs$  builds the union of model fragments into a single fragment.

The Isabelle mechanisation of FRAGMENTA<sup>4</sup> provides a verification and transformation environment for metamodel designs and their instances. By proving theorems, one can check that:

- The individual fragments of both model and metamodel are locally consistent and well-formed. For fragment  $F\_Common$  of Fig. 1, for instance, we need to prove  $\vdash F\_Common \in Fr$ <sup>5</sup>; likewise for the remaining fragments.
- GFGs are well-formed also. For GFG of Fig. 1:  $\vdash MM\_GFG \in GFGr$ .
- Overall models and metamodels are also consistent and well-formed. For the metamodel  $INTO\_SysML$  of Fig. 1:  $\vdash INTO\_SysML \in Mdl$ .

<sup>3</sup> A local check that ensures the compositionality of FRAGMENTA's union operator.

<sup>4</sup> Available at <https://github.com/namalio/Fragmenta>

<sup>5</sup> Such membership predicates are represented in Isabelle as functions to booleans and they capture the well-formedness constraints associated with a FRAGMENTA set.

- Instance models conform to the constraints imposed by the type model.

Section 3 gives further details on INTO-SysML inside FRAGMENTA/Isabelle.

## 2.2 CSP and FDR3

The CSP process algebra [13] is used to describe communicating processes and interaction-driven computations. CSP’s major structuring concept, the process, represents a self-contained component made up of interfaces to enable interaction with a multitude of environments.

Processes communicate by transmitting information along channels. A CSP channel carries messages and has, therefore, a set of associated events, corresponding to all messages that may be transmitted. Process expressions are built using a number of operators, which include:

- Event prefixing, expressed as  $e \rightarrow P$ , describes a process that expects event  $e$  and then behaves as process  $P$ .
- External choice,  $P_1 \sqcap P_2$ , gives the environment the choice of events offered by  $P_1$  and  $P_2$ . Replicated external choice  $\square i : \mathbb{N} \bullet P(i)$  composes the resulting processes using external choice.
- Internal choice,  $P_1 \sqcap P_2$ , non-deterministically chooses to act like  $P_1$  or  $P_2$ .
- Parallel composition,  $P_1 \parallel_A P_2$ , executes the two processes in parallel synchronising on the set of events  $A$ .

FDR3 [12] is CSP’s refinement checker. It checks refinement according to CSP’s denotational models (including traces, failures and failures-divergences), and other properties, including deadlock- and livelock-freedom, and determinism.

## 3 Architectural Modelling in INTO-SysML

The Systems Modelling Language (SysML) [25], a general-purpose notation for systems engineering that builds up on the Unified Modelling Language (UML), is becoming widespread. The INTO-SysML profile [3] customises SysML for architectural modelling in a setting of multi-modelling and FMI co-simulation. It embraces the many themes of the INTO-CPS project<sup>6</sup>, namely, tool interoperability, heterogeneity, holistic modelling and co-simulation, and constitutes the gateway into modelling in the INTO-CPS approach.

The profile introduces specialisations of SysML blocks (known as stereotypes) to represent different types of CPS components, constituting the building blocks that enable a hierarchical description of the CPS architectures that we need. A component is a logical or conceptual unit of the system, corresponding to a software or a physical entity. The profile’s component constructs comprise: **System**, **EComponent** (encapsulating component) and **POComponent** (part-of

<sup>6</sup> The INTO-CPS project aims to create an integrated “tool chain” for comprehensive model-based design of CPSs. For further information, see <http://into-cps.au.dk/>

