Probabilistic Safety Assessment and Management (PSAM)
June 26th - July 1st, 2022
Sheraton Waikiki
Honolulu, O'ahu Hawaii USA

Integrated dynamic probabilistic safety assessments with PyCATSHOO: a new coupling approach

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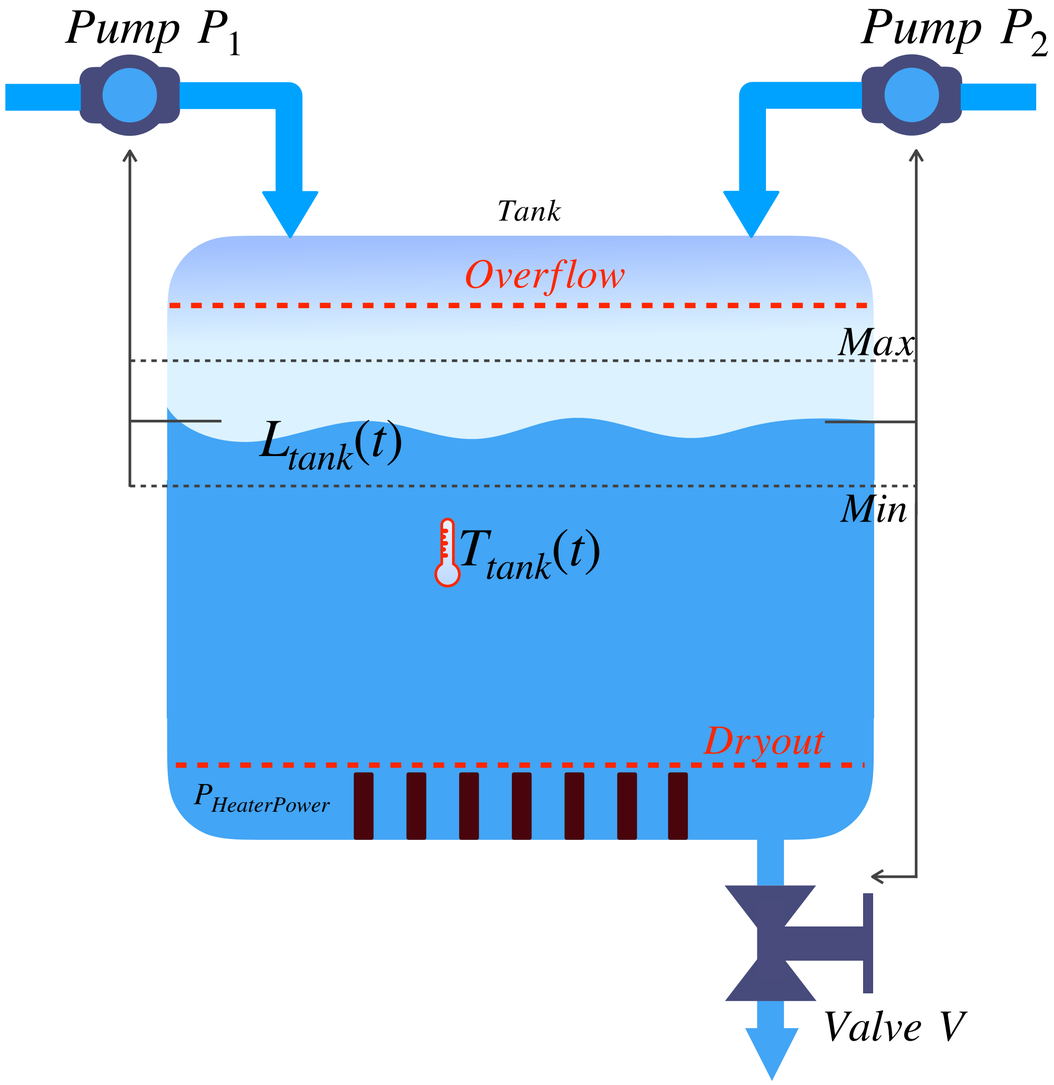
SUMMARY

1. How to model with PyCATSHOO
2. The FMI standard
3. PyCATSHOO and external models

1 HOW TO MODEL WITH PyCATSHOO

HEATED TANK AND PYCATSHOO MODELING APPROACH



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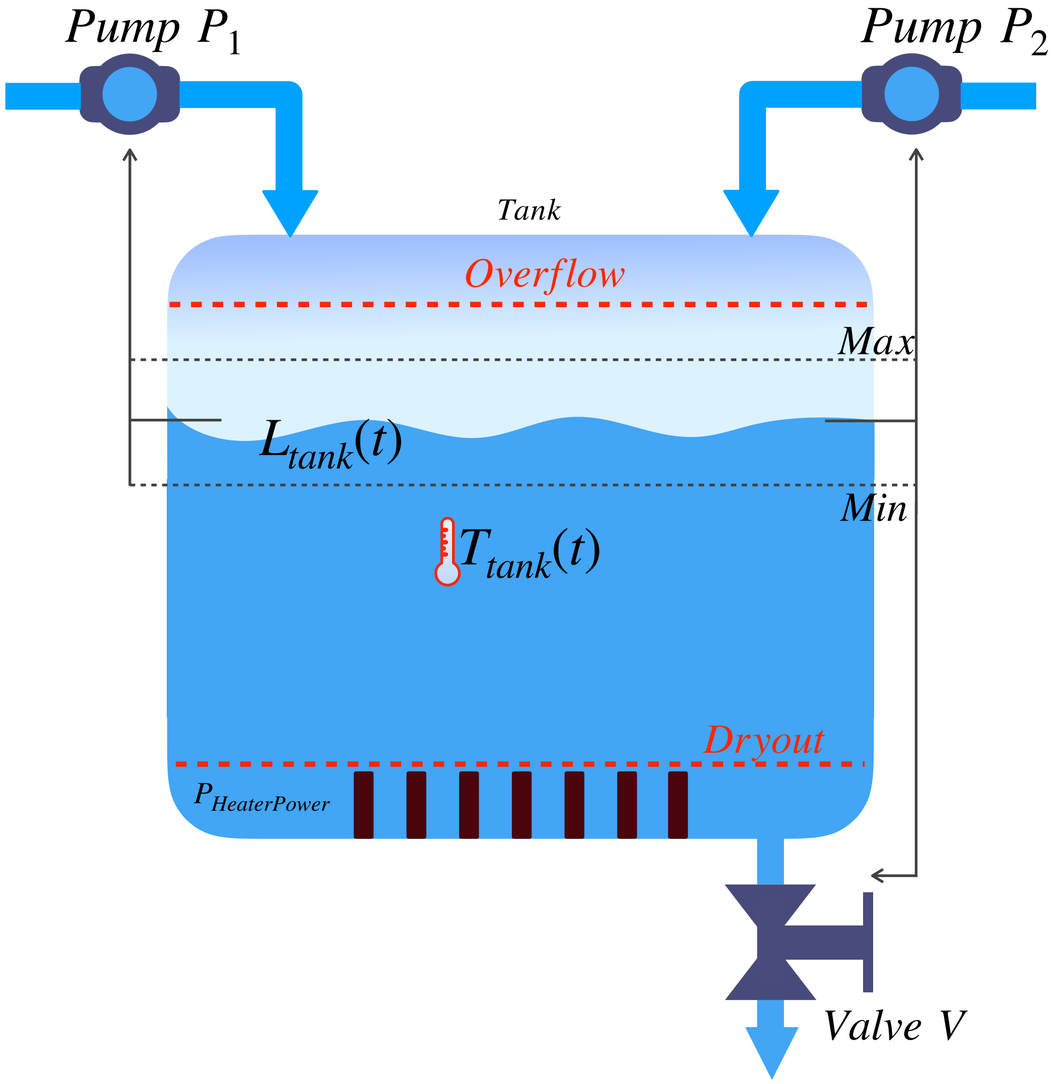

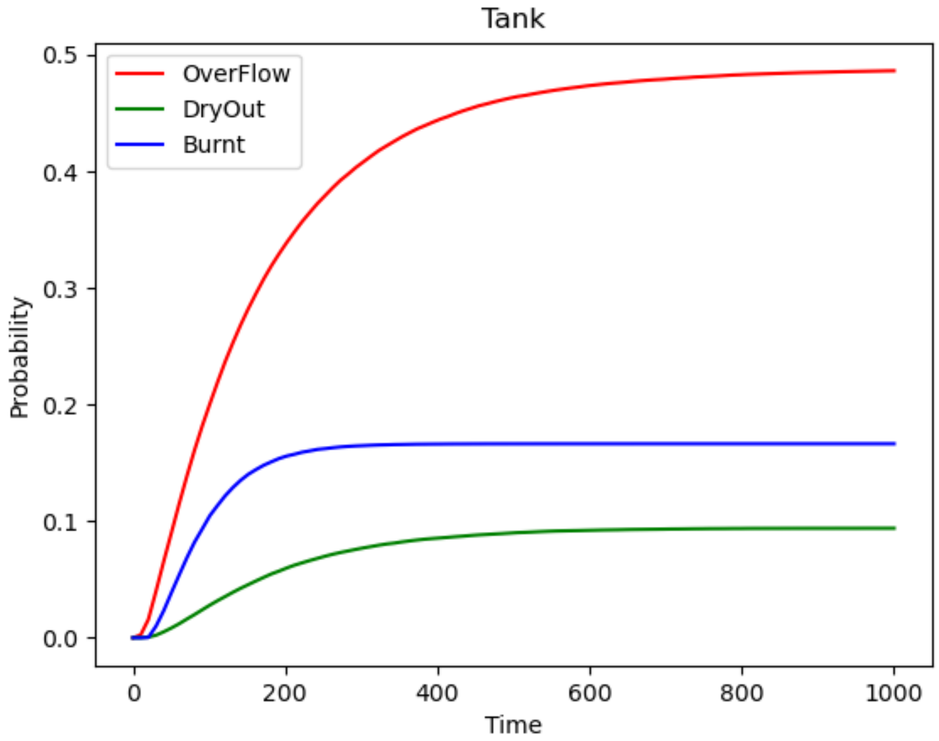

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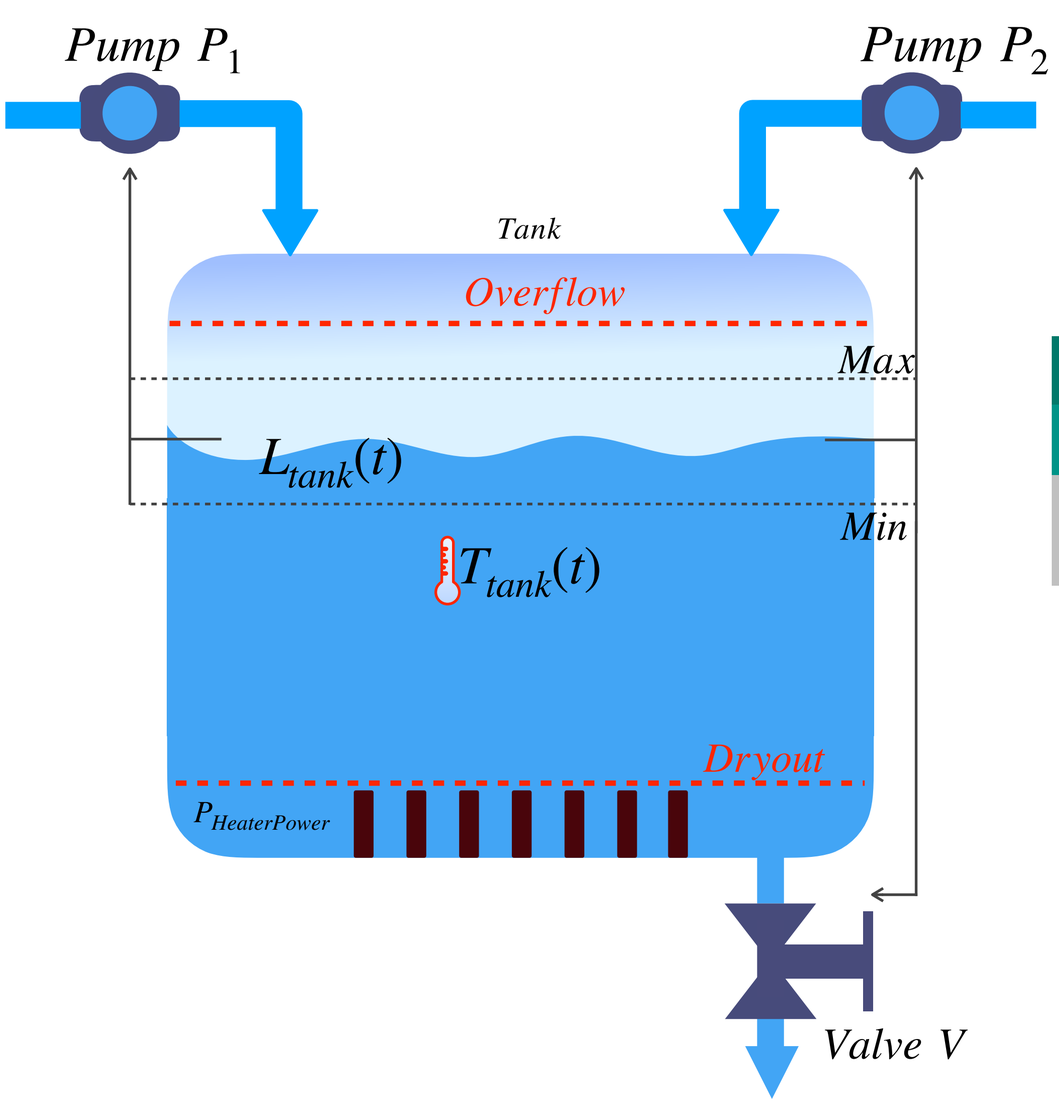

