WHEN TRUST MATTERS

MLFMU: An easy-to-use tool for converting ML models to FMUs

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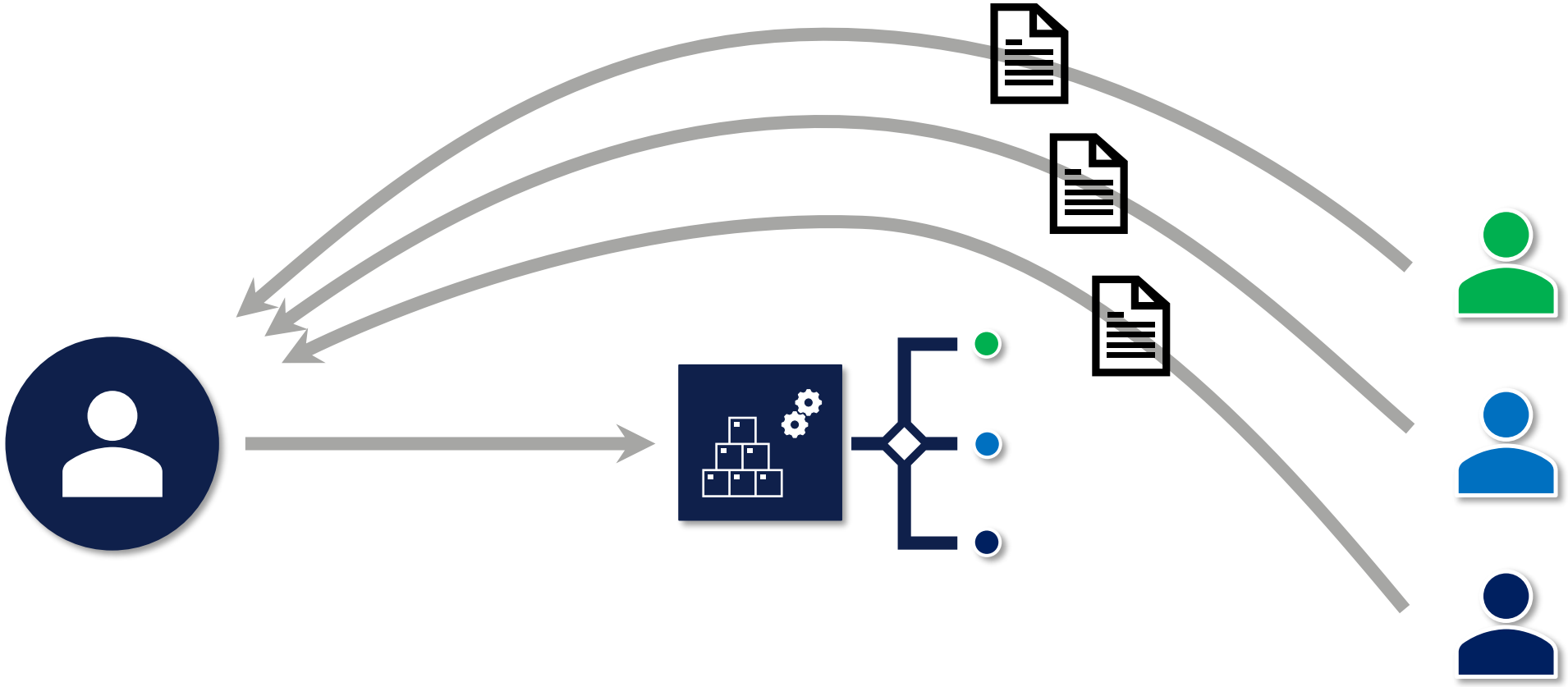
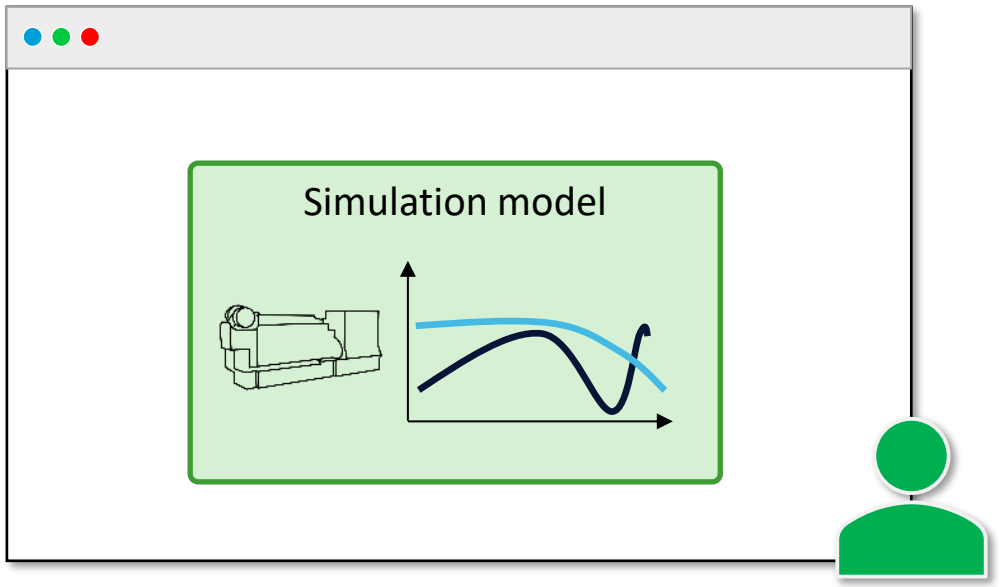
System integration: collaboration beyond data sheets