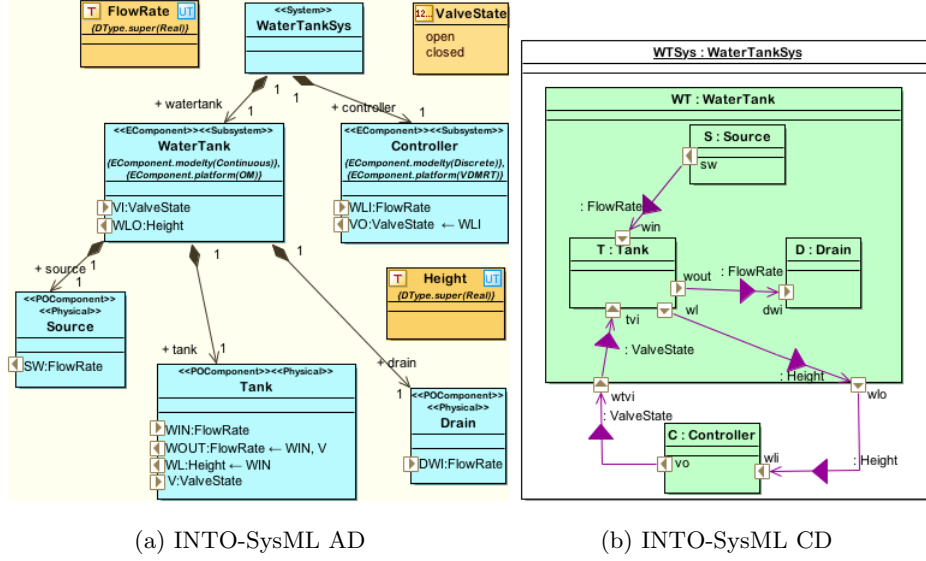


Fig. 2: The INTO-SysML model of the water tanks system

component). A system is decomposed into subsystems (represented as **EComponents**), which are further decomposed into **POComponents**. **EComponents** and **POComponents** may be further classified as **Subsystem** (a collection of inner components), **Cyber** (an atomic unit that inhabits the digital or logical world) or **Physical** (an atom unit pertaining to the physical world). Furthermore, their characterising phenomena may be classified as **discrete** or **continuous**.

Currently, INTO-SysML comprises two diagram types: *architecture diagrams* (ADs) and *connections diagrams* (CDs), specialising SysML block definition and internal block definition diagrams, respectively. They are as follows (see Fig 2):

- ADs (an example is given in Fig. 2a) describe a decomposition in terms of the types of system components and their relations. They emphasise multi-modelling: certain components encapsulate a model built using some modelling tool (such as VDM/RT [20], 20-sim [17] or Open Modelica [11]).
- CDs (an example is given in Fig. 2b) are AD block instances that convey the configuration of the system's components, highlighting flow and connectedness.

The water tanks system, sketched in Fig. 3, is this paper's running example. There is a source of water that fills a tank whose water outflow is controlled by a valve; when the valve is open the water flows into the drain. The valve, managed by a software controller, is opened or closed depending on the tank's water level.

Fig. 2 portrays the architectural model of water tanks, built using INTO-SysML's Modelio implementation<sup>7</sup>. The AD of Fig. 2a is as follows:

<sup>7</sup> Available from <http://forge.modelio.org/projects/intocps-modelio34>.

- The overall system (**WaterTankSys**) comprises two major subsystems, **WaterTank** and **Controller**, which are **EComponents** – they encapsulate separate models. **WaterTank** deals with **continuous** phenomena modelled in Open Modelica. **Controller** is **discrete** and modelled in VDM/RT.
- **WaterTank** has three physical sub-components: **Source**, **Tank** and **Drain** – they are **POComponents** (part-of of a subsystem).
- Enumeration **ValveState** captures the valve's state. Unit types **FlowRate** and **Height**, built from reals, deal with flow rates and water levels.
- Each component provides flow ports to enable communication and the flow of material; the outputs indicate the inputs ports on which they depend.

The CD of Fig. 2b states that the system instance (**WTSys**) is inhabited by one **WaterTank** instance (**WT**) with its sub-components. The **Controller** instance (**C**) receives the water height from **WT** and, in return, directs **WT** to open or close the valve.

