Modelica Extensions for Requirement Modeling and their Implementation

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WHY DO WE WANT TO MODEL REQUIREMENTS?

Why are Requirements Important?

- Requirements Engineering is an important part of the early phases in system design V
- Errors in system requirements cause large cost increase in product development, or even completely failed projects
- Requirements engineering should be an integrated part of Modelica-based model-based system development tools

- Some resources:
  - International Requirements engineering conference home page: ***http://requirements-engineering.org/***
  - Example of requirements engineering journal: ***Requirements Engineering***, Springer Verlag, http://link.springer.com/journal/766

Requirement Engineering Activities

- **Requirements inception** or requirements elicitation
- **Requirements identification** - identifying new requirements
- **Requirements analysis and negotiation** - checking requirements and resolving stakeholder conflicts
- **Requirements specification** (System Requirements Specification)- documenting the requirements in a requirements document
- **System modeling** - deriving models of the system
- **Requirements validation** - checking that the documented requirements and models are consistent and meet stakeholder needs
- **Requirements management** - managing changes to the requirements as the system is developed and put into use

Some Requirement Engineering Products

Product	Link	Notes
IBM Rational DOORS	http://www-01.ibm.com/software/awdtools/doors/	ex. "Telelogic DOORS"; used for system engineering
IBM Rational RequisitePro	http://www-01.ibm.com/software/awdtools/reqpro/	Used for software engineering
IBM Rational Requirements Composer	http://www-01.ibm.com/software/awdtools/rrc/	The followup to IBM Rational RequisitePro
TraceCloud	http://www.tracecloud.com/GloreeJava2/jsp/WebSite/TCHome.jsp	
Blueprint Requirements Definition & Management	http://www.blueprintsys.com/resources/product-brochures/	
Visual Paradigm Requirements Capturing	http://www.visual-paradigm.com/product/vpuml/provides/reqmodeling.jsp	
HP Requirements Management	http://www8.hp.com/us/en/software-solutions/software.html?compURI=1172907	
PTC Integrity for Requirements Engineering	http://www.mks.com/solutions/discipline/rm/requirements-engineering	Formerly MKS Integrity for Requirements Management - optimized for system and software requirements
Polarion REQUIREMENTS	http://www.polarion.com/products/requirements/index.php	Web Requirements Management solution for any product, process or service
RQA Requirements Quality Analyzer for system engineering projects	http://www.reusecompany.com/requirements-quality-analyzer	The Requirements Quality Analyzer tool (RQA) allows you to define, measure, improve and manage the quality of the requirements specifications within the systems engineering proces

Some Requirements Engineering Literature

- Kotonya G. and Sommerville, I. Requirements Engineering: Processes and Techniques. Chichester, UK: John Wiley & Sons
- Software Requirements Engineering Methodology (Development) Alfor,M. W. and Lawson,J. T. TRW Defense and Space Systems Group. 1979.
- Thayer, R.H., and M. Dorfman (eds.), System and Software Requirements Engineering, IEEE Computer Society Press, Los Alamitos, CA, 1990.
- Royce, W.W. 'Managing the Development of Large Software Systems: Concepts and Techniques', IEEE Westcon, Los Angeles, CA> pp 1-9, 1970. Reprinted in *ICSE '87, Proceedings of the 9th international conference on Software Engineering*.
- Requirements bibliography Reviewed November 10th 2011
- Sommerville, I. *Software Engineering*, 7th ed. Harlow, UK: Addison Wesley, 2006.
- Ralph, Paul (2012). "The Illusion of Requirements in Software Development". *Requirements Engineering*.

HOW DO WE REPRESENT REQUIREMENTS?

Modeling requirements in Modelica

- We need a way of marking requirements
  - proposal introduce a new type of specialized class: **requirement**
- Alternatives: inherit from a generic class Requirement or use an annotation

Why are requirements different?

