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Madrid, 24-26 abril, 2024

TRANSFORMANDO
LOS OCÉANOS:
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un mundo CONECTADO y SOSTENIBLE

SIMULATION MODEL ACCREDITATION:
An implementation guide

Basilio Puente Varela

Head of Conceptual & Basic Design, Techno Pro Hispania S.L.

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Model:

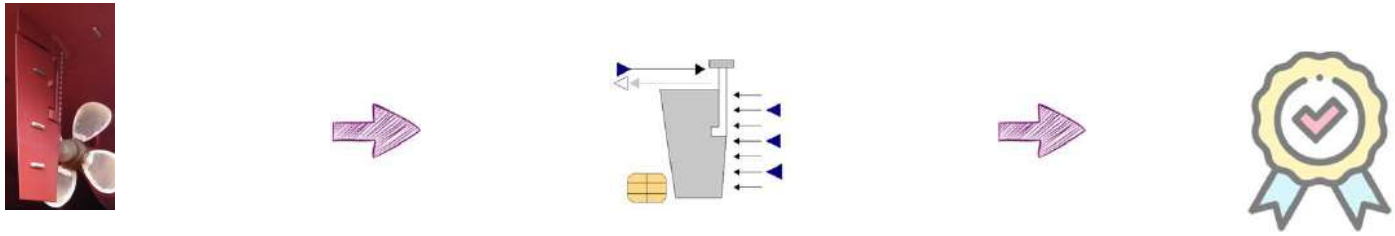
- *A ~~physical~~, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process valid only for a specific purpose.*

Simulation:

- *An "experiment" done over a mathematical model.*

Accreditation:

- *The official certification that a model or simulation and its associated data are acceptable for use for a specific purpose.*



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DANGERS OF NON-ACCREDITED SYSTEMS
SAFETY AND MATERIAL LOSS

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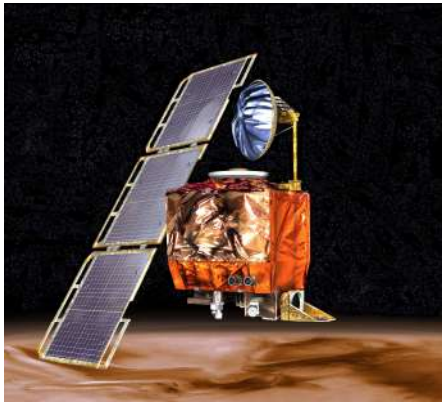

Dangers of non-accredited systems – Mars Climate Orbiter

- *Model Specification:* One of the NASA subcontractors had used English units instead of the intended metric system, which caused the orbiter's thrusters to work incorrectly. Due to this, the orbiter crashed almost immediately when it arrived at Mars in 1999.

Dangers of non-accredited systems – Boeing 737 Max

- *Independent Accreditation:* Since 2009 FAA delegates the accreditation to Boeing for their products
- *Hidden System Features:* MCAS existence was not notified to pilots

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DANGERS OF NON-ACCREDITED SYSTEMS
CYBERSECURITY

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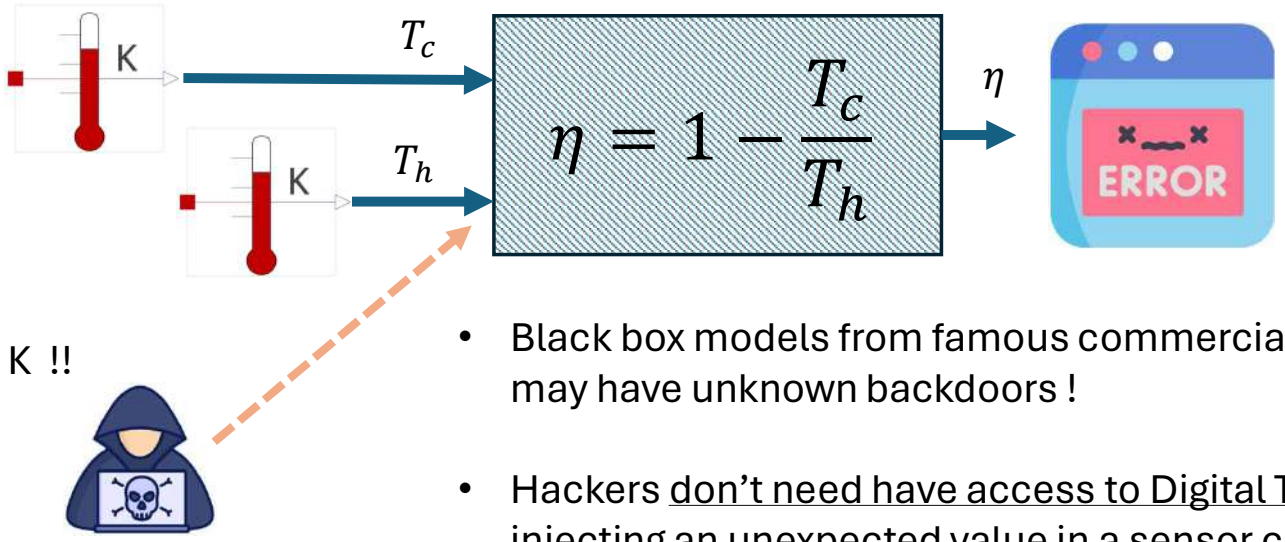

- Black box models from famous commercial libraries may have unknown backdoors !
- Hackers <u>don't need have access to Digital Twin</u>, injecting an unexpected value in a sensor can produce a hangout in the system !