### 3.1 Well-formedness Checking using Fragmenta/Isabelle

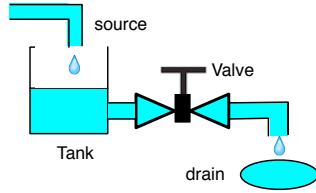


Fig. 3: Water Tanks system.

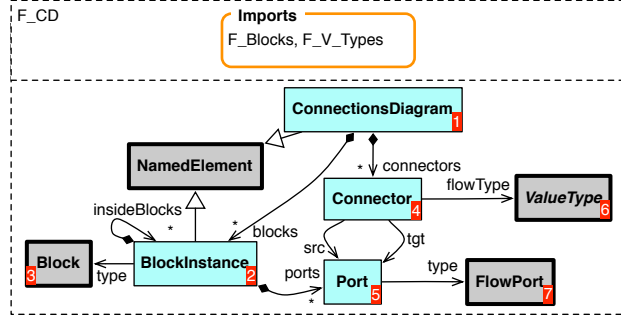
Many things are checked in order to deem a INTO-SysML model, such as one of Fig. 2, consistent, well-formed and type conformant. Such checks are performed on the FRAGMENTA typed representation illustrated in Fig. 4. Fig. 4b gives the FRAGMENTA representation of CD in Fig. 2b and Fig 4a is the metamodel of INTO-SysML CDs; the correspondence from CD to metamodel, entailed by the type morphism, is represented as labels with numbers. In Fig. 4b, the proxies reference elements from the AD of Fig. 2a, nodes labelled 4 correspond to the connectors of the CD, and those labelled 5 correspond to ports.

From the FRAGMENTA base sets of Section 2.1, we build a set of well-formed INTO-SysML models *INTO\_Mdls*. This caters for all profile-specific invariants. The AD invariants are: (i) there is one system block, (ii) **EComponents** are not nested, and (iii) **POComponents** are contained by **EComponents**. The CD invariants are: (iv) instance ports are correctly typed with respect to AD flow ports, (v) connection's flow types correspond to types consistent with the ports being connected (conformity of connectors), and (vi) the CD satisfies multiplicities imposed by AD.

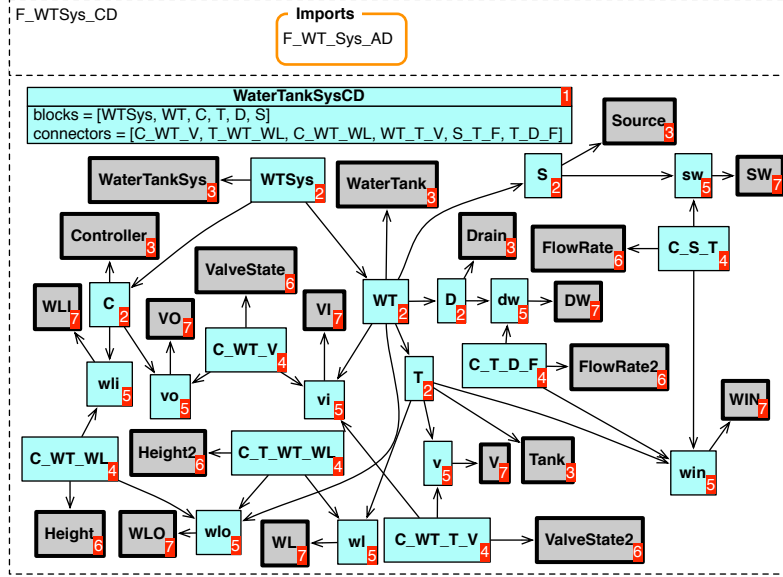
The model of Fig. 2, referred as *M\_WTs*, is subject to the following checks:

- Fragments of AD and CD are well-formed:  $\vdash F_{AD} \in Fr, \vdash F_{CD} \in Fr$ .
- The model's GFG is well-formed:  $\vdash GFG\_WTs \in GFG_r$ .
- Overall model is well formed:  $\vdash M\_WTs \in Mdl$ .
- *M\_WTs* must be a valid INTO-SysML model. Given a type morphism *ty* (illustrated in Fig 4b), we prove:  $\vdash (M\_WTs, ty) \in INTO\_Mdls$ , which entails  $\vdash (M\_WTs, INTO\_SysML, ty) \in MdlTy$ .