- Requirements must have a **status**
- Requirements do **not modify** the physical model
- For specific uses, we need to know which models are requirements, e.g.
  - automatic model composition,
  - requirement verification,
  - …
- Requirement models can (possibly) contain extensions for expressing requirements in a more requirement-designer friendly way (FORM-L macros for example)

Status of a requirement

Example requirement: **when the pump is on the flow must be above a minimum threshold**

- The **status** variable is 3-valued and applies to a specific instant in time:
  - **Violated** : the requirement is applicable and the conditions of the requirement are not fulfilled – the pump is on and the flow is below the minimum required
  - **Not_violated** : the requirement is applicable and the conditions of the requirement are fulfilled – the pump is on and the flow is above the minimum required
  - **Not_applicabl**e : the requirement cannot be applied or is not relevant - the pumps are off

Status of a requirement (2)

- A set of functions for checking the status over the course of the system simjulation
  - **has_been_evaluated()** – true if the requirement was applicable at some point in time
  - **has_been_violated()** – true is the requirement has been violated at least once
  - **can_become_applicable()** – true if the requirement can apply in the future (the time locator can be applicable)

Example 1 - LimitInFlow

```
requirement LimitInFlow "A2: If pump is on then in-flow is
                                    less than maxLevel"
    //qOut from the Source component
    input Real liquidFlow;
    input Boolean pumpOn;
    parameter Real maxLevel = 0.05;
equation
   if (pumpOn) then
     if (liquidFlow < maxLevel) then
       status = Status.not_violated;
     else
       status = Status.violated;
   end if;
   else status = Status.not_applicable; end if;
  end LimitInFlow;
```

Example (2) : No pump shall cavitate

```
package Requirements
    model Req
     /* number of cavitating pumps*/
     input Real numberOfCavPumps = 0;
    /* min. number of operating pumps */
     constant Integer maxNumOfCavPumps = 0;
     /*indication of requirement violation, 0 = means not evaluated */
     output Status status(start=status_not_applicable,fixed=true);

    algorithm
      if numberOfCavPumps > maxNumOfCavPumps then
         status :=  Status.violated;
      else
        status :=  Status.not_violated;
      end if;
    end Req;
  end Requirements;
```

FORM-L and Modelica

- FORM-L a language for property expression proposed by EDF
- Needed to represent FORM_L constructs in Modelica:
  - **A 3-Valued type**, e.g. Boolean3 (true, false, undefined)
  - **A library of types** to represent FORM-L concepts

    Ex:

    type Condition = Boolean3;
  - **A set of macros** to represent FORM-L concepts, that can be expanded to standard Modelica

Example

Modelica :

```
// Form-L: during (On and (MPSVoltage > V170)) check no (Off becomes
true);
requirement Req1_on;
input Real MPSVoltage;
input Boolean on;
input Boolean off;
equation
  if (on and (MPSVoltage > V170)) then
    if (off) then
       status = Status. violated;
    else
       status = Status.not_violated;
    end if;
  else status = Status.not_applicable;
 end if;
end Req1;
```

Example – Using if-expression

Modelica :

```
// Form-L: during (On and (MPSVoltage > V170)) check no (Off becomes
true);
requirement Req1b_is_on;
input Real MPSVoltage;
input Boolean on;
input Boolean off;
equation
  status = if (on and (MPSVoltage > V170)) then
            if(off) Status.violated  else Status.not_violated
       else Status.not_applicable;
end Req1bis;
```

Example(3) – Using Macro AFTER

```
// requirement R9a =
// during (SingleSensorFailure and after (Op.eVReset + s10)) check
NormalPower becomes true;

requirement Req2
input Boolean SingleSensorFailure;
input Boolean eVReset;
input Boolean NormalPower;

equation
  if (AFTER(eVReset, 10) and SingleSensorFailure) then
      if (normalPower) then
        status = Status.not_violated;
        else status = Status.violated;
      end if;
  else status = Status.not_applicable;
 end if;

end Req2;
```

Example(4) – Standard Modelica

```
// requirement R9a =
// during (SingleSensorFailure and after (Op.eVReset + s10)) check NormalPower
becomes true;
model Req2
input Boolean SingleSensorFailure;
input Boolean eVReset;
input Boolean NormalPower;

Boolean wasReset(start=false);
integer tReset;

equation
  when wVReset
     wasReset = true; tReset = time;
  end when;
  if (wasRest and SingleSensorFailure and (tReset + 10 < time)) then
      if (normalPower) ... ?? What should be here?  Why is there Op.eVreset in
FORML-L and eVReset here?  Where is s10 ?  What does it mean??

end Req2;
```

Issues

- Terminology:
  – Requirements? Properties? Assertions? …
- Extensions
  – New embedded language? Nothing? Something in between?