Accredited models are necessary for secure Digital Twins !!!

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LIFETIME SUPPORT OF SIMULATION MODELS

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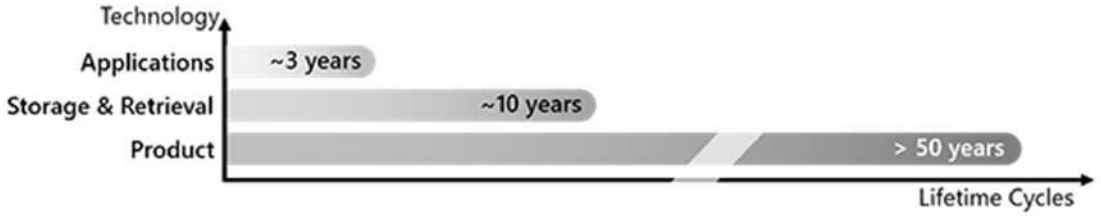
LOTAR
LONG TERM ARCHIVING AND RETRIEVAL



"Long product lifetime requires long term technologies"

Modelica

LOTAR suggest the use of Modelica, FMI and SSP standards on simulation for Long-Term Archiving and Retrieval

fmi Functional Mock-up Interface

SSP System Structure & Parameterization

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MODELING WORKFLOW

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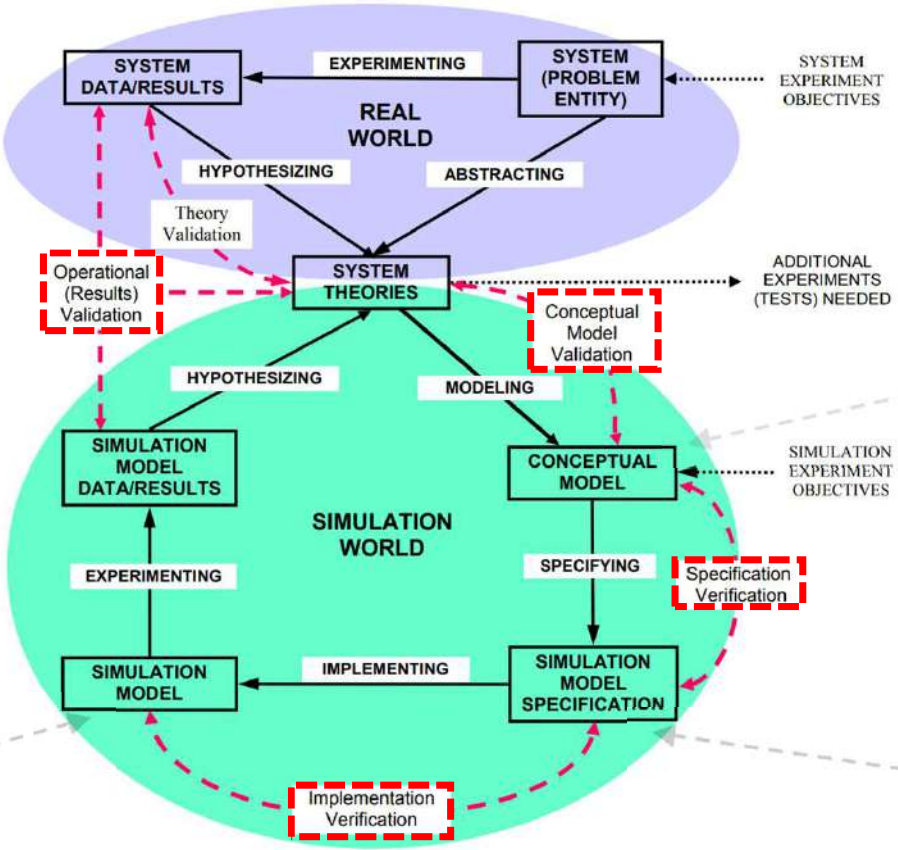
IVV&A

Independent
Verification
Validation &
Accreditation



VERIFICATION AND VALIDATION OF SIMULATION MODELS, Robert G. Sargent

Equations:
V=I*R
F=m*a
…

Tool-dependent source code

How the model will be developed?