These are the checks required for any model resulting from INTO-SysML.



(a) Metamodel of INTO-SysML CDs



(b) INTO-SysML CD of water tanks system (Fig. 2b) in FRAGMENTA

Fig. 4: Metamodel, models and typing morphism (numbered labels) in FRAGMENTA illustrated with INTO-SysML CDs

### 3.2 Fragmenta/Isabelle as a Transformation Engine

To enable usage of model-checkers, FRAGMENTA/Isabelle is used as a transformation engine in the algebraic loops check, which finds cycles in a topology of dependencies in instantaneous component communication (Fig. 5).

Fig. 5a portrays a self-cycle component that is algebraic loop free. Output  $y1$  of  $A$  is connected to  $A$ 's input  $u2$ , but this does not entail an algebraic loop. The topology in Fig. 5b, on the other hand, contains an algebraic loop.



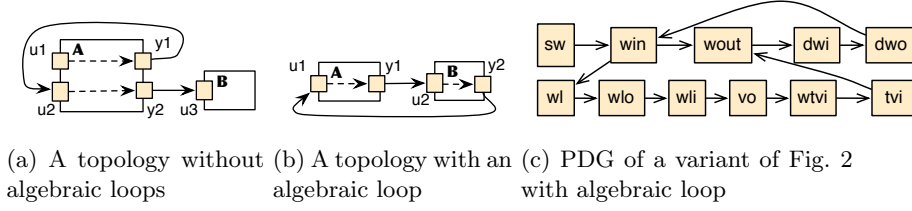


Fig. 5: The algebraic loops check is about finding cycles in a system topology emphasising component communication

Finding algebraic loops equates to detecting cycles in a directed graph describing port dependency relations. An edge between two ports indicates that the target node is instantaneously dependent on the source. This constitutes a *port dependency graph* (PDG), illustrated in Fig. 5c, which portrays a PDG with an algebraic loop corresponding to a variant of the INTO-SysML model of Fig. 2 that puts an extra connector from the **Drain** to the **Tank** (**dwo** to **win**).



Fig. 6: From INTO-SysML models to CSPm

The Isabelle mechanisation introduces a function that produces a PDG from a INTO-SysML model. The resulting PDG, obtained from the ports and connections of CD and the internal dependencies between output and input port types of AD, is derived from both metamodel and model. Another function takes the PDG and produces the CSPm specification to be checked in FDR3. This is summarised in the diagram of functions of Fig. 6.

## 4 Algebraic Loop Verification using CSP

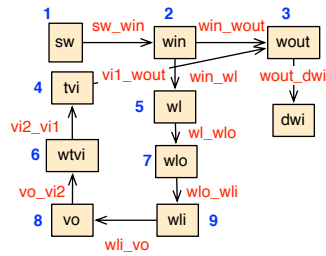


Fig. 7: A PDG with labelled nodes and edges

We represent graphs in CSP and detect cycles on them via a traces-refinement check executed in the FDR3 refinement checker<sup>8</sup>. This is illustrated with the PDG of Fig. 7 (derived from model of Fig. 2), containing labelled edges and numbers assigned to nodes with outgoing edges. We represent edges as CSP channels and nodes as CSP processes. The edges result in the following channel declaration:

**channel** *sw\_win, win\_wout, win\_wli, wout\_dwi, tvi\_wout, wtvi\_tvi, vo\_wtvi, wli\_vo, ...*

The overall graph is a CSP process constructed from sub-processes representing each node. The node processes are an external choice of CSP prefixed expressions