USING REQUIREMENTS FOR VERIFICATION : A CASE STUDY

Requirement Verification vs System Design

- **Formalized Requirements** that should be verified
- **System Model, i.e., Design Alternative Model,** for which the requirements should be verified
- **Application scenarios** with the system model for which the requirements should be verified
- ***Clients (requirement models, scenarios) refer to data from system model components***
- **Clients and providers do not know each other a priori**
- **Mediators** relate a number of clients to a number of providers

Example: System and Requirement

- A system contains several pumps,
- Requirement: *"No pump within the system shall cavitate at any time"*

System model:

```
model SRI
  Machines.PumpA PO1;
  Machines.PumpB PO2;
  Machines.PumpA PO3;
end SRI;

package Machines
  model PumpA
   // Volumetric mass flow-rate inside the pump
   Real Qv = 1;
   // Pressure at the inlet (C1 is the fluid connector at the inlet)
   Real C1_P = 1;
   // Pressure at the outlet (C2 is the fluid connector at the outlet)
   Real C2_P = 1;
  end PumpA;

  model PumpB
   // Volumetric mass flow-rate inside the pump
   Real Qv = 1;
   // Pressure at the inlet (C1 is the fluid connector at the inlet)
   Real C1_P = 1;
   // Pressure at the outlet (C2 is the fluid connector at the outlet)
   Real C2_P = 1;
   // Minimum pressure inside the pump
   Real Pmin = 20;
  end PumpB;
 end Machines;
```

Formalized requirement:

```
package Requirements
  model Req
   /* number of cavitating pumps*/
   input Real numberOfCavPumps = 0;
   /* min. number of operating pumps */
   constant Integer maxNumOfCavPumps = 0;
   /*indication of requirement violation, 0 = means not evaluated */
   output Integer status(start=0,fixed=true);

  algorithm
   if numberOfCavPumps > maxNumOfCavPumps then
     status := 2 "2 means violated";
   else
     status := 1 "1 means NOT violated";
   end if;
  end Req;
 end Requirements;
```

Example: Aux. Functions from Lib.

```
package HFunctions
  function H_is_cavitating
   /* Volumetric flow inside the pump
   input Real vol_flow;
   /* Minimum pressure inside the pump
   input Real Pmin;
   /* Table giving the minimum pressure inside the
   pump as a function of the volumetric flow inside the pump */
   input Real NPSH;
   /* Boolean stating whether the requirement
   for non-cavitation is satisfied (=false) or not (=true) */
   output Boolean is_cavitating;

  algorithm
   is_cavitating := (Pmin < getNPSH(vol_flow));
  end H_is_cavitating;

  function getNPSH
         …
  end getNPSH;
 end HFunctions;
```

For determining whether a pump cavitates, call a library function

getNPSH(vol_flow)

Example: Analysis model

```
model AnalysisModel
  ...
  Requirements.Req req1;
  SRI sri;
end AnalysisModel;
```

Formalized requirement:

```
package Requirements
  model Req
   /* number of cavitating pumps*/
   input Real numberOfCavPumps = 0;
   /* min. number of operating pumps */
   constant Integer maxNumOfCavPumps = 0;
   /*indication of requirement violation, 0 = means not evaluated */
   output Integer status(start=0,fixed=true);

  algorithm
    if numberOfCavPumps > maxNumOfCavPumps then
      status := 2 "2 means violated";
    else
      status := 1 "1 means NOT violated";
    end if;
  end Req;
end Requirements;
```

System model:

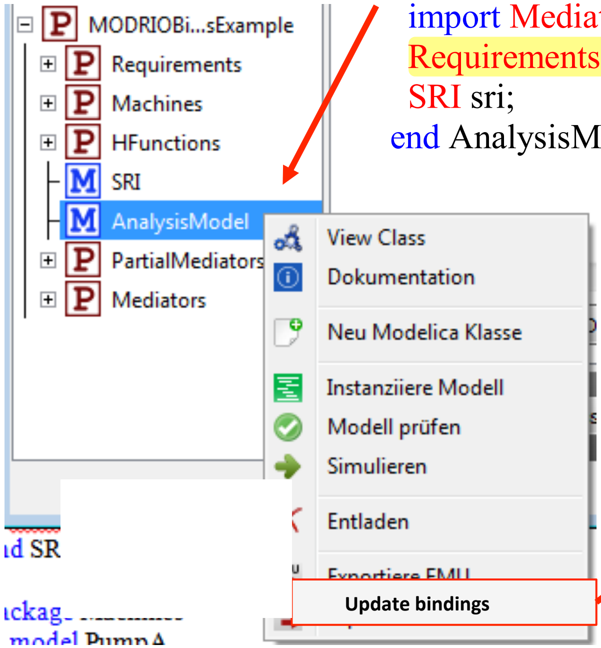
```
model SRI
   Machines.PumpA PO1;
   Machines.PumpB PO2;
   Machines.PumpA PO3;
end SRI;

package Machines
   model PumpA
     // Volumetric mass flow-rate inside the pump
     Real Qv = 1;
     // Pressure at the inlet (C1 is the fluid connector at the inlet)
     Real C1_P = 1;
     // Pressure at the outlet (C2 is the fluid connector at the outlet)
     Real C2_P = 1;
   end PumpA;

   model PumpB
     // Volumetric mass flow-rate inside the pump
     Real Qv = 1;
     // Pressure at the inlet (C1 is the fluid connector at the inlet)
     Real C1_P = 1;
     // Pressure at the outlet (C2 is the fluid connector at the outlet)
     Real C2_P = 1;
     // Minimum pressure inside the pump
     Real Pmin = 20;
   end PumpB;
 end Machines;
```

WHAT DO WE WANT TO ACHIEVE?

What do we want to achieve?

Initial AnalysisModel:

```
model AnalysisModel
  import Mediators.*;
  Requirements.Req req1;
  SRI sri;
end AnalysisModel;
```



Binding:

client instance reference = binding expression

A **binding** is a causal relation which specifies that, at any simulated time, the value given to the referenced client instance shall be the same as the value computed by the right-hand expression.

Updated AnalysisModel model with a binding:

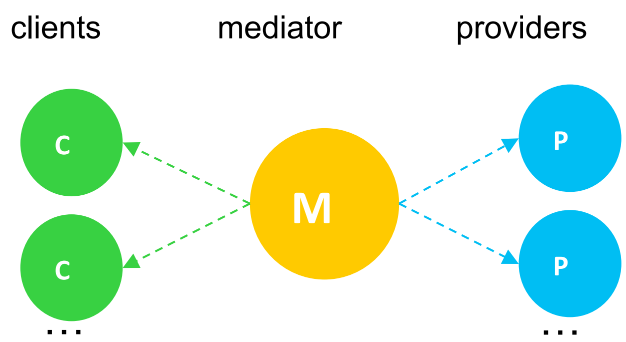
```
model AnalysisModel
  import Mediators.*;
 Requirements.Req req1(numberOfCavPumps=
   sum({
   (if (HFunctions.H_is_cavitating(sri.PO1.Qv, sri.PO1.C1_P, 1))
       then 1 else 0),
   (if (HFunctions.H_is_cavitating(sri.PO2.Qv, sri.PO2.Pmin, 1))
       then 1 else 0),
   (if (HFunctions.H_is_cavitating(sri.PO3.Qv, sri.PO3.C1_P, 1))
       then 1 else 0)}));

 SRI sri;
end AnalysisModel;
```

WHAT DO WE NEED TO ACHIEVE THIS?

Bindings Concept: Basic Idea

- Some models require data: ***Clients***
- Some models can provide require data: ***Providers***
- **Clients and providers do not know each other a priori** !

- **Mediators** relate a number of clients to a number of providers



What do we Need to Capture?

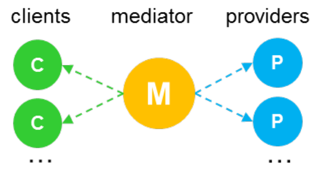
- **Mediator** specifies *which models are **clients*** and *exposes* what ***information*** is needed
- **Providers** are used to infer the *binding expression for clients*

- In our example:
  - A mediator will be used to infer the binding expression that calculates *the number of caviating pumps* in a particular system design model.

- Computing strategy:
  - Each pump model shall return *1* if it cavitates and *0* otherwise
  - Mediator will sum up the values from all the pumps

How do we capture this information?