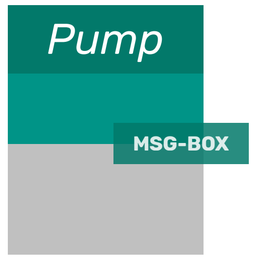

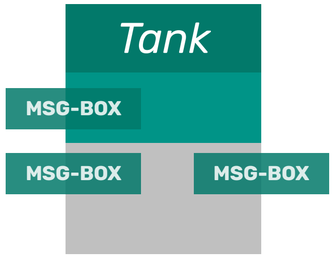

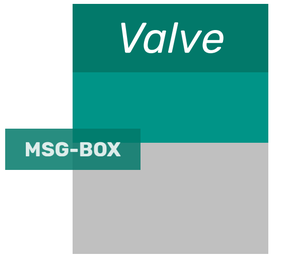

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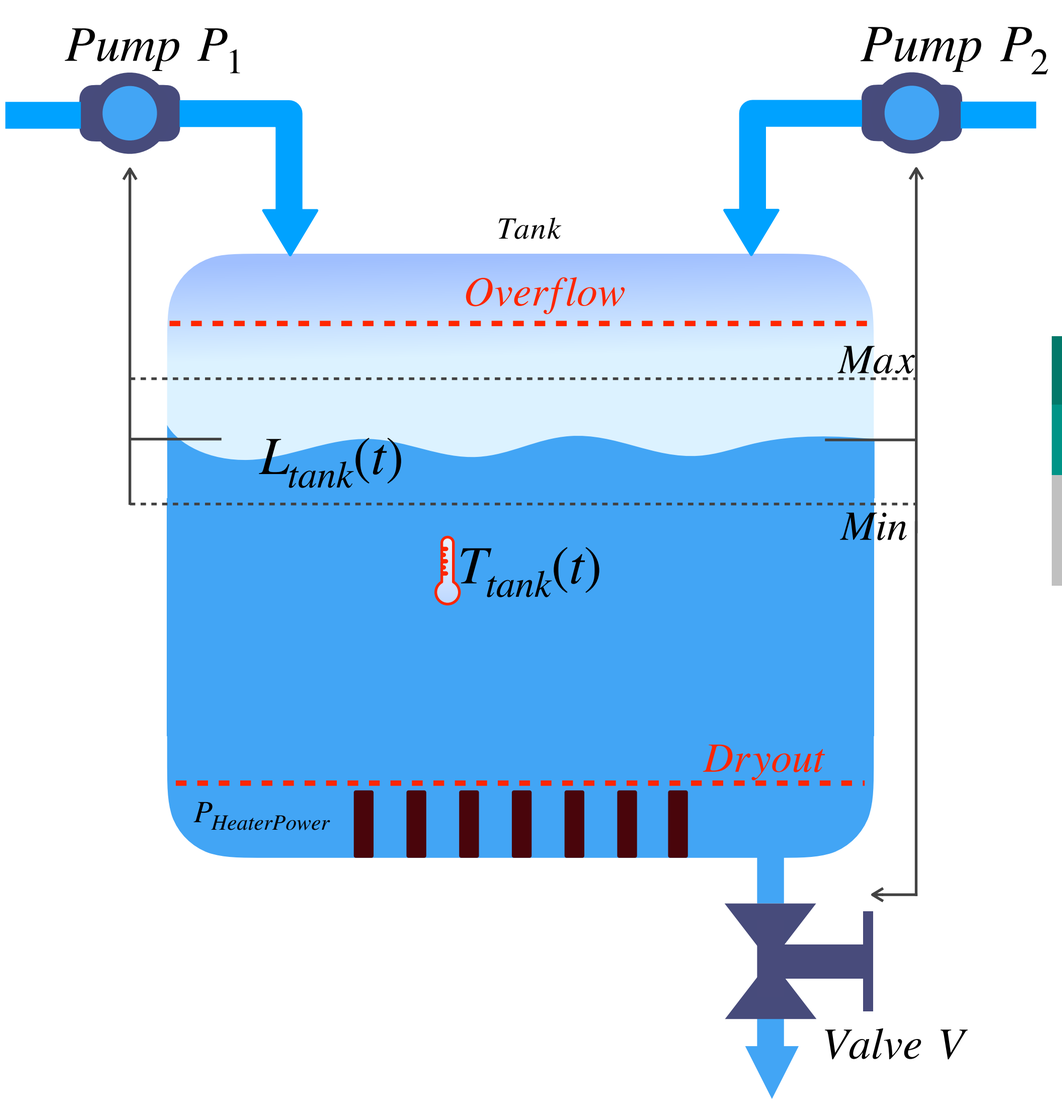

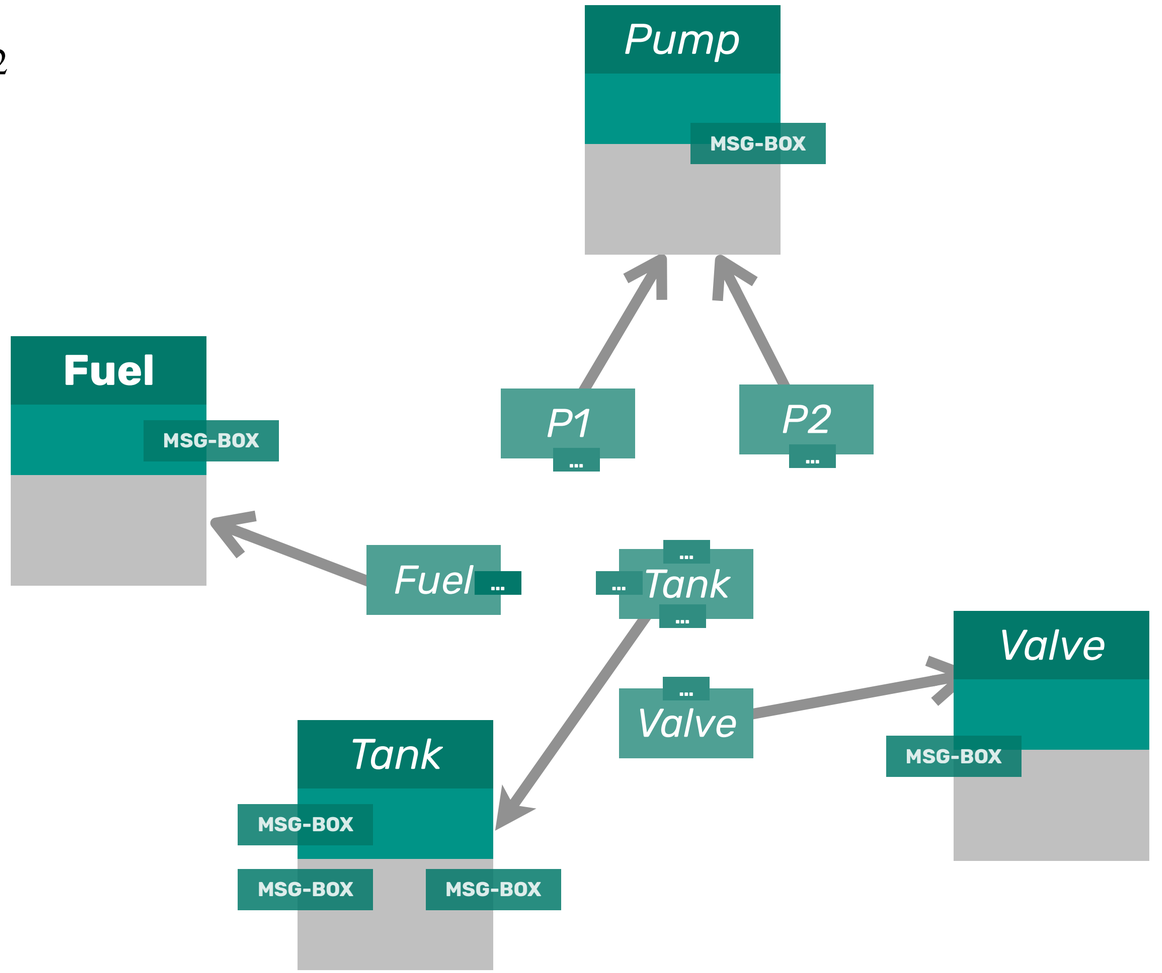

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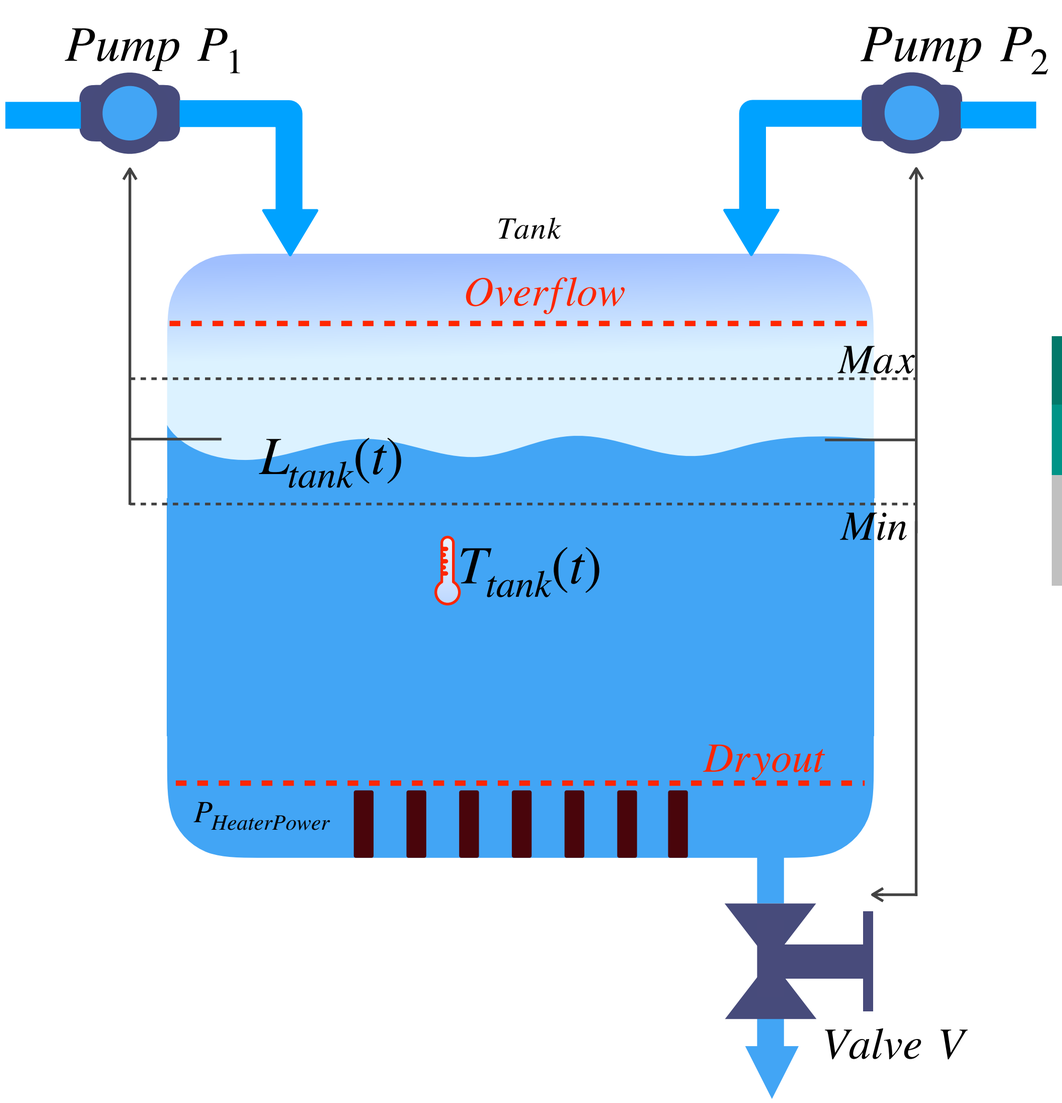