<sup>8</sup> <https://www.cs.ox.ac.uk/projects/fdr/>

for each edge that starts at the node. They offer the events on the corresponding channel and then behave as the process at the end of the edge. An edge to a sink node (no outgoing edges) results in a transition to *SKIP*. The main process is the external choice of all sub-processes. The process for PDG of Fig. 7 is:

$$\begin{aligned}
 PortDependencyGraph = & \\
 \text{let } P(1) = sw\_win \rightarrow P(2) & \\
 P(2) = win\_wout \rightarrow P(3) \sqcap win\_wl \rightarrow P(5) & \\
 P(3) = wout\_dwi \rightarrow SKIP & \\
 \vdots & \\
 \text{within } \sqcap i : 1..9 \bullet P(i) &
 \end{aligned}$$

Cycles are detected through traces refinement. The abstract CSP process to be refined defines all finite paths whose size is at most the number of edges in the graph (those that can be built by combining the graph's edges):

$$\begin{aligned}
 edges = \{sw\_win, win\_wout, wout\_dwi, twi\_wout, wtwi\_twi, vo\_wtvi, \dots & \\
 Limited = & \\
 \text{let } Limited0(E, n) = & \\
 \quad \text{if } n > 0 \text{ then } \sqcap e : E \bullet e \rightarrow Limited0(E, n - 1) \sqcap SKIP \text{ else } STOP & \\
 \text{within } Limited0(edges, 9) &
 \end{aligned}$$

The traces refinement check to be executed in FDR3 is then:

$$\mathbf{assert} \ Limited \sqsubseteq_T PortDependencyGraph$$

All counter-examples are cycles. The function *toCSP* of FRAGMENTA/Isabelle (Section 3.2) yields CSP specifications as outlined above. For the PDG of Fig. 7, FDR3 gives no counter-examples; for Fig. 5c FDR3 yields one counter-example.

## 5 Evaluation

FDR3 is a tool based on model-checking, a verification technique whose drawback is scalability. We compare our CSP approach to detect algebraic loops (Section 4) against one approach based on Alloy [14] and one graph algorithm [15], to gauge scalability.

### 5.1 Experimental Setup

Scalability is evaluated against growing PDGs based on the water tanks running example (Fig. 3). We keep adding tanks to a base water tanks systems to produce systems of cascading water tanks having two versions: one with algebraic loops (drain is connected to first tank) and one without (as per Fig. 3).

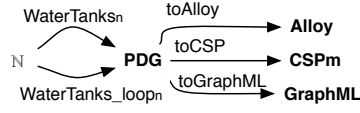


Fig. 8: The experiment’s generation functions

The generation of files to execute in either FDR3, Alloy 4<sup>9</sup> or the implementation of Johnson’s algorithm in JGraphT<sup>10</sup>, involves Isabelle functions that yield PDGs given the number of tanks. We then define functions from PDGs to the abstract syntax of CSP (as per Section 4), Alloy (see below) and Graph ML<sup>11</sup> as per diagram of Fig. 8<sup>12</sup>.

The graph checks and data collection were performed by a Java program that reads the files and calls either Alloy 4 (using the minisat SAT solver), FDR3 or JGraphT, executed on a MacBook Pro with a 2.5 GHz Intel core i7 processor and 16GB RAM memory. The resulting data was the basis of our statistical analysis and production of graphical plots carried out in the R statistical package [24].

## 5.2 The Alloy Model

Alloy [14] is a declarative modeling language based on first-order logic with transitive closure. It is used for data modelling and provides an automatic bounded analysis of a model. Our Alloy model of PDGs is based on the signature *Port*:

```
abstract sig Port {tgt : set Port}{tgt ≠ this}
```

Above, we declare a set of *Port* instances – **abstract** says that *Port* has no instances of its own and that all its instances belong to its extensions (subsets) – with the relation *tgt* between *Ports* declared to be non-reflexive: the *tgt* of some *Port* cannot be itself (*this*).