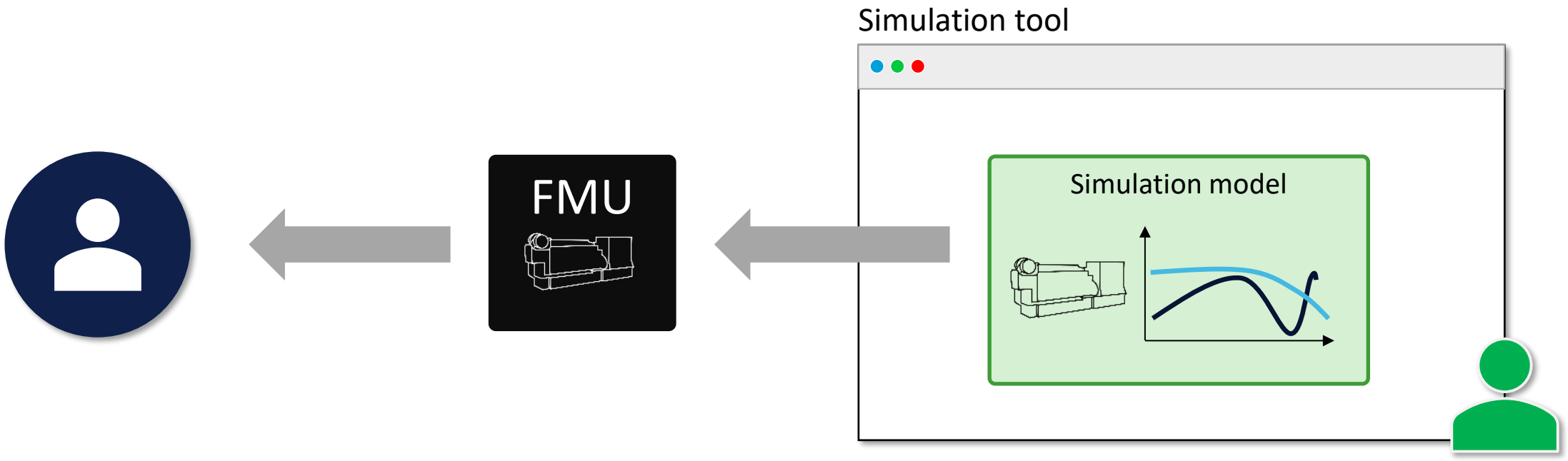


fmi: Functional Mockup Interface

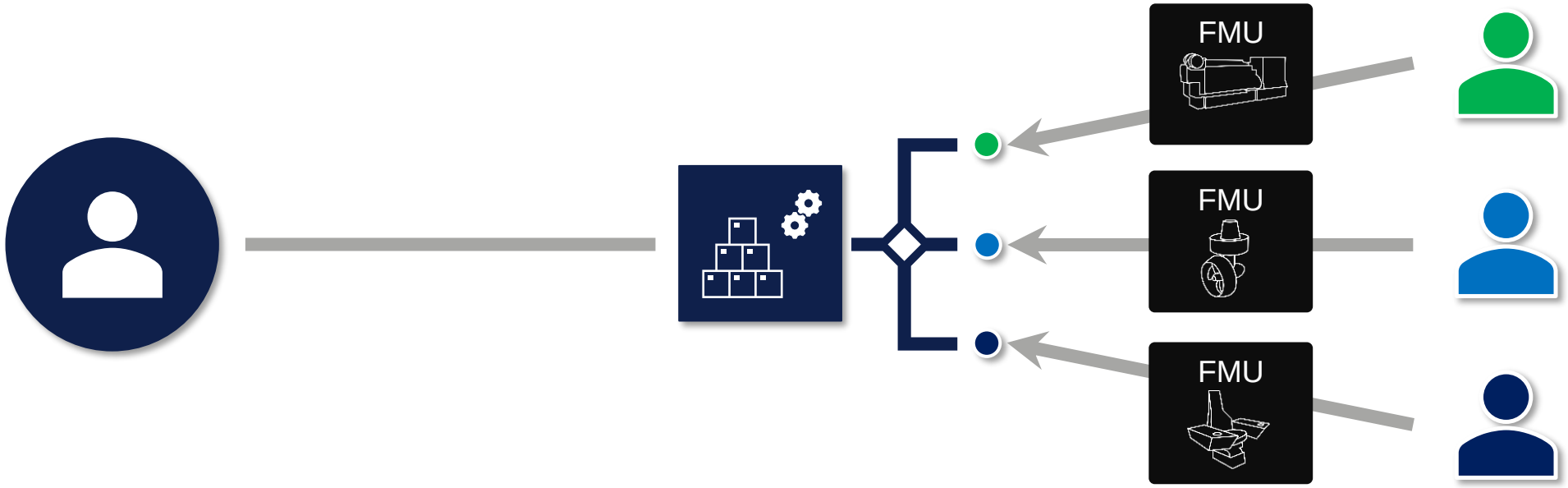
Functional
Mock-Up
Interface



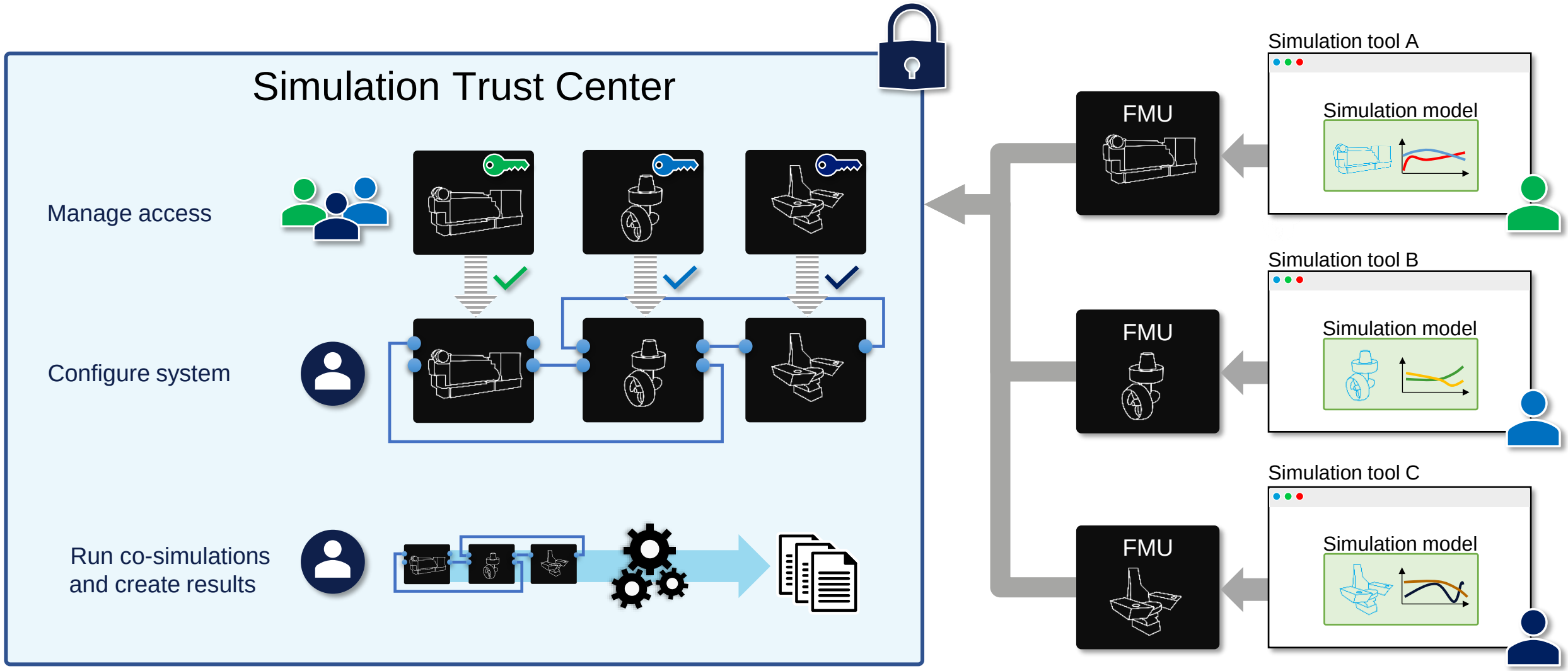
FMU: Functional Mockup Unit



System Integration



STC: Secure Collaboration Space



https://store.veracity.com/simulation-trust-center

Why Machine Learning (ML) models?