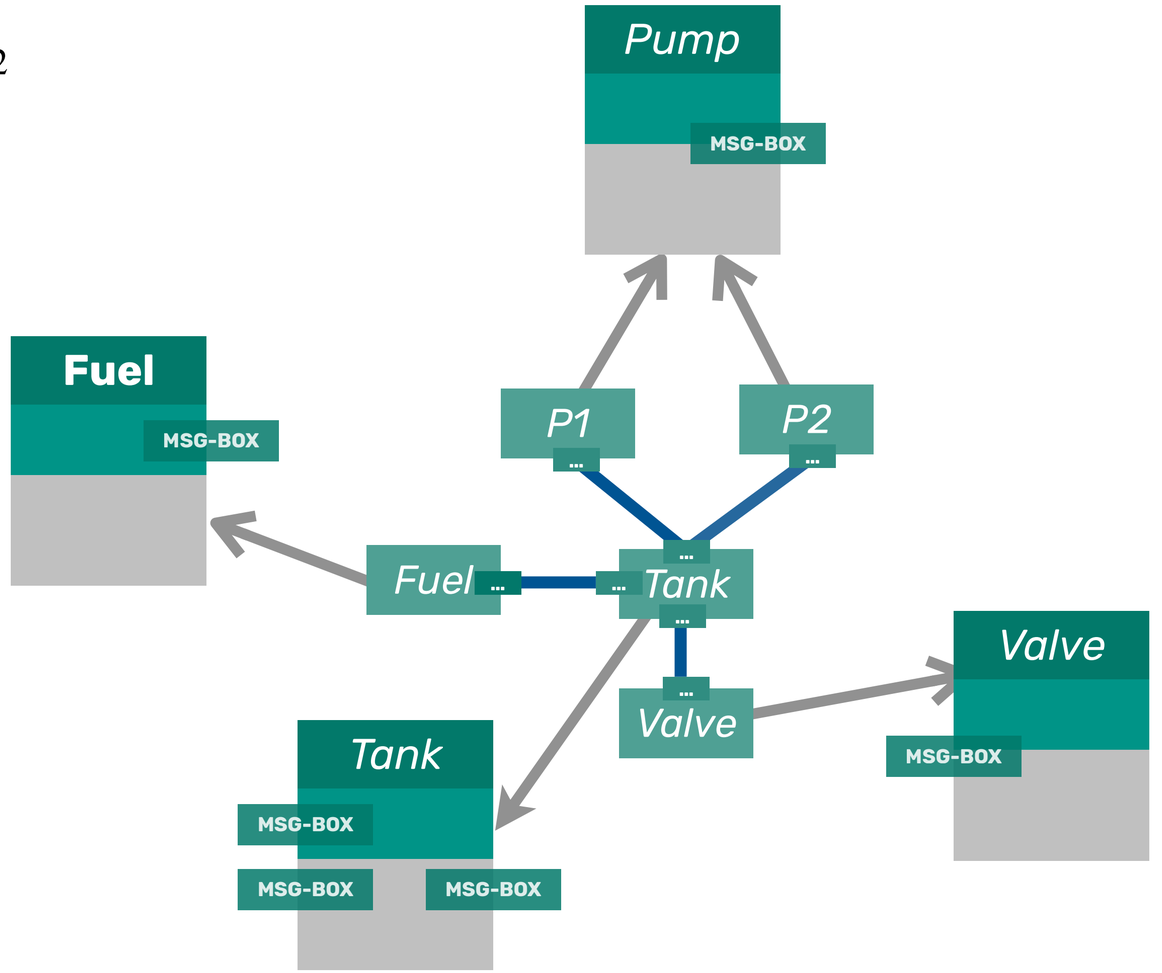

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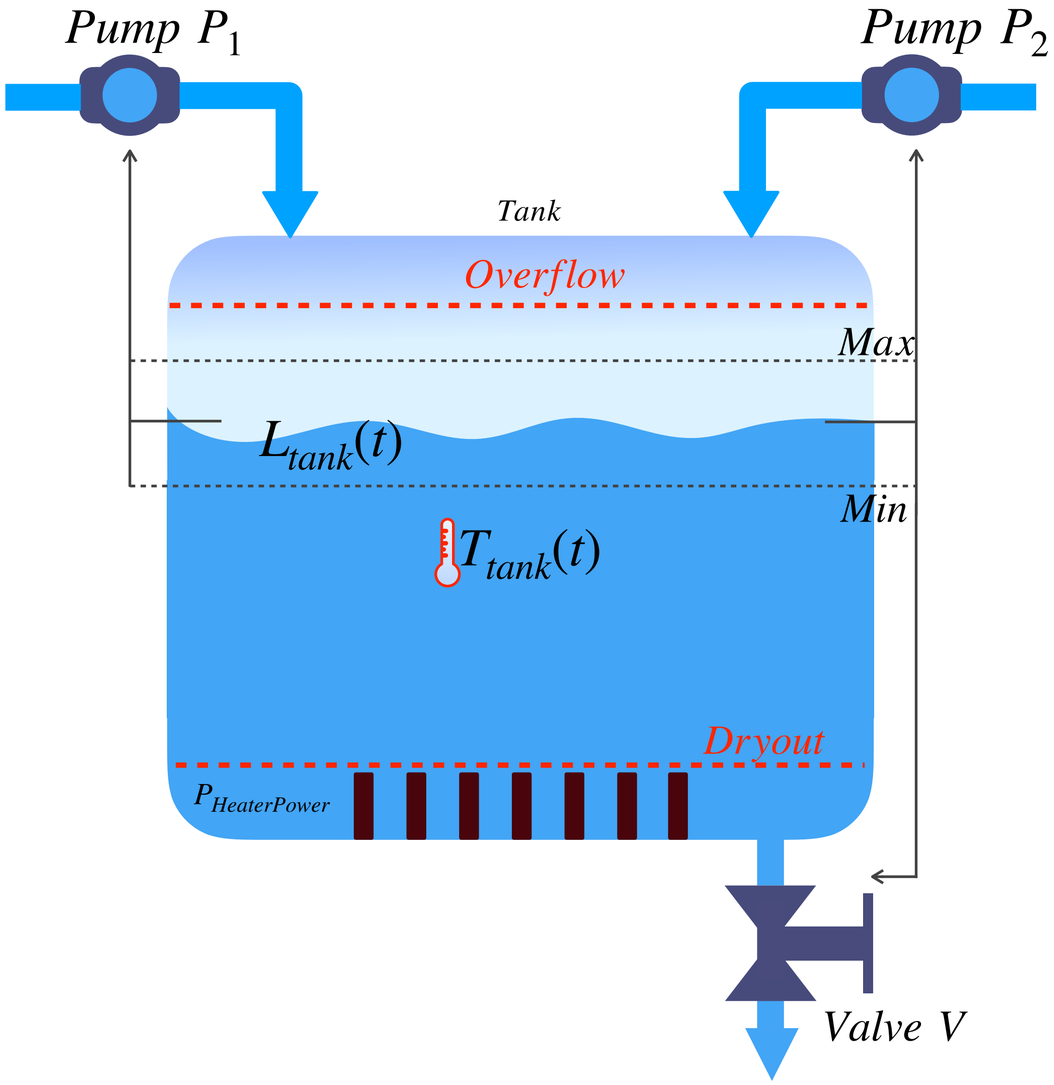
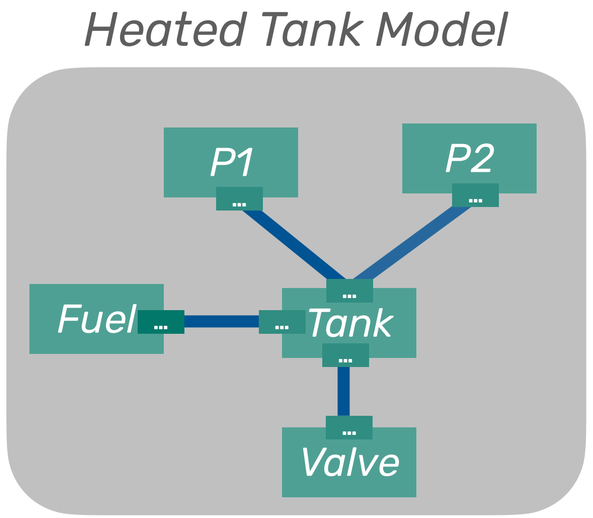


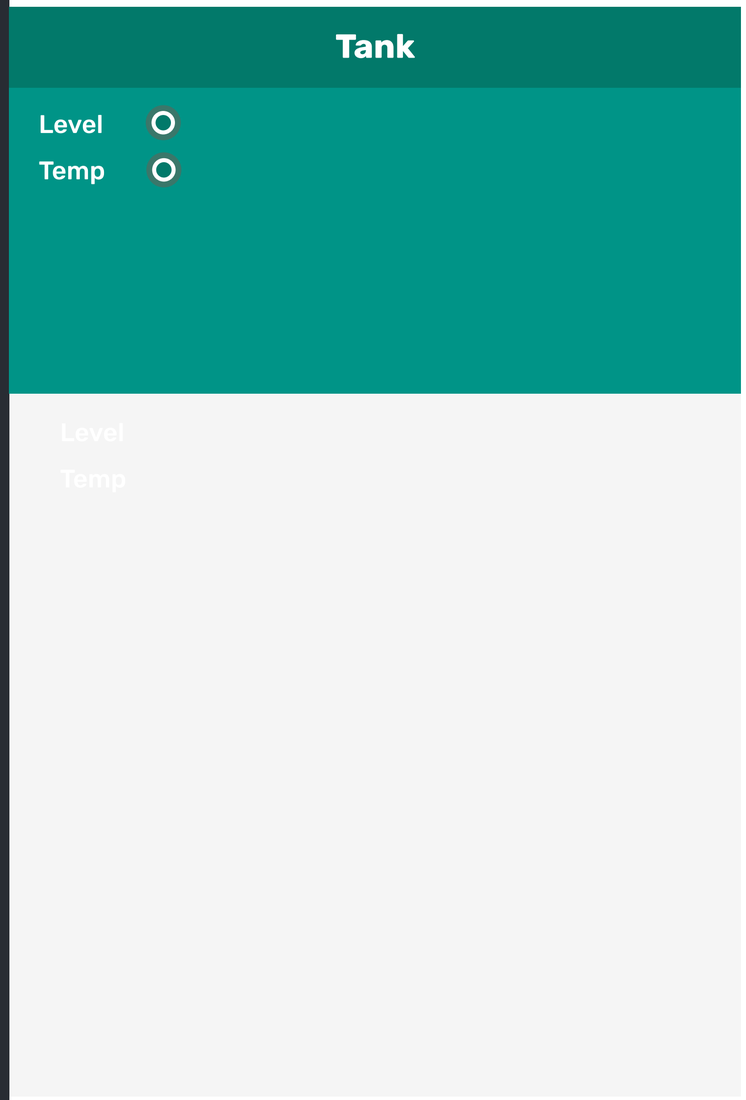


```python
class Tank(Pyc.CComponent):
    def __init__(self, name):
        Pyc.CComponent.__init__(self, name)
```

Tank

```
class Tank(Pyc.CComponent):
    def __init__(self, name):
        Pyc.CComponent.__init__(self, name)

        ……
        self.v_level           = self.addVariable("level", Pyc.TVarType.t_double, 7.)
        self.v_temperature     = self.addVariable("temp" , Pyc.TVarType.t_double, 31.)
```



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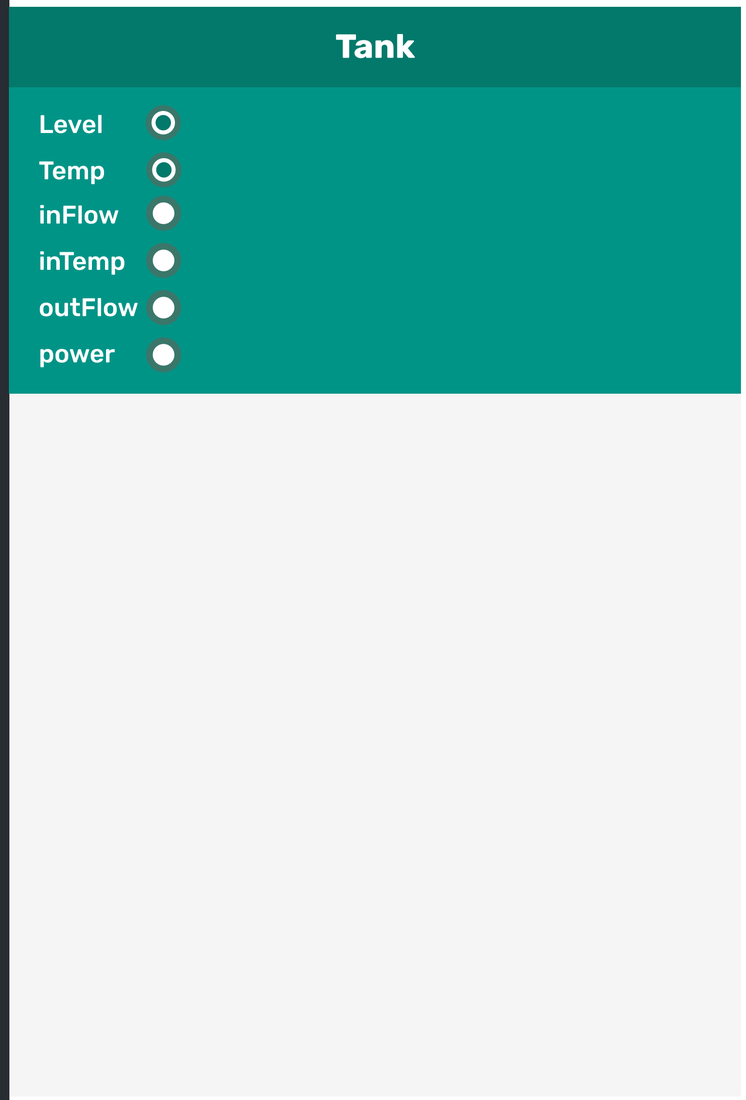
        self.v_temperature    = self.addVariable("temp" , Pyc.TVarType.t_double, 31.)
        ……
        self.r_inFlow         = self.addReference("inFlow")
        self.r_temperature    = self.addReference("inTemp")
        self.r_outFlow        = self.addReference("outFlow")
        self.r_power          = self.addReference("power")
```



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        self.r_inFlow         = self.addReference("inFlow")
        self.r_temperature    = self.addReference("inTemp")
        self.r_outFlow        = self.addReference("outFlow")
        self.r_power          = self.addReference("power")
        ……
        self.addMessageBox("Pump")
        self.addMessageBoxExport("Pump", self.v_level      , "level_outChannel")
        self.addMessageBoxExport("Pump", self.v_temperature, "temp_outChannel")
        self.addMessageBoxImport("Pump", self.r_inFlow     , "inFlow_inChannel")
        self.addMessageBoxImport("Pump", self.r_temperature, "inTemp_inChannel")
```