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MODELING CONCEPTS

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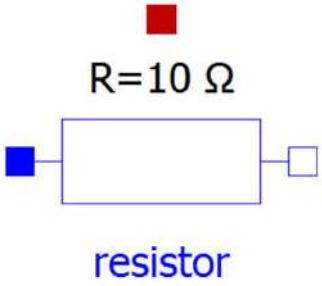
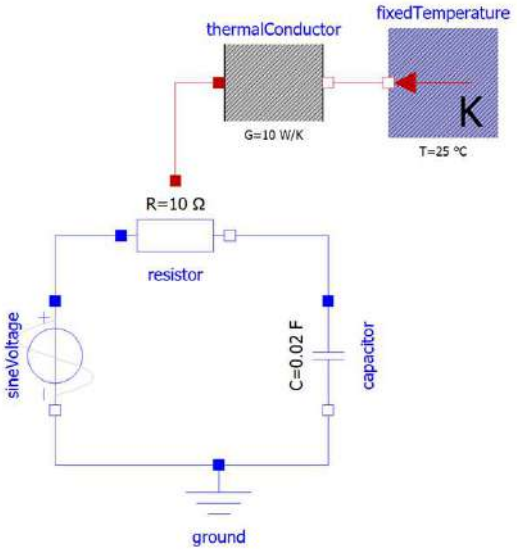
COMPONENT



- Not has balanced system of equations (a component cannot be executed alone)
- Can contain other components inside

SYSTEM



- It is composed by several components communicating together
- Has balanced system of equations (can be executed)

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MODEL CLASSIFICATION

Model Types

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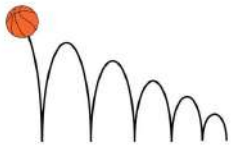
PM: Physics Model



- **WKPE**: Well Know Physical Equations

$$F = m * a$$

- **MPEE**: Mixed Physical/Empirical Equations

$$Cf = 0.075 / (Log10(Re) - 2)^2$$

DM: Data Model

- **DBM**: Data Based Model
- **ROM**: Reduced Order Model

MM: Mixed Model

BBM: Black Box Model

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MODEL CLASSIFICATION

Model Types

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Model Notation

SC: Standard Connector

```
connector Pin "Pin of an electrical component"
  SI.ElectricPotential v "Potential at the pin";
  flow SI.Current i "Current flowing into the pin";
end Pin;
```

PD: Proven Data

Data from experiments or measurements that was accredited for their use on models

RT: Real Time Model

Model designed to have a simulation time much faster than real time

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MODEL CLASSIFICATION

Levels of Accreditation

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Accreditation Levels

CL: Model Credibility Level

Assigned on model quality assessment

CL0: No assessment is required.

CL1: Model performance, stability issues, submodel dedicated test, fault detection, etc… are not necessary.

CL2: Automatic test generator, fault detection, etc.. are not mandatory.

CL3: All main inspections are mandatory.

CL4: Highest level, all assessments are mandatory.

ML: Supplier Maturity Level

Assigned on process quality assessment

ML0: Undocumented processes changing dynamically without control.

ML1: Some processes can be repeated with consistent results.

ML2: Standard processes defined with some degree of improvement over time.

ML3: Processes with metrics, advanced experience on simulation.

ML4: Highest level, efficient processes, and highest experience on simulation.

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MODEL CLASSIFICATION

Accreditation Rules

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Accreditation Rules

1st The supplier ML shall be >= of the model CL

2nd CL shall be calculated as the lesser from model and subcomponent hierarchy used in the model. (inherited CL)

3rd Where a third party cannot audit or test extensively~~, the CL can be complemented with the supplier ML~~ NOT RECCOMENDED

Example: A model is developed to have CL4, but it uses a component that has CL2.

On this situation, the model is assigned CL2, with a potential increase to CL4 after replacing the CL2 component and repeat the validation test .

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MODEL CLASSIFICATION

Examples

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Model Notation

✠ CL3, PM-WKPE, RT

✠ : *Developed under supervision of the signing third party.*

CL3: *Model Credibility Level*

PM-WKPE: *Physics Model using Well Know Physical Equations*

RT: *Real Time capability*

CL2, DM-ROM

Not Developed under supervision of the signing third party.

CL2: *Model Credibility Level*

DM-ROM: *Data Model using Reduced Order Model*

In addition:
- Model scope to be included in model documentation
- Limitations implemented on the model
- Approved solver (embedded on FMU or into documentation)
  e.g.: DASSL, Tolerance: e-6, Max. Step: 0.01 s

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MODEL CLASSIFICATION

Usage of Accredited Models

Target System

	Severity of consequence if function does not work as intended			
	Minor	Significant	Severe	Catastrophic
High uncertainty that model does not represent relevant aspects of the reality	2	3	4	Not Trusted
Medium uncertainty that model does not represent relevant aspects of the reality	1	2	3	4
Low uncertainty that model does not represent relevant aspects of the reality	0	1	2	3

Taken from DNV-RP-0513

Risk Assessment

Required CL

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Conceptual Model Validation

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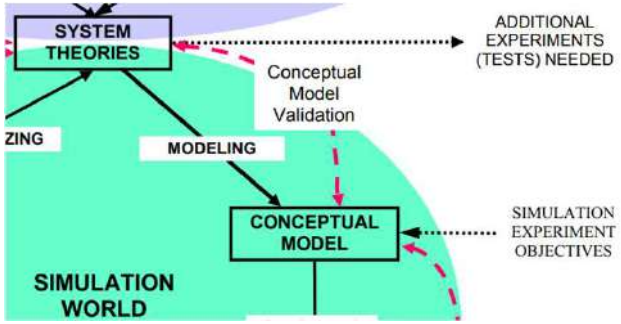
Conceptual Model Validation



Define Model Scope

- Document intended purpose
- Select physics fields to be modelled
- Define input (variables and parameters) and output variables of interest and their accuracy needed
- Search for state-of-art theories and assumptions to be used

Conceptual Model Validation

- The theories and assumptions are well selected for the model purpose?
- The conceptual model covers the variables of interest needs?