Example using Modelica Syntax



Requirement Analyst

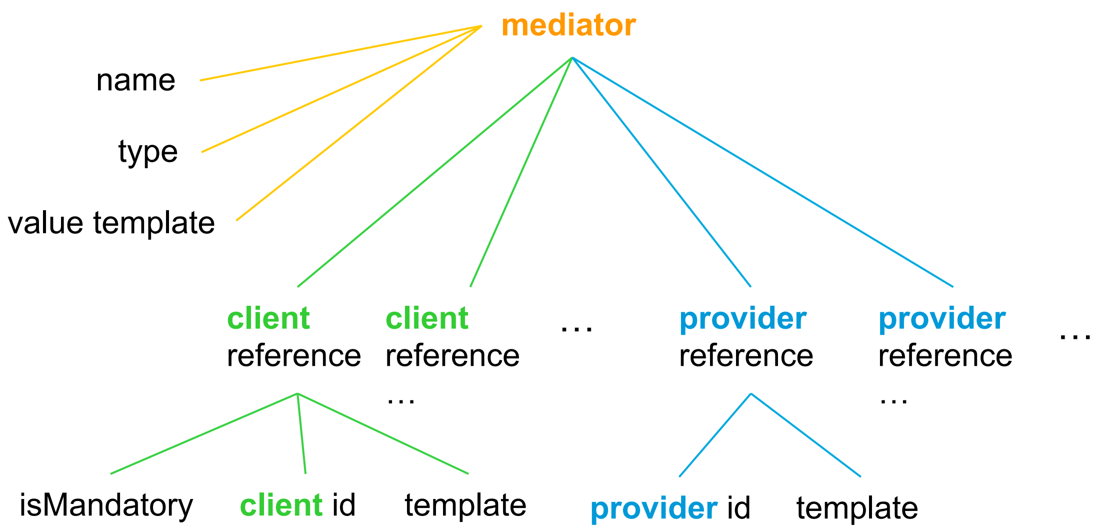
System Designer

```
package PartialMediators
  partial mediator NumberOfCaviatingPumps
    /* Number of cavitating pumps. This mediator is incomplete
    because no provider are defined yet. */

    type Real;

    clients
      mandatory Requirements.Req.numberOfCavPumps;

  end NumberOfCaviatingPumps_C;
end PartialMediators;
```

```
package Mediators
  mediator NumberOfCavitatingPumps_P1
    extends PartialMediators.NumberOfCaviatingPumps_C;

    /* reduces the array of provided values to a single value */
    template sum(:) end template;

    /* list of providers used to compute the number of
    all cavitating pumps */
    providers
      /* reference to the provider model (i.e., its qualified name) */
      Machines.PumpA
        template
          if HFunctions.H_is_caviating(
            getPath().Qv, getPath().C1_P,
            getNPSHTable(A)
          )
          then 1 else 0
        end template;

    /* getPath() is a placeholder that will be replaced with the
    instance path of the pump model */
    Machines.PumpB
      template
        if HFunctions.H_is_caviating(
          getPath().Qv, getPath().Pmin,
          getNPSHTable(B)
        )
        then 1 else 0
      end template;
  end NumberOfCaviatingPumps_P1;
end Mediators;
```

What do we need to capture?

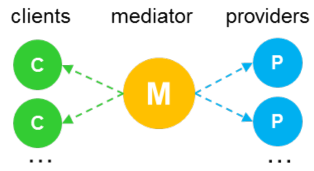
Abstract Syntax View



- **Mediator name** (with optional comments) reflects what is needed by clients
- **Mediator type** must be compatible to each of its clients (for Modelica also the lowest variability of clients should be indicated)
- **Client or provider id** is the <u>qualified name</u> of the client or provider model (e.g. `Package1.Model1.component1`)
- **isMandatory** (true by default) indicates whether the client must be bound. If not, the client component must have a default value.
- All value templates are optional (template, preliminary name, an expression that returns a value)
- **Client or provider template** contains expressions that can contain instance paths (e.g. in Modelica using the dot-notation) for referencing components within the client or provider models
- **Mediator template** can only contain predefined macros (e.g. sum(:), toArray(:), card(:), min(:), max(:), etc.)

HOW TO ACHIEVE OUR GOAL?