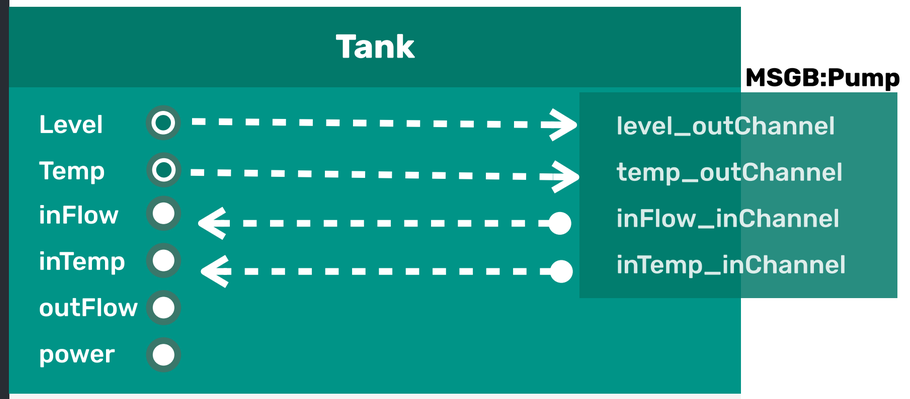

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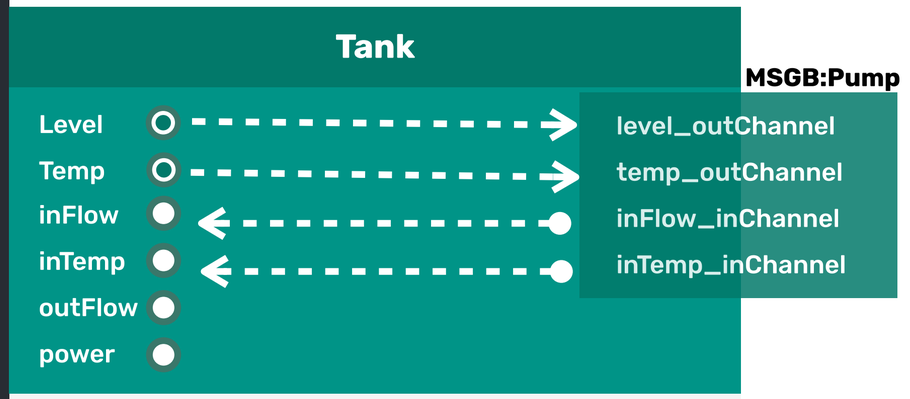
        self.r_temperature    = self.addReference("inTemp")
        self.r_outFlow        = self.addReference("outFlow")
        self.r_power          = self.addReference("power")
        ……
        self.addMessageBox("Pump")
        self.addMessageBoxExport("Pump", self.v_level      , "level_outChannel")
        self.addMessageBoxExport("Pump", self.v_temperature, "temp_outChannel")
        self.addMessageBoxImport("Pump", self.r_inFlow     , "inFlow_inChannel")
        self.addMessageBoxImport("Pump", self.r_temperature, "inTemp_inChannel")
        ……
        pdmp = self.addPDMPManager ("pdmpManager")
        self.addPDMPODEVariable     ("pdmpManager", self.v_level)
        self.addPDMPODEVariable     ("pdmpManager", self.v_temperature)
        self.addPDMPEquationMethod ("pdmpManager", "odeMethod", self.odeMethod)
```



PDMP: pdmpManage

$$\frac{dLevel}{dt} = \frac{\sum_i inFlow[i] - \sum_i outFlow[i]}{area}$$

$$\frac{dTemp}{dt} = \frac{\sum_i inFlow[i] \,.\, (intTemp[i] - Temp)}{Level \,.\, area}$$

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class Tank(Pyc.CComponent):
    def __init__(self, name):
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        ……
        self.v_level          = self.addVariable("level", Pyc.TVarType.t_double, 7.)
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        ……
        self.addMessageBox("Pump")
        self.addMessageBoxExport("Pump", self.v_level      , "level_outChannel")
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        self.addMessageBoxImport("Pump", self.r_inFlow     , "inFlow_inChannel")
        self.addMessageBoxImport("Pump", self.r_temperature, "inTemp_inChannel")
        ……
        pdmp = self.addPDMPManager ("pdmpManager")
        self.addPDMPODEVariable     ("pdmpManager", self.v_level)
        self.addPDMPODEVariable     ("pdmpManager", self.v_temperature)
        self.addPDMPEquationMethod ("pdmpManager", "odeMethod", self.odeMethod)
        ……
    def odeMethod(self):
        iFlow    = self.r_inFlow.sumValue()
        oFlow    = self.r_outFlow.sumValue()
        self.v_level.setDvdtODE((iFlow - oFlow) / self.v_area.dValue())

        sumiFiT = 0
        for i in range(self.r_inFlow.nbCnx()):
            sumiFiT = sumiFiT + self.r_inFlow.dValue(i) * \
                      (self.r_temperature.dValue(i) - self.v_temperature.value())

        self.v_temperature.setDvdtODE(
              (sumiFiT + self.r_power.dValue(0)) / \
              (self.v_level.dValue()* self.v_area.dValue())
                                      )
```

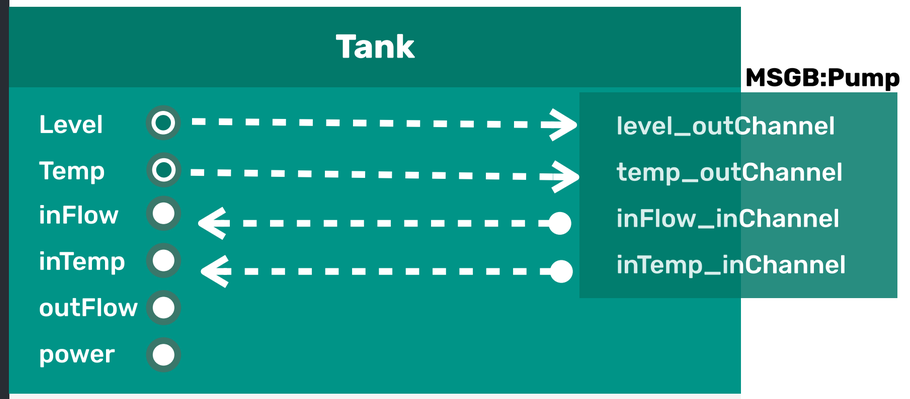

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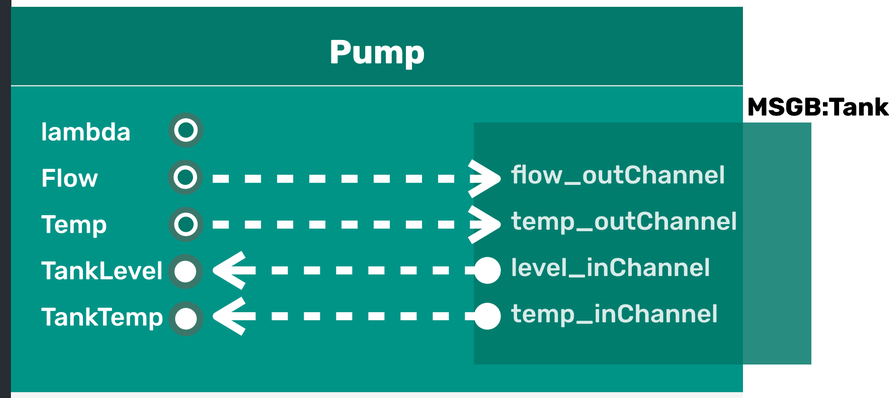
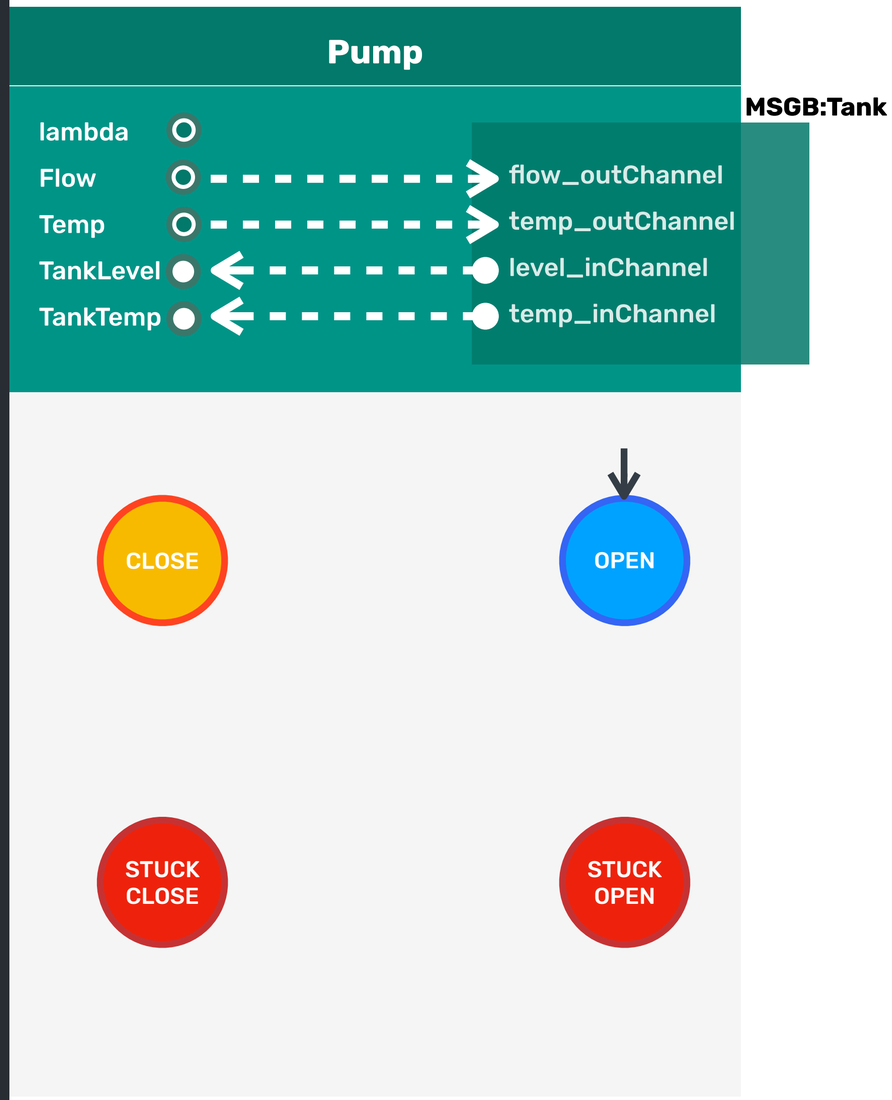


```
class Pump(Pyc.CComponent):
    def __init__(self, name):
        Pyc.CComponent.__init__(self, name)
        ……
        self.automaton       = self.addAutomaton("FuncAutomation")
        self.openState       = self.addState("FuncAutomation", "OPEN"  , 0)
        self.closeState      = self.addState("FuncAutomation", "CLOSE", 1)
        self.stuckOpenState  = self.addState("FuncAutomation", "STUCKOPEN"  , 2)
        self.stuckCloseState = self.addState("FuncAutomation", "STUCKCLOSE", 3)
        self.automaton.setInitState(self.openState)
        self.automaton.addSensitiveMethod("updateFlow", self.updateFlow)
```

```
        ……
    def updateFlow(self):
        if self.openState.isActive() or self.stuckOpenState.isActive()
            self.v_flow.setValue(self.v_nominalFlow.dValue())
        else
            self.v_flow.setValue(0)
```



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        self.stuckOpenState  = self.addState("FuncAutomation", "STUCKOPEN" , 2)
        self.stuckCloseState = self.addState("FuncAutomation", "STUCKCLOSE", 3)
        self.automaton.setInitState(self.openState)
        self.automaton.addSensitiveMethod("updateFlow", self.updateFlow)

        ......
        transO2C = self.openState.addTransition("OPEN_to_CLOSE")
        transO2C.setCondition(lambda : self.r_tankLevel.dValue(0) > \
                                                    self.v_levelMax.dValue())
        transO2C.addTarget(self.closeState, Pyc.TTransType.trans)
```

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    ......
    def updateFlow(self):
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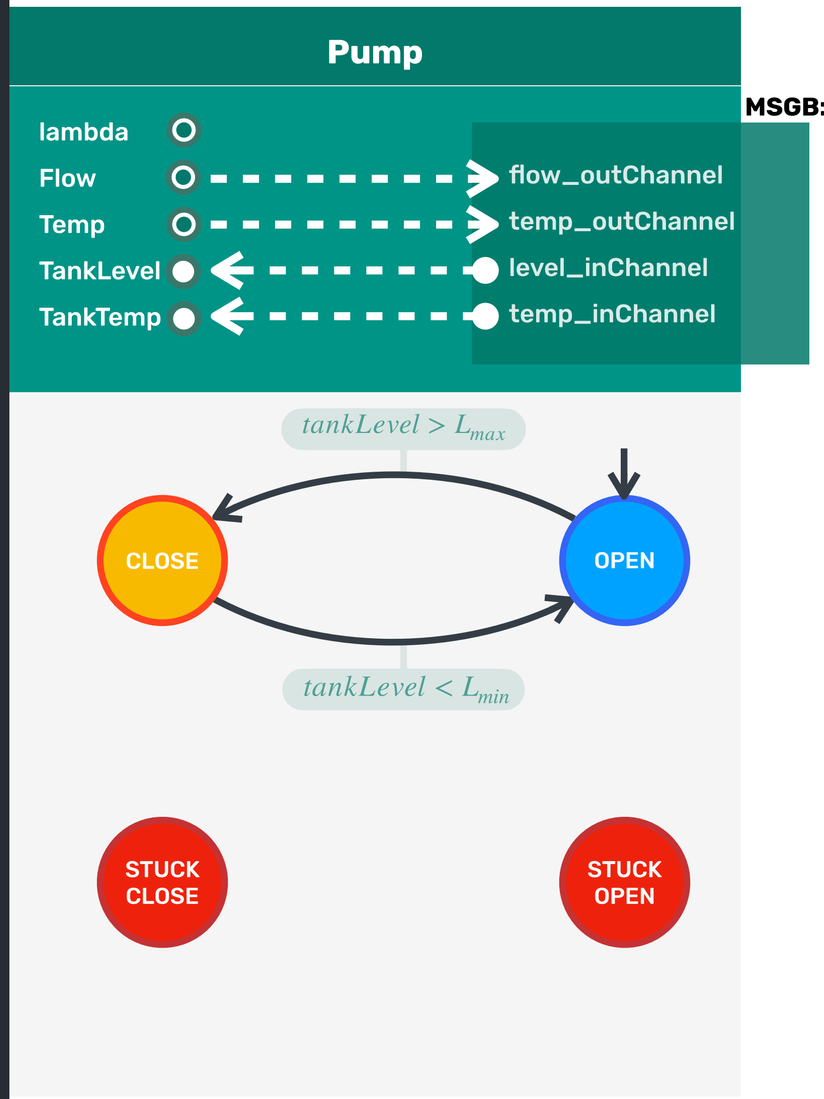

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        self.stuckOpenState  = self.addState("FuncAutomation", "STUCKOPEN" , 2)
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                                       self.v_levelMax.dValue())
        transO2C.addTarget(self.closeState, Pyc.TTransType.trans)

        ……
        trans = self.openState.addTransition("OPEN_to_STUCKOPEN")
        trans.setDistLaw(Pyc.TLawType.expo, self.v_lambda)
        trans.addTarget(self.stuckOpenState, Pyc.TTransType.fault)
        trans.setModifiable(Pyc.TModificationMode.continuous_modification)
```

```python
    ……
def updateFlow(self):
    if self.openState.isActive() or self.stuckOpenState.isActive()
        self.v_flow.setValue(self.v_nominalFlow.dValue())
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        self.v_flow.setValue(0)
```

