Equation-Based Model Data Structure for High Level Physical Modelling, Model Simplification and Modelica-Export

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Outline

• Introduction
  – Plant Modelling Process

• Physics-Based Component Modelling
  – High Level Model Description / HLMD
  – High Level Modelling Tool / HLMT

• Equation-Based Model Data Structure
  – MSModel and Simplification
  – Modelica-Export

• Modelica & HLM/MSModel

• Conclusion
Introduction

Plant Modelling Process
In-vehicle Control System Development

• More challenging requirements
  – Better fuel economy
  – Less emission
  – Proven functional safety
  • including safety under unexpected circumstances
  – Without compromising driveability

• More time and cost are spent
  – How to keep competitiveness?
Concurrent Development

• Avoid bloat of development time and cost
  – Conventional development process:
    • Develop hardware first, software second
  – Instead, develop H/W and S/W together
  – Impact of the concurrent development
    • Experiment may be impossible at early stage of software development process
    • Key is to embrace Model-Based Development
    • Plant modelling is essential for MBD!
Need for Plant Model Creation

• Specific requirements for plant models in a control system development project
  – Not known a priori

• Existing plant model libraries
  – Useful as a starting point for further change to meet specific requirements
  – Too large library is hard to maintain, hinders swift model authoring
Desired Plant Modelling Technologies

1/2

• *Physical component modelling ... “HLMD & HLMT”*

• Data-based modelling
  – Simulated / measured

• Physics-and-data combined system modelling
  – Incremental introduction of a data-based subsystem model into/instead of a part of physics-based system model
  – As more data is made available through experiment
Desired Plant Modelling Technologies 2/2

• Model simplification ... “MSModel”
  – Component-level / System-level
  – Symbolic / Numeric / Symbolic-numeric combined

• Optimization

• Model / Data / Process management
  – Efficient reuse/exchange
  – Process standardization
  – Traceability
Rapid Modelling 1/2

• Plant models have to be built in a timely manner
  – Specific requirement is not known a priori

• Stance:
  – *Have modelling methods at hand, ready to creat/modify a model for a specific need responsively.*
Rapid Modelling 2/2

• Equation-based approach?
  – Versatile, but needs additional methods to be rapid enough

• Sophisticated modelling techniques?
  – Not widely accepted for production use in Toyota, e.g.
    • Abstraction and inheritance
    • Bond-graph
  – “Simple over clever” is preferred
    • Efficient comprehensibility matters a lot
Goal of Plant Modelling Process

• Build a closed-loop simulation system with control software (XiL)
  – MiL ... Control design
  – SiL ... Software implementation verification & validation (V&V)
  – HiL ... ECU V&V - computation load, execution and communication timing etc.
  – Control software is developed using Simulink
  – Simscape is the target platform for plant models
    • Connectivity with Control Software
    • Code-Generation
Plant Modelling Process

- Start from physics-based component modelling
  - Design phase of a plant model component using high level modelling framework, HLMD/HLMT
- Simplify and export to Modelica via MSModel data structure
- Further transform to Simscape for system modelling
  - Perform integration with data-based models, system-level simplification, optimization
- Close loop with control software (MiL/SiL) or ECU (HiL)
Physics-Based Component Modelling

High Level Model Description / HLMD
High Level Model Description / HLMD

• Description of a physical component
  – For efficient design, review and reuse
  – Control volume approach
  – Set of equations can be derived
    • Derivation requires symbolic manipulation

• Domain neutral
  – For continuous system
    • Mechanical, thermal, electric, neumatic, chemical, viscoelastic, electrochemical, ...
    • Includes “piecewise”, only for smooth switching
  – Knowledge on constitutive equations required
 HLMD Example

• Target physical component:
  – A closed chamber

• Combustion occurs inside:

\[ H_2 + O_2 \rightarrow H_2O + \frac{1}{2}O_2 + c \ [J] \]
Modelling Steps to Create HLMD