The actual nodes of the PDG of Fig. 7 extend *Port*:

```
one sig sw, win, wout, dwi, wl, wlo, wli, vo, wlvi, tvi
  extends Port {}
```

Above, the nodes are singletons (constraint *one*) that subset *Port* (*extends*).

The following Alloy fact defines the edges of the graph:

```
fact {sw.tgt = win
      win.tgt = wout + wl
      wout.tgt = dwi
      no dwi.tgt ... }
assert AcyclicTgt {no ^tgt & iden}
check AcyclicTgt for 10
```

Above, each edge is declared through relation *tgt*: *sw.tgt = win* says that there is an edge from *sw* to *win* – operator *.* is the relational image –, *win.tgt = wout + wl*

<sup>9</sup> <http://alloy.mit.edu/alloy/download.html>.

<sup>10</sup> A Java library of graph algorithms – <https://github.com/jgrapht/jgrapht>.

<sup>11</sup> A standard for graphs exchange that enables a direct representation of PDGs – <http://graphml.graphdrawing.org/>.

<sup>12</sup> The Isabelle file that performs the generation, the actual generated files, and the Java code that runs the three approaches, can be found at <http://bit.ly/1WKTIC7>.

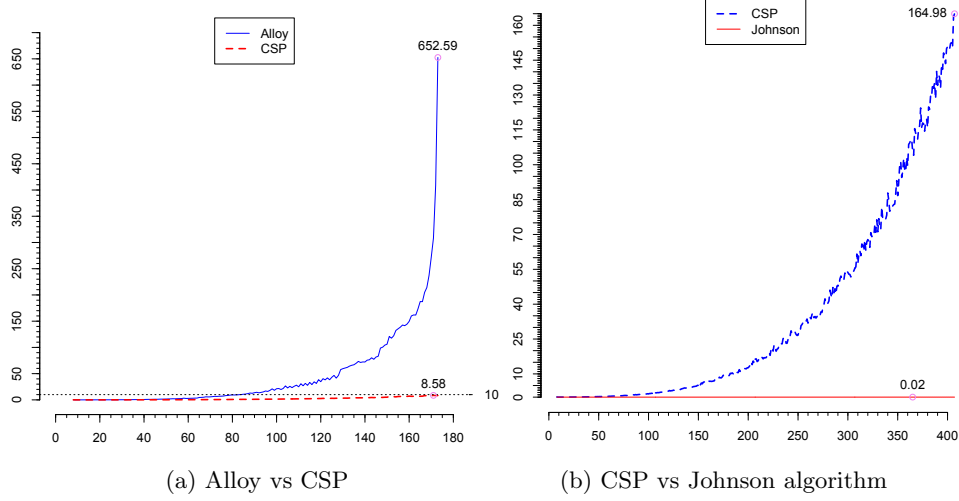


Fig. 9: The performances of the Alloy and CSP solutions (seconds on the ordinate and number of nodes of a graph on the abscissa)

says that there are two edges from `win` to `wout` and `wl` – operator `+` is set union –, and `no dwi.tgt` says that `dwi` has no outgoing edges (set is empty).

Finally, we assert the acyclicity of the relation `tgt` representing the PDG and declare the command to check the assertion:

```
assert AcyclicTgt {no ^tgt & iden}
check AcyclicTgt for 10
```

Above, the assertion says that there can be no elements (operator `no`) in the set resulting from the intersection (operator `&`) of the relation’s transitive closure (`^tgt`) with the identity relation (`iden`). The `check` command includes a scope declaration saying that the analysis should consider at most 10 atoms, the number of nodes of the PDG.

### 5.3 Comparisons

The plots of Fig. 9 depict the data obtained from running the experiments. They display the number of nodes of the analysed graph in the abscissa and the duration of the check (in seconds) in the ordinate.