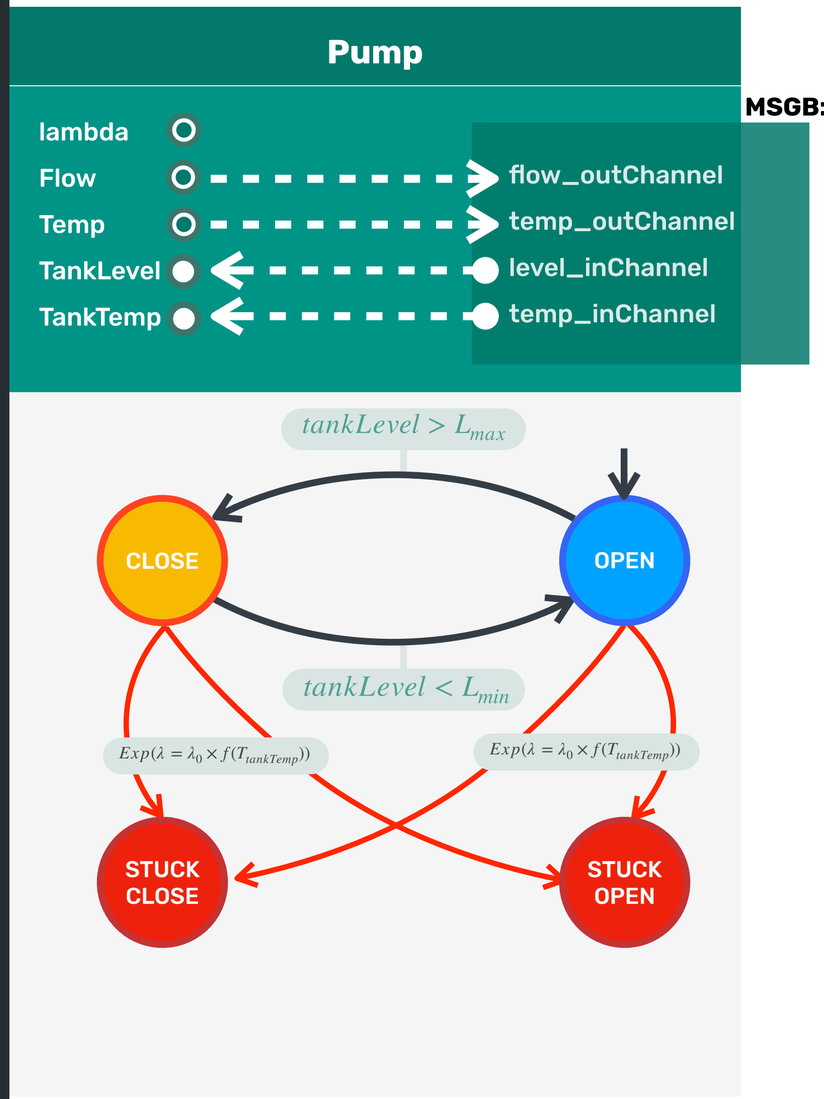

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        trans = self.openState.addTransition("OPEN_to_STUCKOPEN")
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        trans.addTarget(self.stuckOpenState, Pyc.TTransType.fault)
        trans.setModifiable(Pyc.TModificationMode.continuous_modification)

        ……
        pdmp = self.addPDMPManager  (“pdmpManager")
        self.addPDMPExplicitVariable("pdmpManager", self.v_lambda)
        self.addPDMPEquationMethod  ("pdmpManager", "equationMethod",
                                                    self.equationMethod)
```

```
    ……
def updateFlow(self):
    if self.openState.isActive() or self.stuckOpenState.isActive()
        self.v_flow.setValue(self.v_nominalFlow.dValue())
    else
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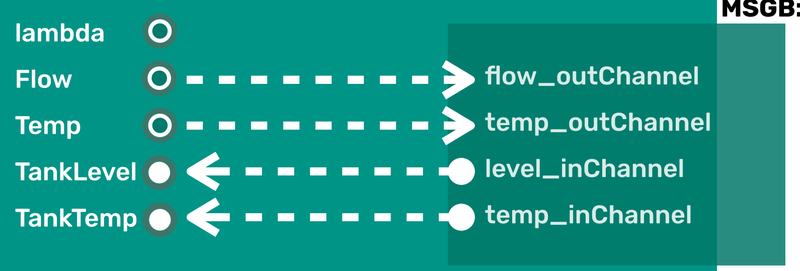
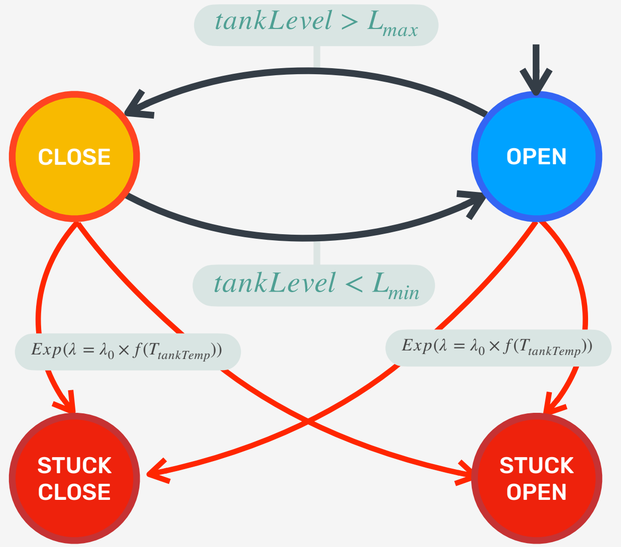
Pump

MSGB:Tank





PDMP : pdmpManage

$$\lambda = \lambda_0 \times (b_1 \times e^{b_c \times (T_{tank} - 20)} + b_2 \times e^{-b_d \times (T_{tank} - 20)})$$

```
class Pump(Pyc.CComponent):
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        self.stuckOpenState  = self.addState("FuncAutomation", "STUCKOPEN" , 2)
        self.stuckCloseState = self.addState("FuncAutomation", "STUCKCLOSE", 3)
        self.automaton.setInitState(self.openState)
        self.automaton.addSensitiveMethod("updateFlow", self.updateFlow)

        ……
        transO2C = self.openState.addTransition("OPEN_to_CLOSE")
        transO2C.setCondition(lambda : self.r_tankLevel.dValue(0) > self.v_levelMax.dValue())
        transO2C.addTarget(self.closeState, Pyc.TTransType.trans)

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        self.addPDMPExplicitVariable("pdmpManager", self.v_lambda)
        self.addPDMPEquationMethod  ("pdmpManager", "equationMethod",
                                                    self.equationMethod)

        pdmp.addWatchedTransition   (transO2C)
```

```
    ……
def updateFlow(self):
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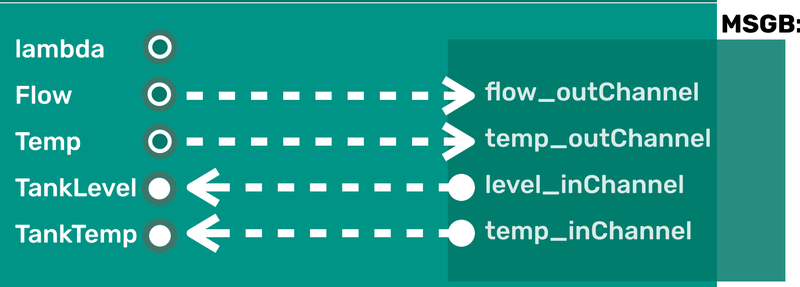
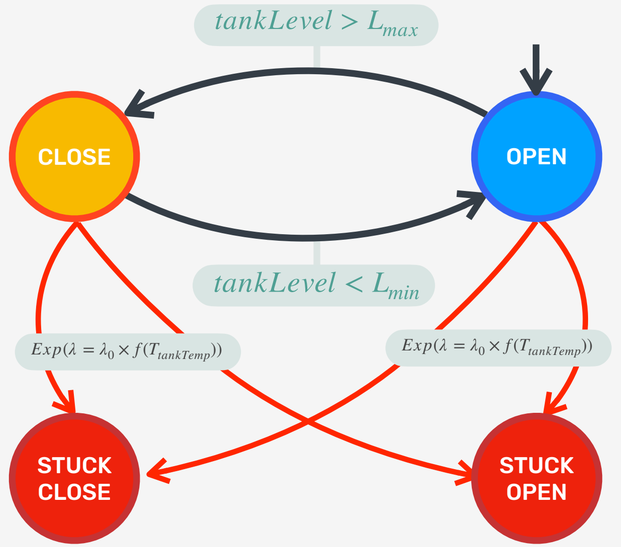
Pump

MSGB:Tank





PDMP : pdmpManage

$$\lambda = \lambda_0 \times (b_1 \times e^{b_c \times (T_{tank} - 20)} + b_2 \times e^{-b_d \times (T_{tank} - 20)})$$

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        self.automaton.addSensitiveMethod("updateFlow", self.updateFlow)

        ……
        transO2C = self.openState.addTransition("OPEN_to_CLOSE")
        transO2C.setCondition(lambda : self.r_tankLevel.dValue(0) > self.v_levelMax.dValue())
        transO2C.addTarget(self.closeState, Pyc.TTransType.trans)

        ……
        trans = self.openState.addTransition("OPEN_to_STUCKOPEN")
        trans.setDistLaw(Pyc.TLawType.expo, self.v_lambda)
        trans.addTarget(self.stuckOpenState, Pyc.TTransType.fault)
        trans.setModifiable(Pyc.TModificationMode.continuous_modification)

        ……
        pdmp = self.addPDMPManager  (“pdmpManager")
        self.addPDMPExplicitVariable("pdmpManager", self.v_lambda)
        self.addPDMPEquationMethod  ("pdmpManager", "equationMethod",
                                                    self.equationMethod)
        pdmp.addWatchedTransition   (transO2C)

        ……
    def equationMethod(self):
        b1 = 3.0295, b2 = 0.7578, bc = 0.05756, bd = 0.2301
       self.v_lambda.setDValue(self.v_lambda0.value()*\
          (b1 * np.exp(+ bc * (self.r_tankTemperature.value(0) - 20)) +
           b2 * np.exp(- bd * (self.r_tankTemperature.value(0) - 20))  ) / (b1 + b2)
        ……
    def updateFlow(self):
        if self.openState.isActive() or self.stuckOpenState.isActive()
            self.v_flow.setValue(self.v_nominalFlow.dValue())
        else
            self.v_flow.setValue(0)
```
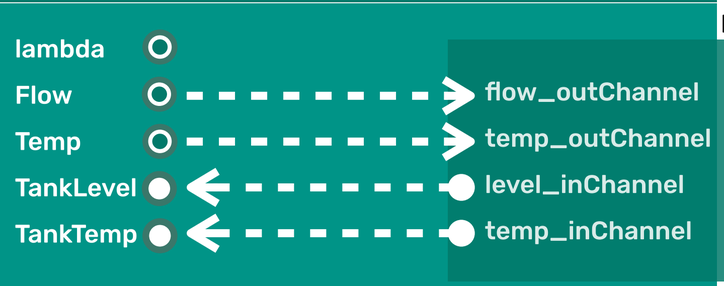
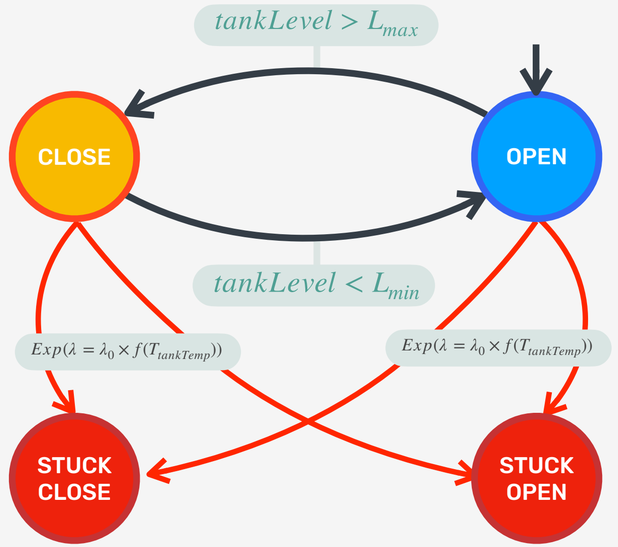

Pump

MSGB:Tank





PDMP : pdmpManage

$$\lambda = \lambda_0 \times (b_1 \times e^{b_c \times (T_{tank} - 20)} + b_2 \times e^{-b_d \times (T_{tank} - 20)})$$