Output

- Conceptual Model Validation document
- Summary of Model Scope (theories, variables, assumptions, etc…) to embed into the component

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Model Specification Verification

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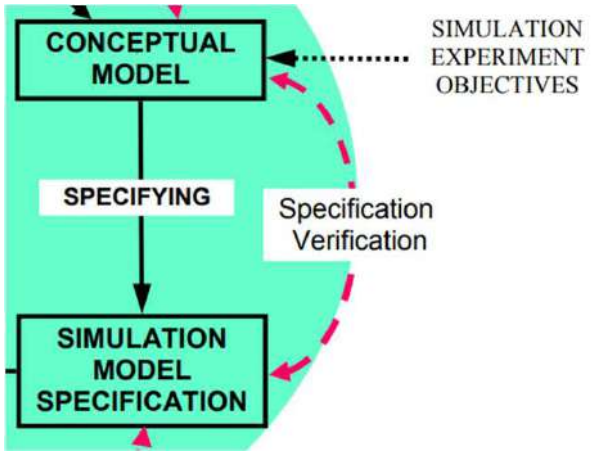
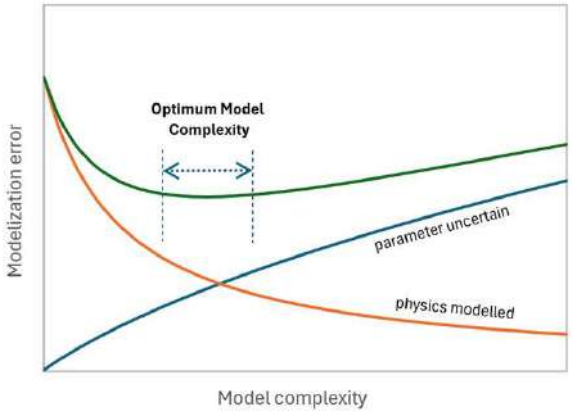
Model Specification Verification





Simulation Model Specification

- Strategy of implementation:
  - ***Divide and conquer***: Complex components shall be divided into smaller ones that need to pass individually all this accreditation. On this respect, the use of accredited components shall save a lot of effort.
  - **KISS** (Kept It Simple, St...id!):
    - Don't add unwanted extra functionality!
    - Don't add (or protect) extra variables!
    - Select the correct level of detail of the model!
  - ***Efficient and Reusable code***:
    Use Partial / Extended models
    Conditional components
    Replaceable components

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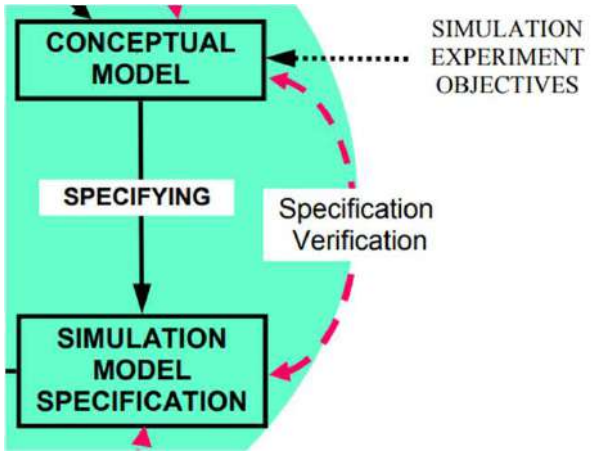

Simulation Model Specification

1. Select and justify the tool / language used
2. Breakdown the model into the optimum number of subcomponents / parts to be developed and connect them in a chart
3. Define all model connections and parameters
4. Define the functionality of each subcomponent / part
5. Define partial validations for each subcomponent / part
6. List all limitations of the model

- *All the model requirements are implemented?*
- *The specification follows and develops the Conceptual Model?*
- *Are the variables of interest represented? Is expected to reach the required accuracy?*

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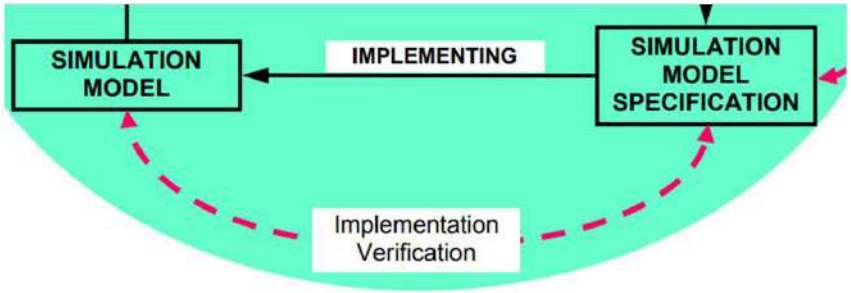