1) Split a physical component (an HLM system) into HLM components
2) Define ports for each HLM component
3) Connect HLM components via ports
4) For each HLM component,
   – Define conservation quantities (CQs)
   – Define flows of CQs
5) Set constitutive equations for CQs and CQ flows
6) Set HLM system-level constraints as needed
Additionally, intermediate variables can be defined inside an HLM component and at a port
Parameters (constant symbols) can be defined as needed
HLMD of Combustion Model in A Closed Chamber

Constraint:

\[
\begin{align*}
P_{\text{unb}}(t) &= P_{\text{bur}}(t) \\
V_{\text{unb}}(t) + V_{\text{bur}}(t) &= V_0
\end{align*}
\]
Equation Construction from HLMD

\[
\frac{d}{dt} N_{\text{H}_2\text{O}, ff}(t) = n_{\text{H}_2\text{toH}_2\text{O}, ff}(t) + n_{\text{O}_2\text{toH}_2\text{O}, ff}(t) - n_{\text{H}_2\text{O}, ff}(t) - e_{ff}(t)
\]

- Equations are built to conserve CQs
Plain Set of HLM Equations

- The combustion model
  - Has 44 equations
    - 13 differential equations (DEs)
    - 31 algebraic equations (AEs)
  - Not ready for simulation in general
    - Physically
      - Could have multiple solutions
    - Mathematically
      - Could be a high-index DAE system
      - May contain redundant equations
Deriving a *Simulatable* Set of Equations

• Fully automated
  – Methods
    • Isolated HLM component detection
      – for single solution selection
    • Symbolic manipulation including index reduction
      – for high-index DAE, redundant equations
  – Derives index-1 DAEs or ODEs

• Proof of single solution existence
  – Research in progress
Simulatable Set of Equations

• The combustion model
  – Plain HLM had 44 equations
    • 13 DEs
    • 31 AEs
  – Simulatable HLM has 43 equations:
    • 11 DEs (7 explicit, 4 implicit)
      – 8 differential variables (DVs) need initial conditions
      – 3 other variables are algebraic (AVs)
    • 32 AEs (32 explicit, 0 implicit)
FYI: 7 Explicit Differential Equations

\[ 1, \ldots, \frac{d}{dt} \text{bur.NH2O}(t) = 2\text{NO2I}(t) - 2\text{NO2O}(t) \]

\[ 2, \ldots, \frac{d}{dt} \text{bur.NO2}(t) = \text{NO2O}(t) \]

\[ 3, \ldots, \frac{d}{dt} \text{bur.f}(t) = \frac{-2 \text{bur.f}(t) \text{NO2I}(t) + \text{bur.f}(t) \text{NO2O}(t) + 12 \text{NO2I}(t) - 7 \text{NO2O}(t)}{\text{bur.NO2}(t) + \text{bur.NH2O}(t)} \]

\[ 4, \ldots, \frac{d}{dt} \text{mid.NH2O}(t) = -4839449 \text{NO2I}(t) + 4839449 \text{NO2O}(t) \]

\[ 5, \ldots, \frac{d}{dt} \text{mix.NH2}(t) = -2 \text{NO2I}(t) + 2 \text{NO2O}(t) \]

\[ 6, \ldots, \frac{d}{dt} \text{mix.NO2}(t) = -\text{NO2I}(t) \]

\[ 7, \ldots, \frac{d}{dt} \text{mix.p}(t) = -\frac{1}{5} \frac{5 \text{mix.p}(t) \left( \frac{d}{dt} \text{mix.V}(t) \right) + 2 \text{mix.e}(t)}{\text{mix.V}(t)} \]