Fig. 9a shows that there is a clear substantial difference in favour of CSP against Alloy. CSP’s maximum duration is 8.58s, Alloy’s is 652.59s. The two approaches start to diverge with small to medium size graphs (number of nodes  $> 17$ ). The p-value, obtained from the paired data plotted in Fig. 9a using the Wilcoxon statistical test<sup>13</sup>, of  $< 2.2^{-16}$  ( $< 0.001$ ) indicates a very large

<sup>13</sup> It is a non-parametric test that compares the two sampled distributions without assuming that they follow the normal distribution.

difference. We derived estimates of functions that fit the data of both Alloy and CSP to yield estimates of time complexity: Alloy has complexity  $O(Exp)$ , whereas CSP has complexity  $O(n^3)$  –  $n$  is number of nodes of graph.

Fig. 9b, on the other hand, shows that Johnson’s algorithm performs substantially better than CSP. The former’s maximum duration is  $0.02s$ , CSP’s is  $164.98s$ . The p-value of  $< 2.2^{-16}$  ( $< 0.001$ ) signals a very large difference. The estimated function that fits the data endorses the algorithm’s linearity claim.

## 6 Discussion

The following discusses the results presented in the paper.

**A prelude to co-simulation.** The work presented here statically checks an architectural design of a CPS in preparation for co-simulation. This is done at the high-level architectural design to provide early warnings of any issues so that the appropriate remedial action can be taken. It is a preliminary check – done before delving into the details of global co-simulation and local modelling and analysis of each component – to ensure that the models to be co-simulated are, among other things, free of both connector conformity issues and algebraic loops. These checks are performed using the Isabelle proof assistant and the FDR3 model-checker; both constitute an intimate part of our verification toolset.

**Into-SysML profile.** The paper presents a profile of SysML (defined in [3]), designed as a DSL, for architectural modelling of CPSs in a setting of multi-modelling and FMI co-simulation. The profile imposes a systems decomposition paradigm oriented towards multi-modelling: the overall system architecture is a decomposition of subsystems (**E-components**), which encapsulate their own models, which are further decomposed as **POComponents** to give a more accurate account of the inner structure of each subsystem. This design enables a holistic algebraic loop analysis that considers the inner details of each subsystem. Guidance on the definition of SysML models for multi-modelling is provided in [10], aiding CPS engineers in modelling a CPS architecture both holistically and in a decomposed form suitable for co-simulation.

The profile’s design caters for FMI co-simulation. The **E-component** subsystems of the architecture result in FMI’s Functional Mock-up Units (FMUs) to be co-simulated; FMUs are generated by the corresponding modelling framework.

**Fragmenta as prototyping environment.** The profile’s DSL design was brought to life by FRAGMENTA and its accompanying Isabelle mechanisation. FRAGMENTA/Isabelle, built as part of the work presented here, constitutes a prototyping environment built on top of FRAGMENTA’s mathematical theory that provides reasoning and transformation capabilities for metamodels and their instances. As this paper demonstrates, it can be used in real-world settings; ideally, however, FRAGMENTA designs should be specialised and optimised as part of fully fledged visual modelling environments.

**Algebraic loops.** It is interesting to contrast the two model-based approaches to check algebraic loops. Alloy represents a graph directly (Section 5.2) as a

relation between nodes; the property to check is stated as an ordinary formula of the relational calculus. The CSP approach (Section 4), on the other hand, is edge-oriented to suit CSP’s communication model based on channels; a graph is the communications established between nodes (CSP processes) chosen from the environment (external choice); the property is expressed in an ingenious, but less evident way: through an abstract process and a traces refinement check.

FDR3 and Alloy 4 are both based on model-checking; however, the CSP solution outperforms Alloy by a substantial margin. Alloy’s exponential time complexity is attributed to the complexity of SAT whose worst-case time complexity is exponential [21,19] – the Alloy solution resorts to the transitive closure, a computationally demanding operation (specialised algorithms do it in  $O(n^3)$ ). An important factor in CSP’s lower  $O(n^3)$  time complexity lies in the use of traces refinement, based on the simplest denotational model of CSP and with the least expensive time complexity, which is polynomial according to [16].