Model Implementation Verification

Model Equations

- Set the applicability limits

This equation is only valid for Pe_D < 0.2 :

Always document code!

```
Nu_D_f = 1/(0.8237 - 0.5*log(Pe_D)) "Obtained from reference [Lienhard]";
```

The model will be protected to not be used outside this validity range:

```
assert(Pe_D < 0.2, "!E0001 [ComponentX]: Only valid for Pe_D < 0.2 !", level = AssertionLevel.error);
```

Assertion Level = Error -> The simulation stops if the condition is not satisfied, the error message is shown

```
assert(Pe_D < 0.2, "!W0001 [ComponentX]: Only valid for Pe_D < 0.2 !", level = AssertionLevel.warning);
```

Assertion Level = Warning -> The simulation continues with a warning message if the condition is not satisfied

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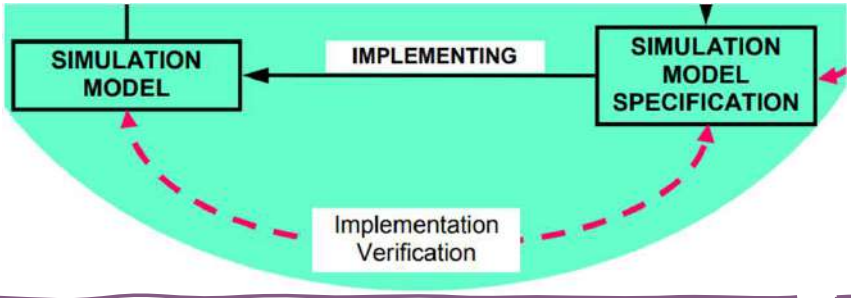


Model Equations

- Avoid weak points

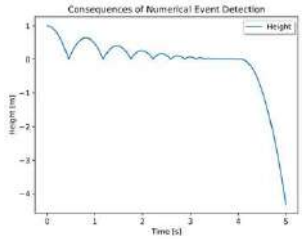
Avoid divisions by zero:

```
if noEvent(WaterSpeed > 0) then
    Drag_Vect = Water_Speed_XY/WaterSpeed;
else //If speed is zero
    Drag_Vect = {0, 0};
end if;
```

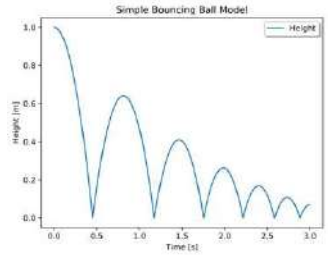
Avoid (a==b) when “a” and “b” are Real numbers etc.....

Avoid numerical artifacts:

```
when h<0 then
  reinit(v, -e*pre(v));
end when;
```




```
when {h<0,h<-eps} then
  done = h<-eps;
  reinit(v, -e*(if h<-eps then 0 else pre(v)));
end when;
```



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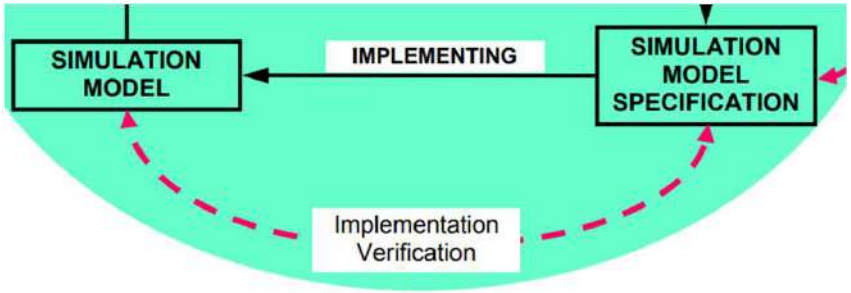

Model Equations

- Enhance numerical methods

Linearize equations if present an advantage:

Equation used if you want linearize emissive power

Usual equation

```
TRad = if linearize then (TRad4 + 3*T04)/(4*T03) else TRad4^(1/4);
```

Aid initialization phase of large nonlinear systems of equations with "homotopy":

Model equation

```
m_flow = homotopy(actual     = turbulentFlow_dp(dp, rho, lambda),
                  simplified = dp/dp_nominal * m_flow_nominal);
```