2 THE FMI STANDARD

FMI OVERVIEW

- **Origin**

  MODELISAR (2008-2011) an ITEA2 project →FMI

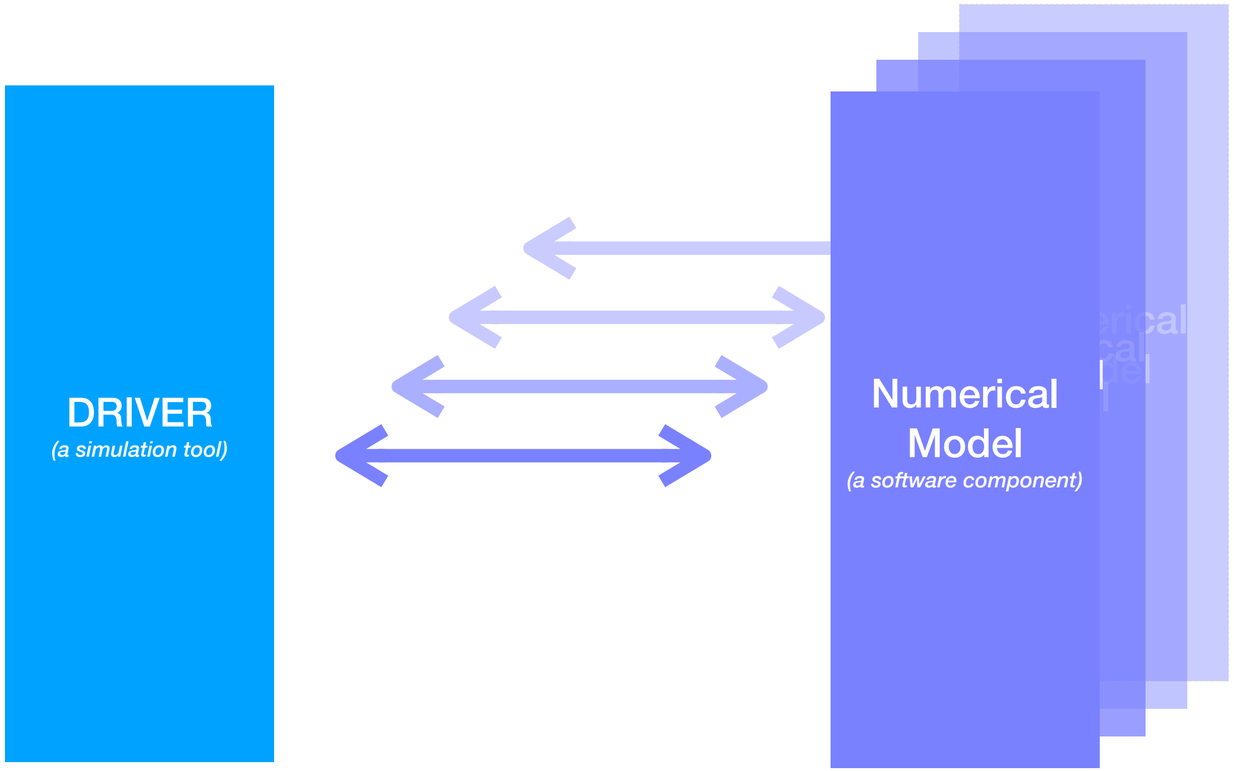
- **Motivation**

  The Problem of Interoperability between software components from different suppliers and different simulation stools

- **Current status**

  FMI is a permanent project of Modelica association

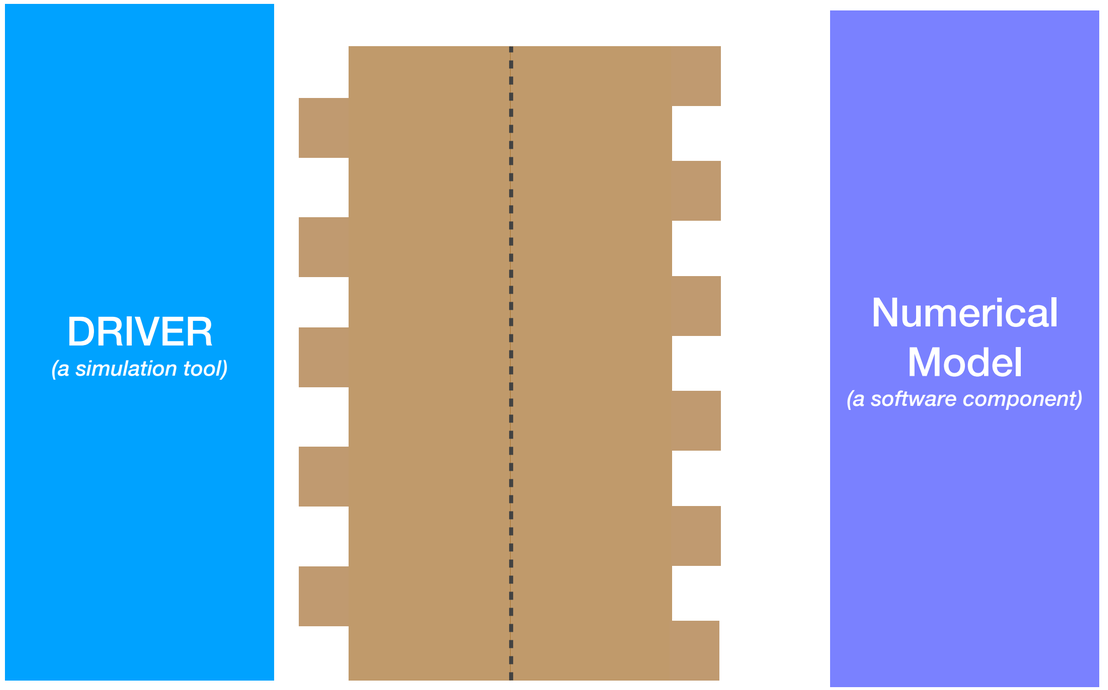
COUPLING IN HYBRID DYNAMIC PROBABILISTIC ASSESSMENT



Model of
Discrete/Stochastic Behavior

Model of
Continuous/Deterministic Physics

FMI CO-SIMULATION COUPLING APPROACH



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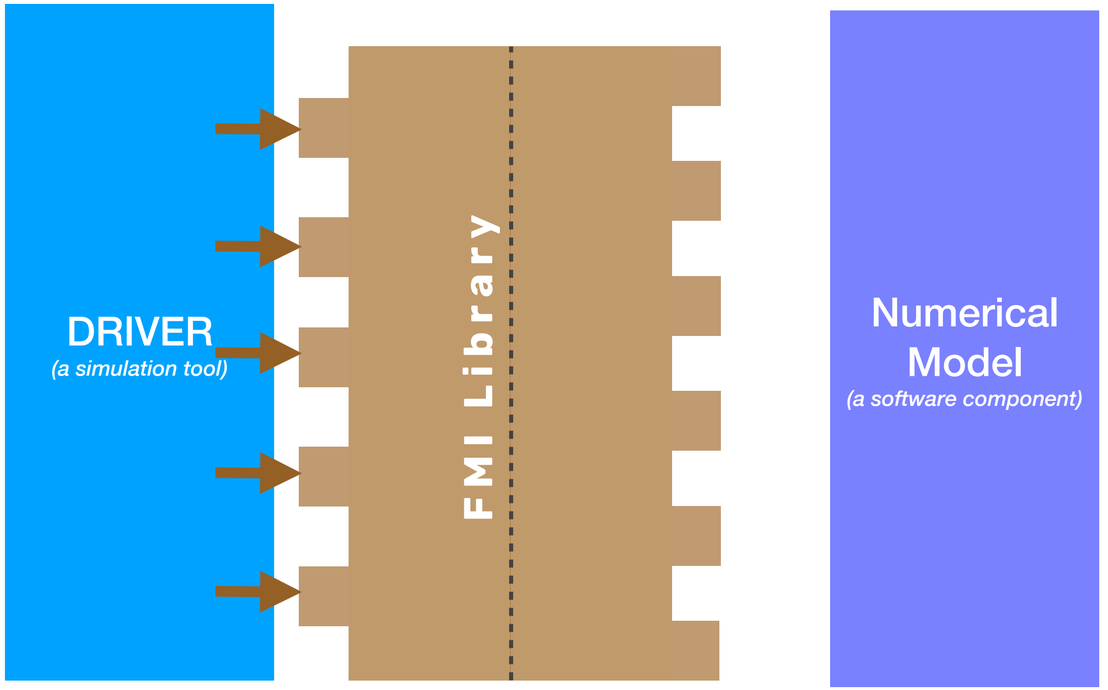

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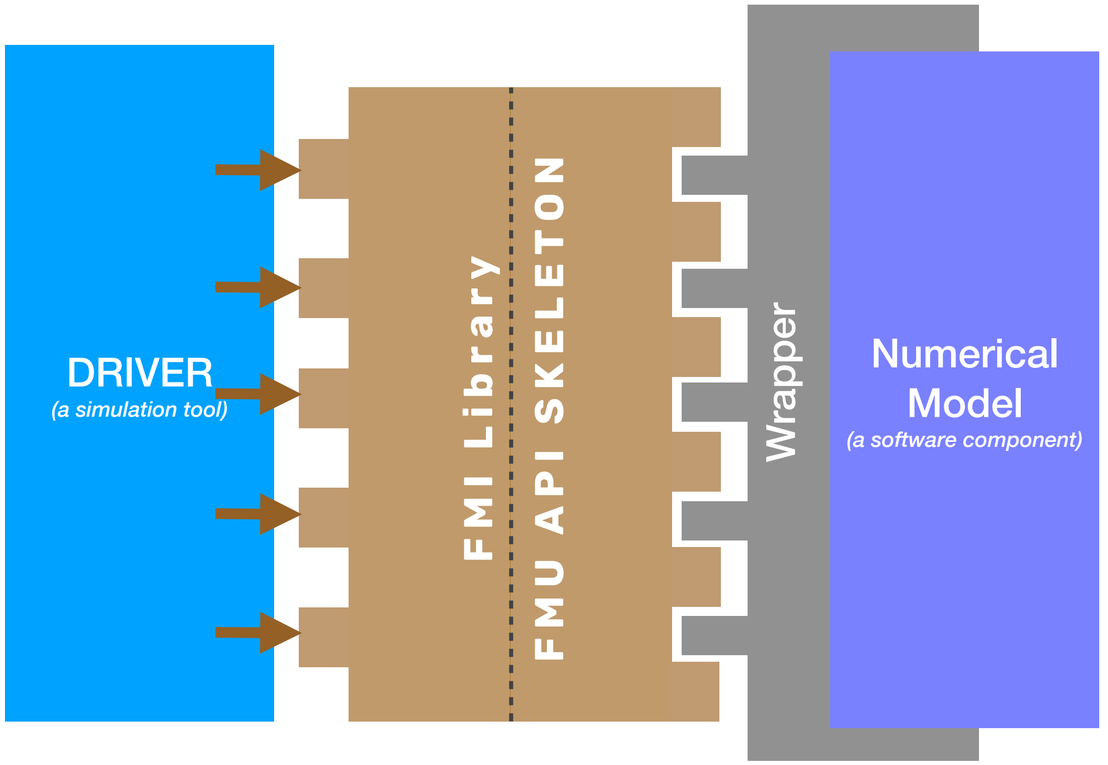

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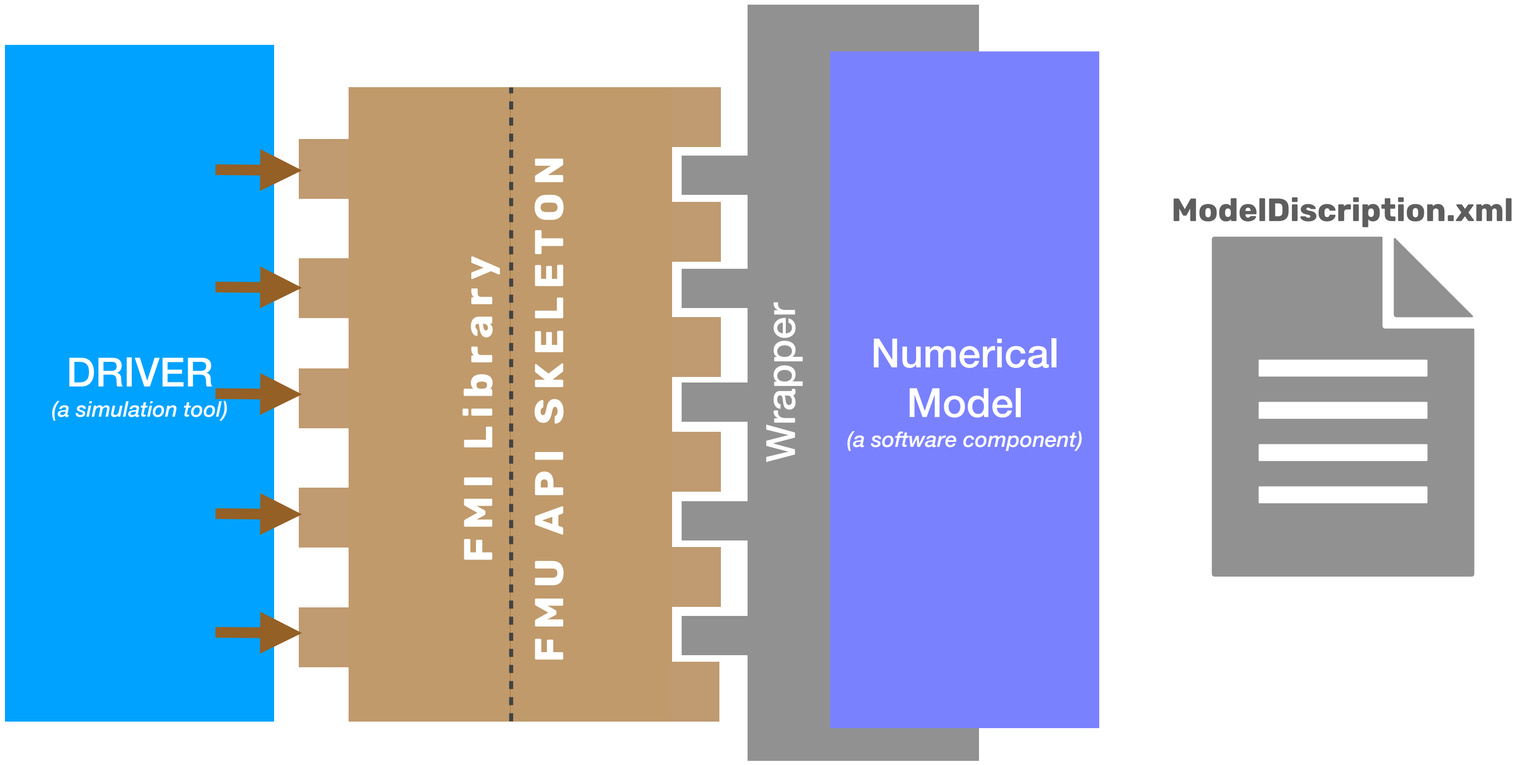