(Parameter values have been assigned.)
FYI: 4 Implicit Differential Equations

\[ 1, \ldots, \left(16 \operatorname{mix}(p(t)) \operatorname{mix}(\text{No}_2(t)) + \operatorname{mix}(p(t)) \operatorname{mix}(\text{NH}_2(t)) \left( \frac{d}{dt} \operatorname{mix}(V(t)) \right) \right) + \left( -\operatorname{mix}(\text{NH}_2(t)) - 16 \operatorname{mix}(\text{No}_2(t)) \right) \operatorname{mix}(e(t)) \\
+ 63 \operatorname{mix}(p(t)) \operatorname{mix}(V(t)) \text{no}_2(t) + \operatorname{mix}(p(t)) \operatorname{mix}(V(t)) \text{no}_2O(t) = 0 \]

\[ 2, \ldots, \left(5 \operatorname{mix}(p(t)) \operatorname{bur}(\text{No}_2(t)) \operatorname{bur}(f(t)) + 5 \operatorname{mix}(p(t)) \operatorname{bur}(\text{NH}_2o(t)) \operatorname{bur}(f(t)) \left( \frac{d}{dt} \operatorname{mix}(V(t)) \right) \right) + \left( 10 \operatorname{mix}(V(t)) \operatorname{bur}(\text{No}_2(t)) \\
+ 10 \operatorname{mix}(V(t)) \operatorname{bur}(\text{NH}_2o(t)) - 2 \operatorname{bur}(f(t)) \operatorname{mix}(V(t)) \operatorname{bur}(\text{No}_2(t)) - 2 \operatorname{bur}(f(t)) \operatorname{mix}(V(t)) \operatorname{bur}(\text{NH}_2o(t)) + 2 \operatorname{bur}(\text{No}_2(t)) \operatorname{bur}(f(t)) \\
+ 2 \operatorname{bur}(\text{NH}_2o(t)) \operatorname{bur}(f(t)) \operatorname{mix}(e(t)) + \left( 48394500 \operatorname{mix}(V(t)) \operatorname{bur}(\text{No}_2(t)) + 48394500 \operatorname{mix}(V(t)) \operatorname{bur}(\text{NH}_2o(t)) \\
- 10 \operatorname{mix}(p(t)) \operatorname{mix}(V(t))^2 \operatorname{bur}(f(t)) + 60 \operatorname{mix}(p(t)) \operatorname{mix}(V(t))^2 + 10 \operatorname{bur}(f(t)) \operatorname{mix}(p(t)) \operatorname{mix}(V(t)) - 60 \operatorname{mix}(p(t)) \operatorname{mix}(V(t)) \right) \text{no}_2I(t) + \left( \\
-48394500 \operatorname{mix}(V(t)) \operatorname{bur}(\text{No}_2(t)) - 48394500 \operatorname{mix}(V(t)) \operatorname{bur}(\text{NH}_2o(t)) + 5 \operatorname{mix}(p(t)) \operatorname{mix}(V(t))^2 \operatorname{bur}(f(t)) - 35 \operatorname{mix}(p(t)) \operatorname{mix}(V(t))^2 \\
- 5 \operatorname{bur}(f(t)) \operatorname{mix}(p(t)) \operatorname{mix}(V(t)) + 35 \operatorname{mix}(p(t)) \operatorname{mix}(V(t)) \right) \text{no}_2O(t) = 0 \]

\[ 3, \ldots, 601365581 \operatorname{mix}(\text{No}_2(t)) \operatorname{mix}(p(t)) \operatorname{mix}(\text{NH}_2(t)) - 9621849296 \operatorname{mix}(\text{No}_2(t))^2 \operatorname{mix}(p(t)) + \left( 601365581 \operatorname{mix}(\text{No}_2(t)) \operatorname{mix}(p(t)) \operatorname{mix}(\text{NH}_2(t)) \\
+ 9621849296 \operatorname{mix}(\text{No}_2(t))^2 \operatorname{mix}(p(t)) \right) \left( \frac{d}{dt} \operatorname{mix}(V(t)) \right) + \left( 6250000000000000 \operatorname{mix}(\text{NH}_2(t)) \\
+ 6250000000000000 \operatorname{mix}(\text{No}_2(t)) \right) \text{no}_2I(t) = 0 \]