Simplified equation to start the initial solution iterative process

Avoid algebraic loops

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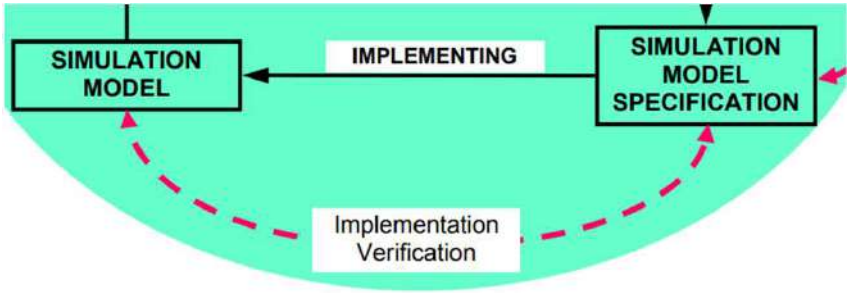

Model Equations

- Enhance numerical methods

Set the derivatives of complex functions:

```
function f
  input Real x;
  input Real y;
  output Real z;
  annotation(derivative=df);
algorithm
  z := // some expression involving x and y
end f;
```

Derivative

```
function df
  input Real x;
  input Real y;
  input Real dx;
  input Real dy;
  output Real dz;
algorithm
  dz := // some expression involving x, y, dx and dy
end df;
```

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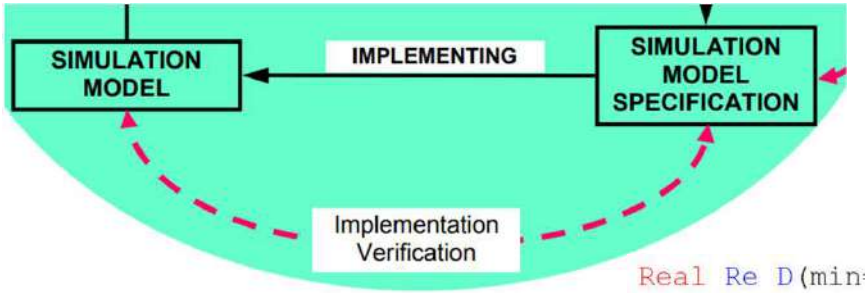

Model Implementation Verification

Model Parameters and Variables

- Examples

```
Real Re D(min=0, max=1e8, start=10000, fixed=false) "Reynolds number";
```

Document variable

```
Real z "Uninteresting variable" annotation(HideResult=true);
```

Hide uninteresting variables on results

```
type Real // Note: Defined with Modelica syntax although predefined
  RealType ⟨value⟩; // Not an attribute; only accessed without dot-notation
  parameter StringType quantity    = "";
  parameter StringType unit        = "" "Unit used in equations";
  parameter StringType displayUnit = "" "Default display unit";
  parameter RealType min = -Inf, max = +Inf; // Inf denotes a large value
  parameter RealType start;                  // Initial value
  parameter BooleanType fixed = true,  // default for parameter/constant;
                        = false; // default for other variables
  parameter RealType nominal;              // Nominal value
  parameter BooleanType unbounded = false; // For error control
  parameter StateSelect stateSelect = StateSelect.default;
equation
  assert(min <= ⟨value⟩ and ⟨value⟩ <= max, "Variable value out of limit");
end Real;
```

Mass, temperature, etc..

Units

Min and max limits

Start value (mandatory)

Suggested start value

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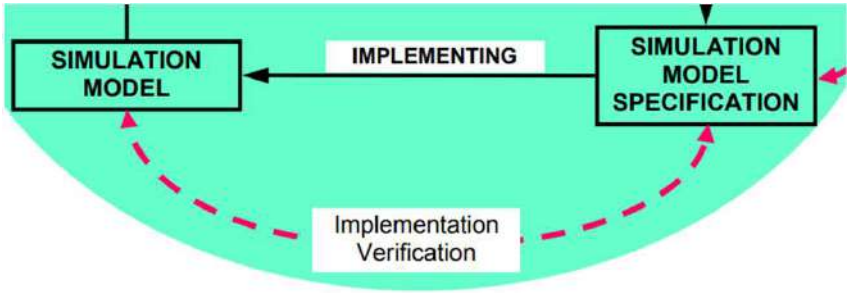

julia

+

Modelica Language

=

Modia.jl

Model Parameters

Advanced parameter information:

```
c = 1400.8
  min    = 0
  max    = 1e6
  unit   = "N.m/rad"
  description = "Compliance spring constant"

  Traceability
    source    = Calibrated
    info      = "Based on measurements on test bed B in project XYZ."
    reference = "modelica://ProjectXYZData/ReportXYZ_B17.pdf"
  Uncertainty
    source       = Estimated
    type         = TruncatedNormalTolerance
    nominal      = 1400.8
    relTol       = 0.05    // 5% relative tolerance
    stdDevFactor = 3       // 99.7% at the limits of underlying normal distribution
  Calibration
    start      = 1000
    min        = 100.0
    max        = 5000.0
    __ToolA_Setup = "modelica://ProjectXYZLib/Resources/calibrateDrive.mos"
```