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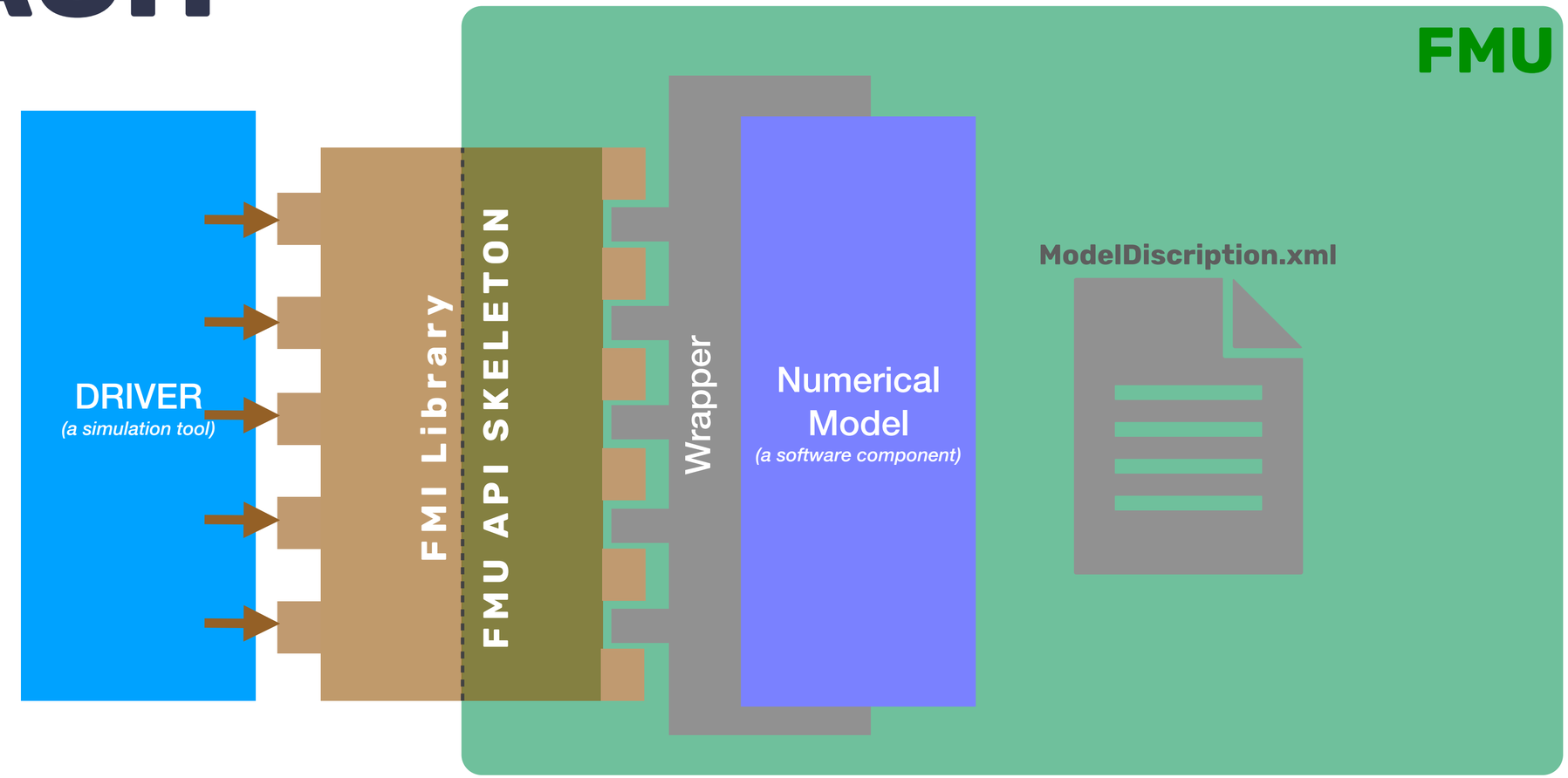

Model of
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Model of
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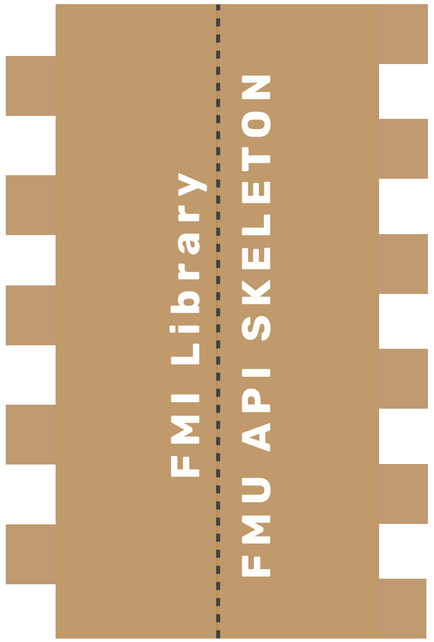
FMI CO-SIMULATION COUPLING APPROACH

```
……
fmi2_import_get_variable_name

……

fmi2_import_get_real
fmi2_import_get_integer
……
fmi2_import_set_real
fmi2_import_set_integer
……
fmi2_import_get_fmu_state
fmi2_import_set_fmu_state
……
fmi2_import_do_step
……
```




```
……

fmi2GetReal
fmi2GetInteger
……
fmi2SetReal
fmi2SetInteger
……
fmi2GetFMUstate
fmi2SetFMUstate
……
fmi2DoStep
……
```

FMI Library

FMU API Skeleton

FMI CO-SIMULATION COUPLING APPROACH

```
……
fmi2_import_get_variable_name

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fmi2_import_get_real
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fmi2_import_set_fmu_state
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```

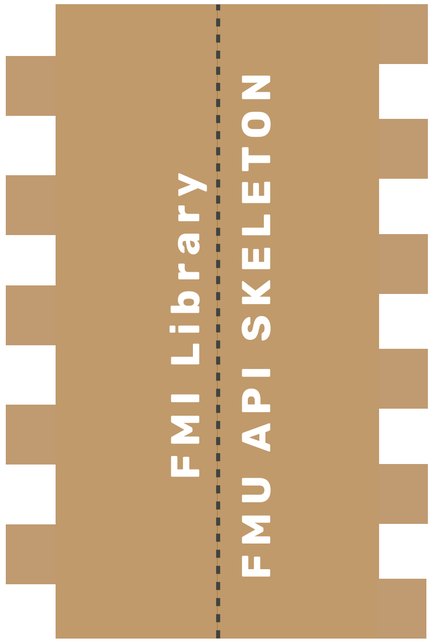


```
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fmi2GetReal
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fmi2SetFMUstate
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fmi2DoStep
……
```

FMI Library

FMU API Skeleton

3 PYCATSHOO AND EXTERNAL MODELS

FMI CO-SIMULATION COUPLING APPROACH

```
……
fmi2_import_get_variable_name

……

fmi2_import_get_real
fmi2_import_get_integer
……
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fmi2_import_set_integer
……
fmi2_import_get_fmu_state
fmi2_import_set_fmu_state
……
fmi2_import_do_step
……
```

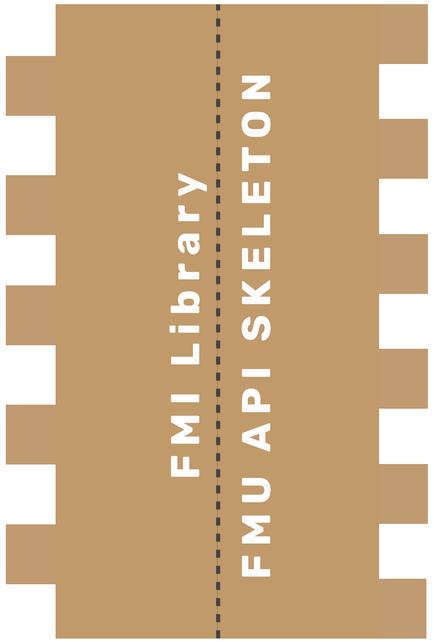


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FMI CO-SIMULATION COUPLING APPROACH

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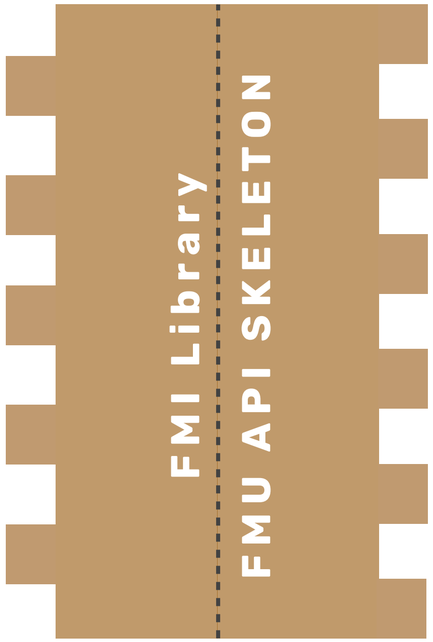
fmi2_import_set_fmu_state
……
fmi2_import_do_step
……
```




```
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fmi2GetReal
fmi2GetInteger
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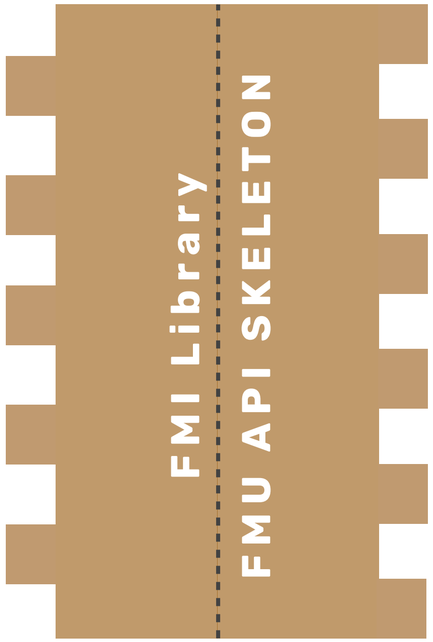
……
fmi2GetFMUstate
fmi2SetFMUstate
……
fmi2DoStep
……
```

FMI CO-SIMULATION COUPLING APPROACH WITH PYCATSHOO

1. Load an FMU
2. Bind FMU Variables to PyCATSHOO Variables



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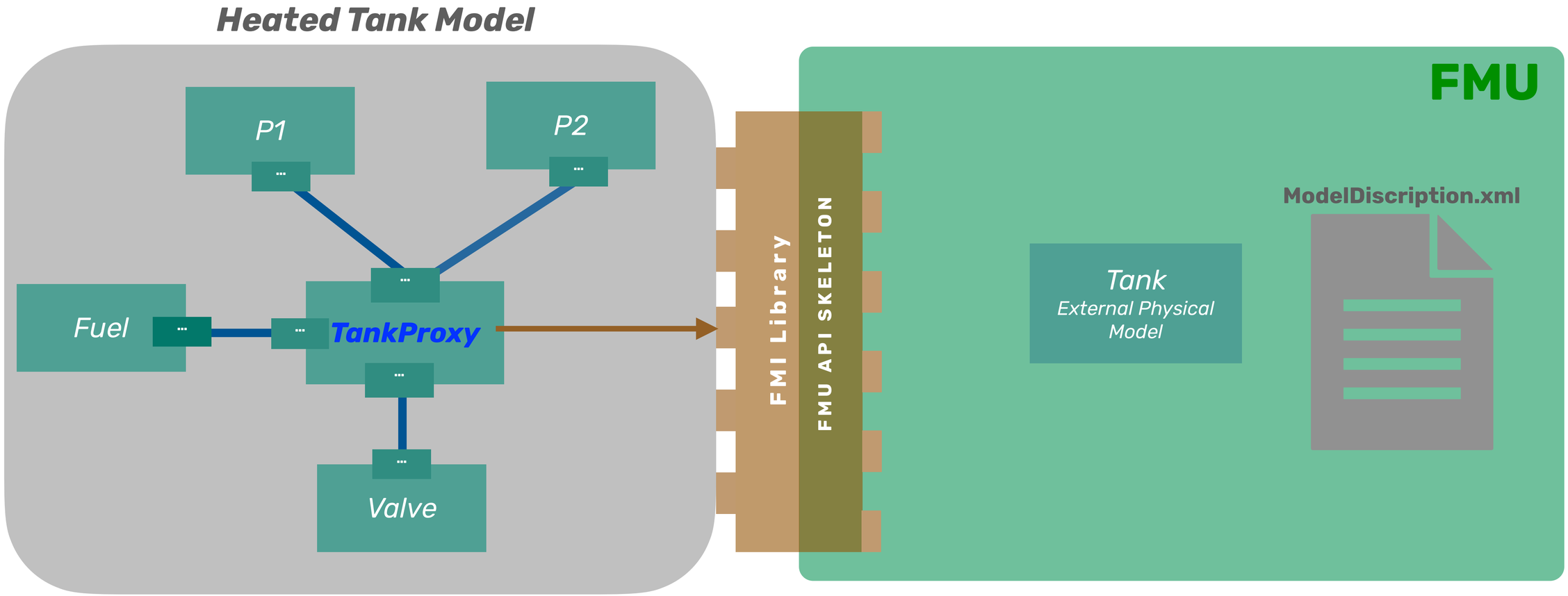
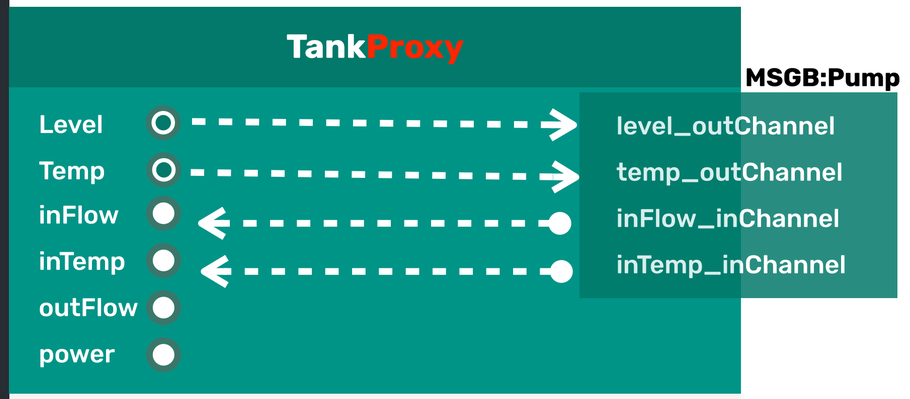
……