\[ 4, \ldots, 601365581 \operatorname{mix}(\text{NH}_2(t))^2 \operatorname{mix}(p(t)) - 9621849296 \operatorname{mix}(\text{No}_2(t)) \operatorname{mix}(p(t)) \operatorname{mix}(\text{NH}_2(t)) + \left( 601365581 \operatorname{mix}(\text{NH}_2(t))^2 \operatorname{mix}(p(t)) \\
+ 9621849296 \operatorname{mix}(\text{No}_2(t)) \operatorname{mix}(p(t)) \operatorname{mix}(\text{NH}_2(t)) \right) \left( \frac{d}{dt} \operatorname{mix}(V(t)) \right) + \left( 1250000000000000 \operatorname{mix}(\text{NH}_2(t)) \\
+ 12500000000000000 \operatorname{mix}(\text{No}_2(t)) \right) \text{no}_2I(t) + \left( -12500000000000000 \operatorname{mix}(\text{NH}_2(t)) - 12500000000000000 \operatorname{mix}(\text{No}_2(t)) \right) \text{no}_2O(t) = 0 \]

(Parameter values have been assigned.)
FYI: Observation in HLMD

- Variables in 11 DEs in the combustion model
Physics-Based Component Modelling

High Level Modelling Tool / HLMT
High Level Modelling Tool / HLMT

- A software package for HLMD
  - Toyota developed with Maplesoft, owns IP
  - 1st prototype in 2008
  - 2nd prototype development plan later this year
- Modelling in HLMD and simulation possible
- Built on top of Maple, commercial symbolic manipulation software from Maplesoft
  - API available as Maple library, in addition to GUI
- Hoping to make it open
  - MSModel is the first step
HLMT GUI

- Model tree
- Diagram editor
- Messages
- Equations editor & viewer
Simulation in HLMT

• Plots of the combustion model simulation

- Volume of unbunred gas
- Pressure of unbunred gas
- Volume of bunred gas
- Pressure of bunred gas
Future Topic for HLM Framework

• Equation-based physical knowledge base repository
  – Repository of constitutive equations in various engineering domains:
    • Mechanical, thermal, electric, neumatic, chemical, viscoelastic, electrochemical, ...
  – Necessary for efficient modelling in HLM framework
  – Open format/specification preferred

• Proof of single solution existance
Equation-Based Model Data Structure

MSModel & Simplification
Equation-Based Model Simplification Research Project

• A research collaboration project between Maplesoft and Toyota
  – Symbolic / Numeric / Combined methods
  – Algorithms are implemented in Maple
  – Supports HLMD models

• MSModel data structure
  – Designed in this project
  – Realized in Maple language
MSModel

• Data Structure for Model Simplification
  – Designed for open R&D collaboration on equation-based model simplification methods
  – Specification has been published in our paper
  – Neutral for equation-based languages and tools

• Requirements: it can...
  – Store information generated in HLMT
    • Either plain or simulatable equations
  – Store a simplified/simulatable set of equations
  – Provide convenience for simplification methods
  – Generate a Modelica representation
MSModel Elements

• Core equations
  – Required to compute at every integration step

• Non-core equations
  – Required to compute only when necessary

• Additional information
  – Useful pieces of information for simplification and Modelica-export
    • Variable list etc.
Core Equations

• Required to compute at every integration step:
  – Differential equations / DEs
  – Algebraic equations / AEs
  – Intermediate equations / IEs
    • Stored in straight-line causal arrangement
    • No derivatives
Non-core Equations

• Required to compute only when necessary:
  – Dependent equations
    • Stored in straight-line causal arrangement
    • May be implicit
    • May contain derivatives
Additional Information

- Parameters
- Inputs and outputs
- Name, type, value of variables
- Blackbox functions
  - lookup tables, user-defined functions
Fictitious Example of MSModel

```plaintext
msm := Record(MSMODEL,
    DE=[ ( diff(x1(t),t)=-a*x1(t)+u1(t) ), ...],
    DV=[ 'x1' , ...],
    AE=[],
    AV=[],
    t='t',
    intermediate=(Array(1..0,[])),
    intermediateVariables=[],
    dependent=(Array(1..3,{
        1=[{ e1(t)=-1/2*sin(x1(t)) },{e1(t)}],
        2=[{ e2(t)=u1(t)*e1(t) },{e2(t)}],
        3=[{ y(t)=e1(t)+e2(t) },{y(t)}] })),
    dependentVariables=[ 'e1' , ...],
    parameters=[ 'a' , ...],
    inputs=[ 'u1' , ...],
    outputs=[ 'e1' , ...],
    variables=(table(
        (x1)=Record(MSVARIABLE, name=x1, type="differential", value=.9, unit=(NULL)),
        (a)=Record(MSVARIABLE, name=a, type="parameter", value=2, unit=(NULL)),
        ...)),
    blackboxes=[]
);
```
Equation-Based Model Simplification Methods