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Model Validation

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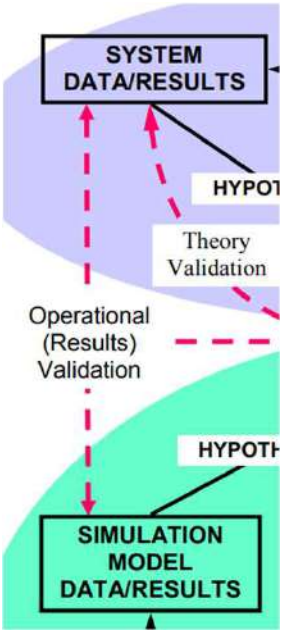
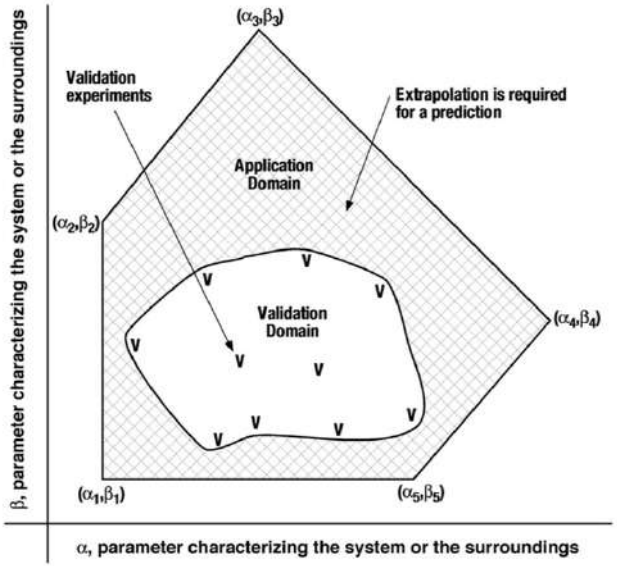
Model Validation





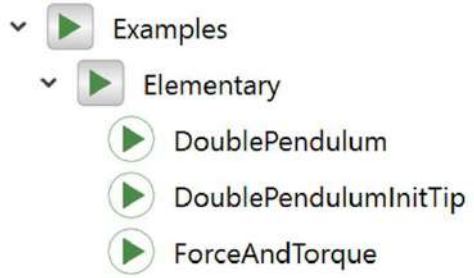
Trucano, T.G. et al (2002)

Model Validation Procedure

1. *Map the scope of the validation*
2. *List the validation experiments and simulate*
3. *Compare results and accuracy*
4. *Simulate for application domain and judge the results*

Validation Archiving

1. *Include validation test to be shipped with the model*
2. *Create usage examples and document them*



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Model Accreditation

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Model Accreditation

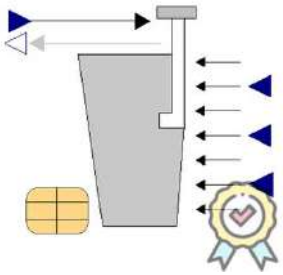
Accreditation Metadata

```
__Accreditation_MetaData = {
  // Third Party that accredit the model
  {"AccreditationID", "E4R-324456"},
  {"AccreditationBy", "Third Party Company"},
  {"AccreditationAuthor", "Jane Doe"},
  {"AccreditationRelatedSigns", "SIGN_ID1,SIGN_ID2,..."},

  // Model developer metadata
  {"Organization", "Developer Company"},
  {"MainDeveloper", "John Doe"},
  {"Contact", "john.doe@developercompany.ext"},
  {"ModelLicense", "BSD 3-clause"},
  {"DeveloperRelatedSigns", "SIGN_ID5,SIGN_ID6,..."},

  // Accreditation details
  {"DevelopedUnderSupervision", "YES"},
  {"ModelType", "PM"},
  {"ModelSubType", "WKPE"},
  {"AdditionalNotation", "RT"},
  {"CredibilityLevel", "3"},
  {"DevelopmentCredibilityLevel", "4"},
  {"MaturityLevel", "4"},

  // V&V details
  {"ApprovedSolver", "DASSL"},
  {"Tolerance", "1e-6"},
  {"MaxStep", "0.01"},
  {"Tool", "OpenModelica"},
  {"ToolVersion", "v1.22.1"}},
```



Document the Accreditation

Accreditation

Model Notation

⊞ **CL3, PM-WKPE, RT**

Approved Solver

DASSL, Tolerance: 1e-6, Max. Step: 0.01s, Tool: OpenModelica, Tool Version: v1.22.1

Model Scope

Model developed within the following scope:
- No transitory heat transfer
- Uncompressible liquids
- etc...

Model Limitations

This model is limited to:
- Pe < 0.2
- etc...