FMI CO-SIMULATION COUPLING APPROACH WITH PYCATSHOO

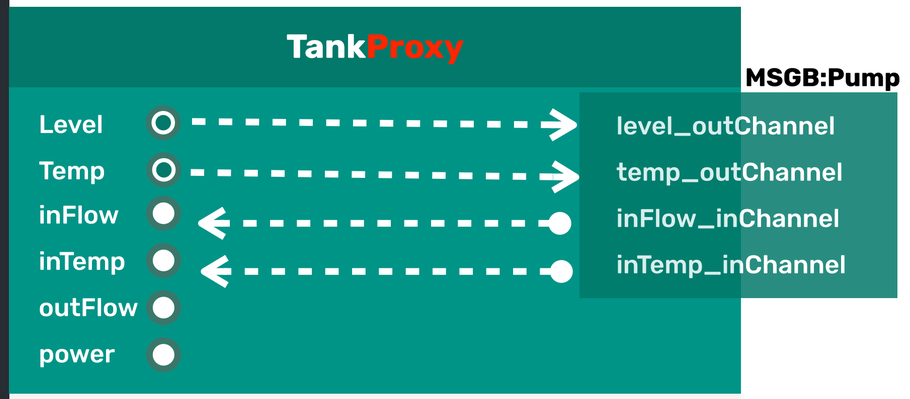


```
class TankProxy(Pyc.CComponent):
    def __init__(self, name):
        Pyc.CComponent.__init__(self, name)
```



```
class TankProxy(Pyc.CComponent):
    def __init__(self, name):
        Pyc.CComponent.__init__(self, name)

        ……
        self.fmu = self.system().addFMU(“MyFMIFolder/heatedTank.fmu”, "FMU")
```



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        Pyc.CComponent.__init__(self, name)

        ……
        self.fmu = self.system().addFMU(“MyFMIFolder/heatedTank.fmu”, "FMU")

        ……
        self.v_temperature = self.fmu.variable(“FMUTank.Temperature")
        self.v_level       = self.fmu.variable("FMUTank.Level")
        self.v_fmuPower    = self.fmu.variable('FMUTank.Power')
        ……
        ……

        ……
```

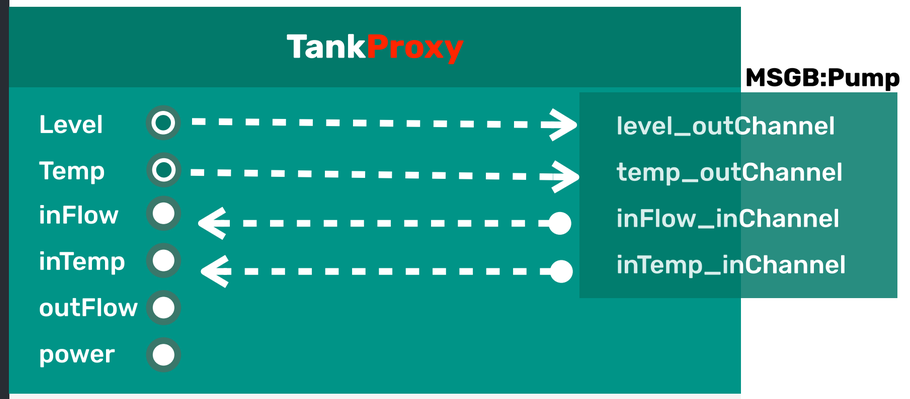

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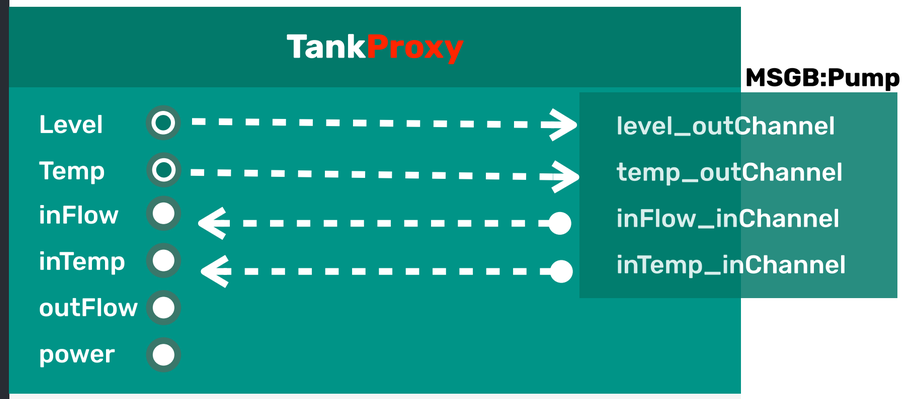
        ……
        self.v_temperature = self.fmu.variable(“FMUTank.Temperature")
        self.v_level       = self.fmu.variable("FMUTank.Level")
        self.v_fmuPower    = self.fmu.variable('FMUTank.Power')
        ……
        ……

        ……


        pdmp = self.addPDMPManager  ("pdmpManager")

        pdmp.addFMU( self.system().FMU(“FMU"))

        self.addPDMPBeginMethod("pdmpManager", "beginMethod",  self.beginMethod)
```



PDMP: pdmpManage

Relies On FMU for equation solving

Ensures FMU Variables initialisation

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        ……
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        self.v_level       = self.fmu.variable("FMUTank.Level")
        self.v_fmuPower    = self.fmu.variable('FMUTank.Power')
        ……
        ……

        ……


        pdmp = self.addPDMPManager  ("pdmpManager")

        pdmp.addFMU( self.system().FMU(“FMU"))

        self.addPDMPBeginMethod("pdmpManager", "beginMethod",  self.beginMethod)


    def beginMethod(self):

        ……

        self.v_fmuPower.setDValue(self.r_power.sumValue());

        ……
```
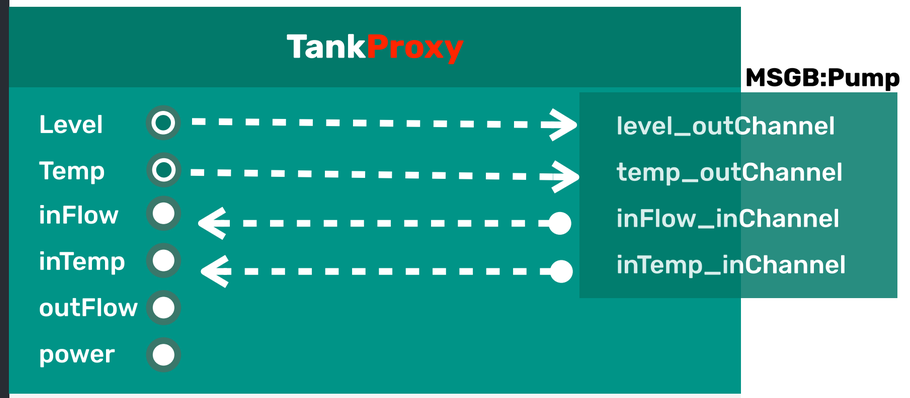
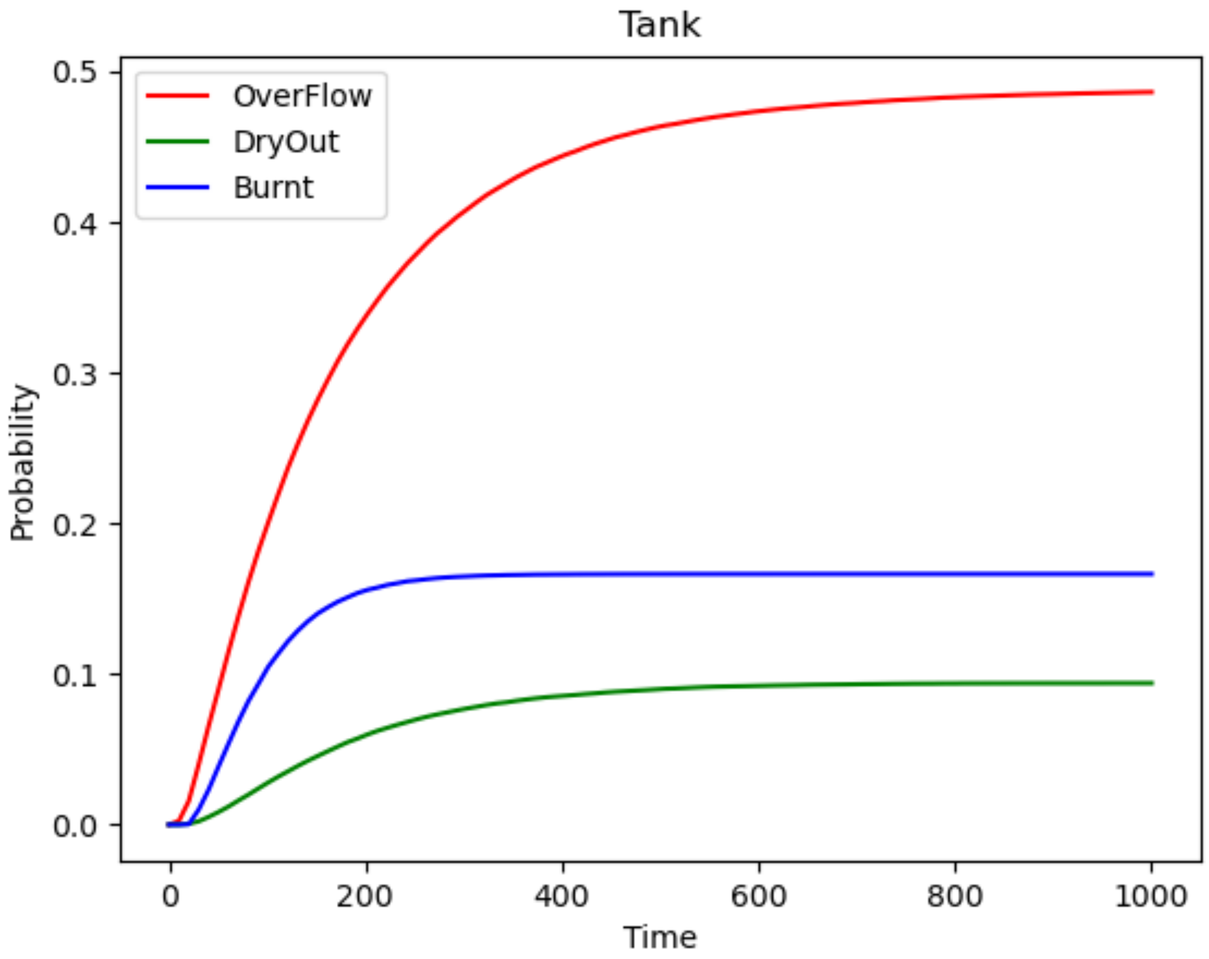



PDMP: pdmpManage

Relies On FMU for equation solving

Ensures FMU Variables initialisation

FMI CO-SIMULATION WITH PYCATSHOO: OUTPUTS



FMI CO-SIMULATION WITH PYCATSHOO: OUTPUTS

COMPUTATION TIMES FOR DIFFERENT NUMBERS OF SIMULATED SEQUENCES *(10 threads on six-core Intel® i7-8750H / 32GB)*				
Number of sequences	**10^3**	**10^4**	**10^5**	**10^6**
Full PyCATSHOO Model	1.2 s	2.20 s	16.4 s	180 s

FMI CO-SIMULATION WITH PYCATSHOO: OUTPUTS

COMPUTATION TIMES FOR DIFFERENT NUMBERS OF SIMULATED SEQUENCES *(10 threads on six-core Intel® i7-8750H / 32GB)*				
Number of sequences	**10^3**	**10^4**	**10^5**	**10^6**
Full PyCATSHOO Model	1.2 s	2.20 s	16.4 s	180 s
PyCATSHOO using external FMU	1.7 s	7.7 s	69 s	727 s

4 CONCLUSIONS AND OUTLOOK

CONCLUSIONS AND OUTLOOK

- **FMI standard in PyCATSHOO**
  - ✓ *PyCATSHOO can now use external physical models that conform to FMI*
  - ✓ *FMI API complexity taken care of by PyCATSHOO*

- **What next?**
  - ✓ *Application to an industrial-sized study: HVAC?*
  - ✓ *Exploring the potential benefits of the FMI Model Exchange approach*

PyCATSHOO.org

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