• Potential simplification methods to apply
  – Elimination
    • Removal of elementary equations (constants, equivalences)
    • Abstraction of common subexpressions (sum, products)
  – Generalized projection method for index reduction
  – Exact parameter reduction
  – etc. etc.

• Introduce intermediate variables and equations
  – As needed when the model can be reduced
  – Opcount is used to check how much reduced
FYI: Opcount

• Operation counts
  – Weighted counts of the number of operations
    • + 5; * 6; - 1; / 10; ^ 40; eval 50; > 5; and so on
  – Parameter symbols are replaced with values before counting
  – The cost of piecewise is the most expensive branch
Model Simplification Example

• The combustion model
  – Simulatable equations had 43 equations
    • Core: 11 DEs, 8 DVs; 32 AEs, 3 AVs; 0 IEs, 0 IVs
    • Non-core: 33 depEs, 33 depVs
    • 2093 opcounts
  – Simplified model has 28 equations
    • Core: 9 DEs, 6 DVs; 0 AEs, 3 AVs; 7 IEs, 7 IVs
    • Non-core: 12 depEs, 12 depVs
    • 1733 opcounts (17% reduction)
FYI: 9 Simplified DEs

1. \( eO(t) - mix.p(t) \left( \frac{d}{dt} mix.V(t) \right) - 4839450 no2I(t) + 4839450 no2O(t) \right) mix.Nh2(t) + \left( 16 eO(t) - 77431200 no2I(t) \\
\quad - 16 mix.p(t) \right) \left( \frac{d}{dt} mix.V(t) \right) + 77431200 no2O(t) \right) mix.No2(t) - 63 v_6(t) \left( no2I(t) - \frac{1}{9} no2O(t) \right) = 0

2. \( v_{13}(t) \left( -1 + \frac{d}{dt} mix.V(t) \right) mix.No2(t)^2 + \left( v_{14}(t) mix.Nh2(t) \left( -1 + \frac{d}{dt} mix.V(t) \right) + 625000000000000 no2I(t) \right) mix.No2(t) \\
\quad + 625000000000000 no2I(t) mix.Nh2(t) = 0

3. \( v_{12}(t) \left( \frac{d}{dt} mix.V(t) \right) + \left( v_{11}(t) - 5 \right) \left( \frac{d}{dt} mix.p(t) \right) + 2 eO(t) \right) bur.No2(t)^2 + \left( 11 mix.p(t) \left( \frac{d}{dt} mix.V(t) \right) + \left( 11 mix.V(t) - 11 \right) \left( \frac{d}{dt} mix.p(t) \right) \\
\quad + 4 eO(t) \right) bur.Nh2o(t) - 2 v_{13}(t) \left( no2I(t) - no2O(t) \right) \right) bur.No2(t) + 6 bur.Nh2o(t) \left( \frac{d}{dt} mix.p(t) \right) - bur.V(t) \left( \frac{d}{dt} mix.p(t) \right) \\
\quad + \frac{1}{3} eO(t) \right) bur.Nh2o(t) + \frac{1}{6} v_{13}(t) \right) no2O(t) = 0

4. \( v_{11}(t) \left( \frac{d}{dt} mix.p(t) \right) + v_{12}(t) \left( \frac{d}{dt} mix.V(t) \right) + 2 eO(t) - 9678900 no2I(t) + 9678900 no2O(t) = 0