Generated Binding Expression



Mediator that contains **client** references:

```
partial mediator NumberOfCaviatingPumps_C
   type Real
   clients
     isMandatory Requirements.Req.numberOfCavPumps;
…
```

Mediator that also contains **provider** references:

```
mediator NumberOfCavitatingPumps_P1
  extends NumberOfCaviatingPumps_C;

  template sum(:) end template;
  providers
    Machines.PumpA
     template
      if HFunctions.H_is_caviating(getPath().Qv, getPath().C1_P,
                                   getNPSHTable(A)) then 1 else 0
     end template;
    …
```

Mediator definition

Model with generated binding for client req1.numberOfCavPumps:

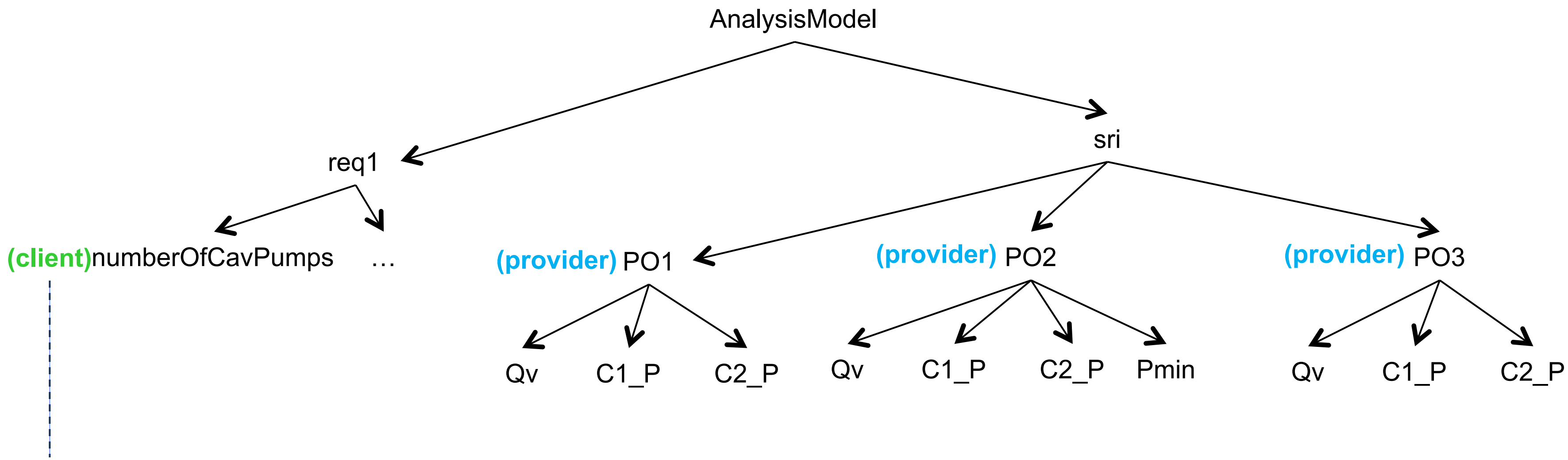
```
model AnalysisModel
  …
  Requirements.Req req1(numberOfCavPumps= sum({
    (if (HFunctions.H_is_cavitating(sri.PO1.Qv, sri.PO1.C1_P, 1)) then 1 else 0),
    (if (HFunctions.H_is_cavitating(sri.PO2.Qv, sri.PO2.Pmin, 1)) then 1 else 0),
    (if (HFunctions.H_is_cavitating(sri.PO3.Qv, sri.PO3.C1_P, 1)) then 1 else 0)}));
…
```

Generated binding expressions for clients

Note, getPath() is replaced by provider model instance path within the given context

Generating Bindings Expression

Instantiation Tree



Inferred binding expression: numberOfCavPumps= sum({
(if (HFunctions.H_is_cavitating(sri.PO1.Qv, sri.PO1.C1_P, 1)) then 1 else 0),
(if (HFunctions.H_is_cavitating(sri.PO2.Qv, sri.PO2.Pmin, 1)) then 1 else 0),
(if (HFunctions.H_is_cavitating(sri.PO3.Qv, sri.PO1.C1_P, 1)) then 1 else 0)}))

To be stored as modified in AnalysisMode1: req1 (numberOfCavPumps = …

Client model qualified name: Requirements.Req.numberOfCavPumps (used to identify it as client based on mediator references)
Client instance path in AnalysisModel1: req1.numberOfCavPumps
Mediator (used to inferring the binding expression): Mediators.NumberOfCaviatingPumps_P1
Mediator operation (used to inferring the binding expression): sum(:)
Providers (used to inferring bindings expression): sri.PO1, sri.PO2, sri.PO3