Despite being beaten by Johnson’s algorithm, our CSP solution is used in our verification approach, which employs FDR3 for more sophisticated checks of FMI co-simulations [1]. It is difficult for general-purpose model-checking to outperform specialised algorithms taking advantage of problem specificities.

The experimental setup varies size but not structure, which remains essentially the same throughout the different water tanks systems. However, as the results show, this is enough to expose differences; furthermore, as discussed above, the obtained results are in accordance with theoretical results.

## 7 Related Work

Feldman et al [9] generate FMI model descriptions from Rhapsody SysML models and FMUs from statecharts to enable integration with continuous models. Unlike our work, this does not define a profile that embodies a paradigm that makes sense in a setting of multi-modelling and FMI-co-simulation, and that is designed to generate FMI-compliant architectures. Pohlmann et al [23] propose a UML-based DSL for real-time systems, which generates FMUs from model components described as real-time statecharts. Our work specialises the SysML block diagrams, which is a more appropriate standard notation for architectural modelling, and supports multi-modelling.

This paper applies the FRAGMENTA theory presented in [2] to a real-world problem. This required an extension to the Isabelle/HOL theory of [2], developed to prove that paper’s main theorem. This extension builds an infrastructure to support automated verification and transformation for visual modelling languages. FRAGMENTA/Isabelle constitutes a prototyping environment supporting all the novel aspects of FRAGMENTA, namely: a formal theory of proxies and its verified theory of decomposition and the support for fragmentation strategies. This is the first time that the novel theory of modularity with its Isabelle mechanisation is applied to a real-world application. To our knowledge, this is also the first prototyping environment based on a proof assistant that provides formal reasoning and transformation capabilities for visual models.

The approach to connector conformity used here is based on typing. It supports sub-typing according to the inheritance relations specified in the meta-model; for instance, in INTO-SysML, natural numbers may be used when integers are expected because the metamodel says that the former is a subtype of the latter. This is checked as part of FRAGMENTA’s typing morphisms. This is different from the *connector compatibility* of [7], which performs validations based on interface contracts, a relation between allowed inputs and outputs [26].

Broman et al [6] require that FMI component networks are algebraic-loop free as a pre-condition to the deterministic composition results of their FMI master algorithms, proposing port-dependency graphs as a means to perform such checks. Unlike the work presented here, [6] does not study different approaches to detect algebraic loops; it suggests algorithms that topologically sort a graph, which yield an error if the graph has a cycle. Our approach provides actual cycles as feedback to designers in the context of algebraic loop analysis.

## 8 Conclusions

This paper has presented our approach to check a SysML model in preparation for co-simulation. This involves checking the consistency and well-formedness of the INTO-SysML model and its conformance with respect to its metamodel based on FRAGMENTA’s typed representation. The actual checks are carried out using FRAGMENTA’s Isabelle mechanisation, ensuring, among other things, connector compatibility. The paper then showed how the FRAGMENTA-based representation can be transformed into other modelling languages to perform a check for the absence of algebraic loops in the INTO-SysML model using FRAGMENTA’s Isabelle mechanisation as a transformation engine. The paper presented a novel CSP approach to detect algebraic loops by checking a traces refinement in FDR3. The paper’s evaluation highlighted how our CSP approach based on refinement-checking performs well when compared with an Alloy SAT-based model-checking approach, but that it does not perform better than a special-purpose graph algorithm. The work presented in this paper is done in tandem with the effort on the formal semantics of FMI in CSP [1].

**Acknowledgements.** This work was supported by EU project INTO-CPS (Horizon 2020, # 644047, <http://into-cps.au.dk/>). Thanks are due to Etienne Brosse who implemented the INTO-SysML profile in the Modelio tool.

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