5. \( v_{14}(t) \left( -1 + \frac{d}{dt} mix.V(t) \right) mix.Nh2(t)^2 + \left( v_{15}(t) \left( -1 + \frac{d}{dt} mix.V(t) \right) mix.No2(t) + 125000000000000 no2I(t) \\
\quad - 1250000000000000 no2O(t) \right) mix.Nh2(t) + 1250000000000000 mix.No2(t) \right) \left( no2I(t) - no2O(t) \right) = 0

6. \( \frac{d}{dt} bur.Nh2o(t) = 2 no2I(t) - 2 no2O(t) \\
7. \( \frac{d}{dt} mix.Nh2(t) = -2 no2I(t) + 2 no2O(t) \\
8. \( \frac{d}{dt} bur.No2(t) = no2O(t) \\
9. \( \frac{d}{dt} mix.No2(t) = -no2I(t)

(Parameter values have been assigned.)
FYI: 7 Intermediate Equations

1 = \{ \{ \text{bur}.V(t) = -\text{mix}.V(t) + 1 \}, \{ \text{bur}.V(t) \} \}
2 = \{ \{ v_6(t) = \text{mix}.p(t) \text{mix}.V(t) \}, \{ v_6(t) \} \}
3 = \{ \{ v_{11}(t) = 5 \text{mix}.V(t) \}, \{ v_{11}(t) \} \}
4 = \{ \{ v_{12}(t) = 5 \text{mix}.p(t) \}, \{ v_{12}(t) \} \}
5 = \{ \{ v_{14}(t) = 601365581 \text{mix}.p(t) \}, \{ v_{14}(t) \} \}
6 = \{ \{ v_{15}(t) = 9621849296 \text{mix}.p(t) \}, \{ v_{15}(t) \} \}
7 = \{ \{ v_{13}(t) = \text{mix}.p(t) \text{bur}.V(t) \}, \{ v_{13}(t) \} \}

(Parameter values have been assigned.)
Equation-Based
Model Data Structure

MSModel & Modelica-export
Modelica-Export from MSModel

• A feature implemented in Maplesoft-Toyota MSModel realization
• Modelica is viewed as a “hub” for global plant modelling R&D effort
• But, MSModel is not limited to Modelica
Modelica-Exported Combustion Model