USING BINDINGS FOR VERIFICATION MODEL COMPOSITION

Composing Verification Models

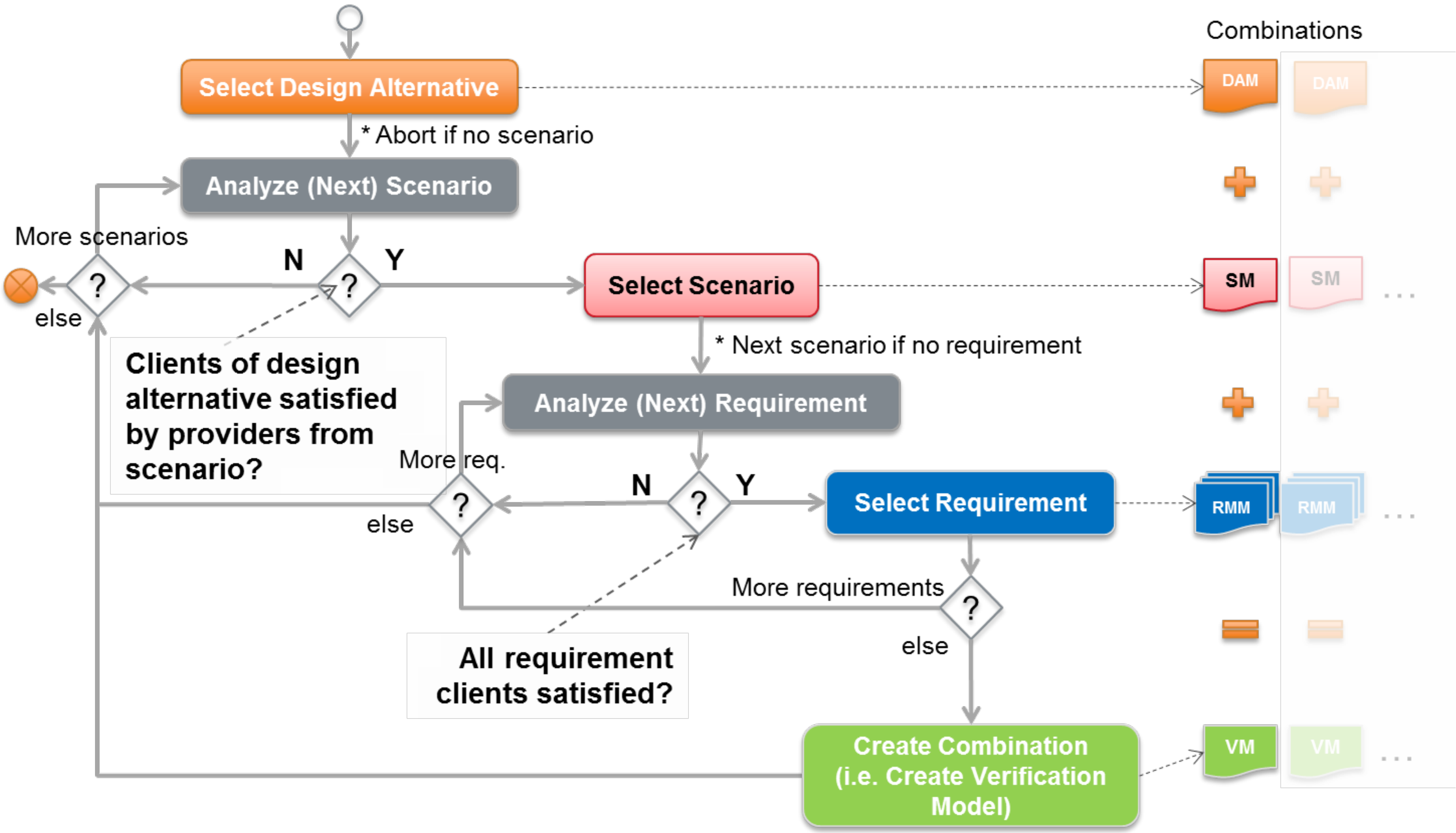
main idea

- Collect all **scenarios**, **requirements**, import **mediators**
- Generate/compose *verification models* automatically:
  - Select the **system model** to be verified
  - Find all **scenarios** that can stimulate the selected system model (i.e., for each mandatory client check whether the binding expression can be inferred)
  - Find **requirements** that are implemented in the selected system model (i.e., **check** whether for **each requirement** for all mandatory clients binding expressions can be inferred)

- Present the list of scenarios and requirements to the user
  - The user can select only a subset or scenarios or requirements he/she wishes to consider

Generating/Composing Verification Models

algorithm



Issues

- Best representation:
  - Modelica Syntax? XML? Annotations?