Details

Accreditation ID:	E4R-324456
Accredited By:	Third Party company
Accreditation Author:	Jane Doe
Accreditation Date:	18/02/2024 8:09:23 (Last signed date)
Developed By:	Developer Company
Maturity Level:	4
Main Developer:	John Doe
Contact:	john.doe@developercompany.ext
Model License:	BSD 3-Clause

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Model Accreditation

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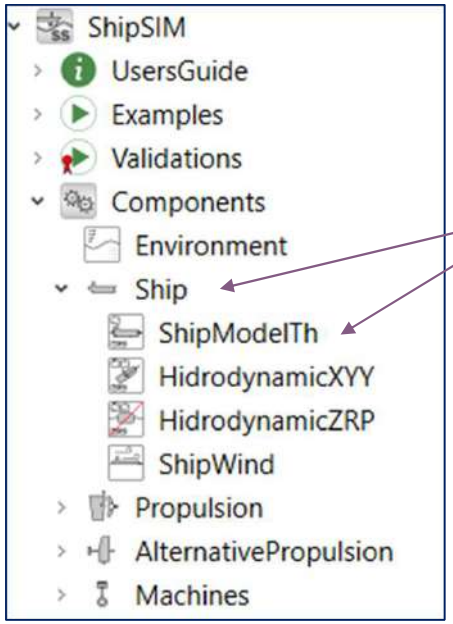
Sign & Stamp



Digital Signature

Developers, Quality reviewers, Accreditation Third Party Company, etc… Can sign a component model or a part of a library

Several signatures can exist for the same component/part of a library.

The signatures are then embedded into source code, making it inseparable from the models

```
__DigitalSignature = {
 {"SignID", "SIGN_ID1"},
 {"SignedBy", "Third Party Company"},
 {"SignAuthor", "Jane Doe"},
 {"SignTimeStamp", "18/02/2024 8:09:23"},
 {"SignCertificate", "Link to certificate"},
 {"HashAlgorithm", "SHA512"},
 {"HashValue", "3f2d0.....eab663e"},
 {"Signature", "0298e304f0.......7b718a"}});
```

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What about IP protection?

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Intellectual Property

Intellectual Property

Source Code Level
(similar to another Project document)

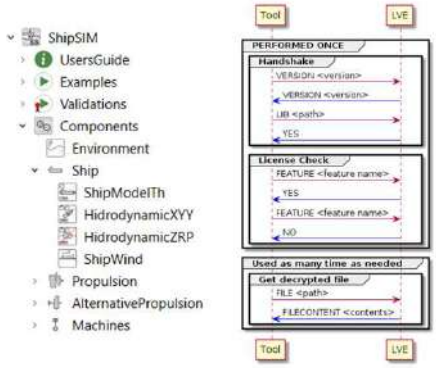
- Restricted access to servers
- Restricted access to I/O peripheral
- Restricted access to Internet
- Restricted access to components/parts of library

```
CoB[1] = sum(LCB_aux[:]) - BM1*Modelica.Math.sin(Trim);
CoB[2] = sum(TCB_aux[:]) - BMt*Modelica.Math.sin(Heel);
CoB[3] = sum(VCB_aux[:]) + BM1*(1 - Modelica.Math.cos(Trim)) + BMt*(1 -
COB_pos.r_vect = CoB;
B_ForceWorld.force = {0, 0, Disp*Modelica.Constants.g_n};
/Equations
COF_pos.r_vect = {Lpp/2, 0, Draft/2} "Measure the speed on the point spe
der(Yaw) = absoluteAngularVelocity.w[3];
Surge = absoluteVelocity.v[1];
Sway = absoluteVelocity.v[2];
Heave = absoluteVelocity.v[3];
connect(frame_a, COB_pos.frame_a) annotation( ...);
connect(COB_pos.frame_b, B_ForceWorld.frame_b) annotation( ...);
connect(ShipMass.frame_a, frame_a) annotation( ...);
connect(absoluteAngularVelocity.frame_a, frame_a) annotation( ...);
connect(COF_pos.frame_b, absoluteVelocity.frame_a) annotation( ...);
connect(frame_a, COF_pos.frame_a) annotation( ...);
```

Library Level
SEMLA Protocol

- Encrypted Library
- Client-License Server communication for decrypt and use of the library
- Simulation tool SEMLA support

Alternative: Code Obfuscation



Executable Level(FMU)
(similar to other software)

- Anti-disassembly techniques
- Code Obfuscation (Modelica source code it's more difficult to obtain from compiled code than other simulation tools based directly on C)

Original Source Code Before Rename Obfuscation	Reverse-Engineered Source Code After Rename Obfuscation
private void CalculatePayroll (SpecialList employee-Group) { while (employeeGroup.HasMore()) { employee = employeeGroup.GetNext(true); employee.UpdateSalary(); Distribute Check(employee); } }	private void a(a b) { while (b.a()) { a = b.a(true); a.a (); a.(a); } }

Accreditation Process Chart

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Final Overview

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Accreditation Process

Test Data

System Theories

Model Requirements

Third Party Accreditation Company

Conceptual Model Validation

Conceptual Model

Results Validation

Sign & Stamp

Notation Scope Limitations

Implementation Verification

Model Specification Verification

Simulation Model

```
if noEvent(WaterSpeed > 0) then
    Drag_Vect = Water_Speed_XY/WaterSpeed;
else //If speed is zero
    Drag_Vect = {0, 0};
end if;
```

Final Product

Usage

Long Term Archival

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Basilio Puente Varela

bpuente@tphispania.com

Thank you for your attention!