equation

\[
\begin{align*}
(v_{12} \cdot \text{der}(\text{mix}_V) + (v_{11} - 5) \cdot \text{der}(\text{mix}_p) + 2 \cdot eO) \cdot \text{bur}_\text{No2}^2 &\quad + ((11 \cdot \text{mix}_p \cdot \text{der}(\text{mix}_V) + (11 \cdot \text{mix}_V - 11) \cdot \text{der}(\text{mix}_p) + 4 \cdot eO) \cdot \text{bur}_\text{Nh2o} - 2 \cdot v_{13} \cdot (\text{no2I} - \text{no2O})) \cdot \text{bur}_\text{No2} + 6 \cdot \text{bur}_\text{Nh2o} \cdot ((\text{mix}_p \cdot \text{der}(\text{mix}_V) - \text{bur}_V \cdot \text{der}(\text{mix}_p) + 1/3 \cdot eO) \cdot \text{bur}_\text{Nh2o} + 1/6 \cdot v_{13} \cdot \text{no2O}) = 0; \\
(eO - \text{mix}_p \cdot \text{der}(\text{mix}_V) - 4839450 \cdot \text{no2I} + 4839450 \cdot \text{no2O}) \cdot \text{mix}_\text{Nh2} + (16 \cdot eO - 77431200 \cdot \text{no2I} - 16 \cdot \text{mix}_p \cdot \text{der}(\text{mix}_V) + 77431200 \cdot \text{no2O}) \cdot \text{mix}_\text{No2} - 63 \cdot v_6 \cdot (\text{no2I} - 1/9 \cdot \text{no2O}) = 0; \\
v_{14} \cdot (-1 + \text{der}(\text{mix}_V)) \cdot \text{mix}_\text{Nh2}^2 &\quad + (v_{15} \cdot (-1 + \text{der}(\text{mix}_V)) \cdot \text{mix}_\text{No2} + 12500000000000000 \cdot \text{no2I} - 12500000000000000 \cdot \text{no2O}) \cdot \text{mix}_\text{Nh2} + 12500000000000000 \cdot \text{no2I} \cdot \text{mix}_\text{No2} + (no2I - no2O) = 0; \\
v_{15} \cdot (-1 + \text{der}(\text{mix}_V)) \cdot \text{mix}_\text{No2}^2 &\quad + (v_{14} \cdot \text{mix}_\text{Nh2} \cdot (-1 + \text{der}(\text{mix}_V)) + 6250000000000000 \cdot \text{no2I}) \cdot \text{mix}_\text{No2} + 6250000000000000 \cdot \text{no2I} \cdot \text{mix}_\text{Nh2} = 0; \\
v_{11} \cdot \text{der}(\text{mix}_p) + v_{12} \cdot \text{der}(\text{mix}_V) + 2 \cdot eO - 9678900 \cdot \text{no2I} + 9678900 \cdot \text{no2O} = 0; \\
\text{der}(\text{bur}_\text{Nh2o}) &\quad = 2 \cdot \text{no2I} - 2 \cdot \text{no2O}; \\
\text{der}(\text{mix}_\text{Nh2}) &\quad = -2 \cdot \text{no2I} + 2 \cdot \text{no2O}; \\
\text{der}(\text{bur}_\text{No2}) &\quad = \text{no2O}; \\
\text{der}(\text{mix}_\text{No2}) &\quad = -\text{no2I}; \\
\text{bur}_V &\quad = -\text{mix}_V + 1; \\
v_6 &\quad = \text{mix}_p \cdot \text{mix}_V; \\
v_{11} &\quad = 5 \cdot \text{mix}_V; \\
v_{12} &\quad = 5 \cdot \text{mix}_p; \\
v_{13} &\quad = \text{mix}_p \cdot \text{bur}_V; \\
v_{14} &\quad = 601365581 \cdot \text{mix}_p; \\
v_{15} &\quad = 9621849296 \cdot \text{mix}_p;
\end{align*}
\]
Simulation Result 1/2

- The exported combustion model
- Produced in OpenModelica-1.7.0
Simulation Result 2/2

- Produced in MapleSim-4.5

Volume of unbunred gas

Pressure of unbunred gas

Volume of bunred gas

Pressure of bunred gas
Future Topic for MSModel

• Connectivity management for components
  – Open issue for MSModel
  – Need a design to cover HLMD, Modelica and Simscape at least
    • Modelica – Connector
    • Simscape – Domain
Modelica & HLM/MSModel
Modelica & HLM Framework 1/2

• HLMD & HLMT
  – Framework to create physical components
    • The whole purpose of HLMD/HLMT
    • Other features are out of scope (by design)

• Modelica & Modelica-based Tools
  – Modelling and simulation platform for the DAE system
    • Much more feature rich than the HLM framework
  – Inside of a Modelica component does not necessarily have to follow physical principles
Modelica & HLM Framework 2/2

- HLM framework can complement Modelica (and Simscape) for component creation
  - MSModel plays a key role to bridge HLMD and Modelica
  - Toyota is considering Simscape in addition to Modelica
Functional Mock-up Interface & MSModel

• Primary purpose of MSModel:
  – Equation-based model simplification
    • No support for many Modelica features

• Primary purpose of FMI:
  – Integrated simulation of Modelica-based components
Conclusion
Conclusion 1/2

• Introduced in this presentation
  – HLM framework
    • Physical component modelling method
    • Can complement Modelica, Simscape
  – MSModel
    • Data structure for model simplification
    • Key to bridge HLM and Modelica
    • Specification has been published

• Key technology
  – Symbolic manipulation
    • For model simplification
    • Hope to have more research in an open environment
Conclusion 2/2

• Future topics
  – HLM framework
    • Proof of single solution existance
    • Physical knowledge base repository
  – MSModel
    • Connectivity management
Thank you.