Advent of AI: It is common now to create ML models from data

Don’t have an accurate simulation model (yet) but need a model ASAP

Need a model that can run faster than the physics-based high-fidelity model

How to create FMUs from ML models?

Premise:
We want to be able to use powerful tools, e.g. PyTorch or TensorFlow, to build ML models.

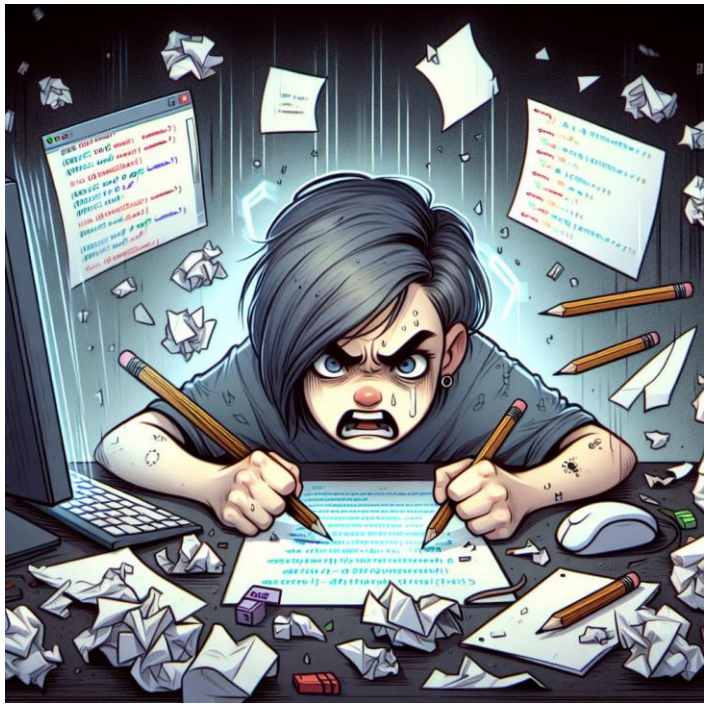
Current options:

a. Use PythonFMU and download/include (for example) PyTorch in FMU

b. Export Tensorflow lite to C code, then wrap C code as FMU

c. Export ML model for import to Matlab/Simulink, then export from there to FMU

None of these are great options..



ONNX: Open Neural Network Exchange

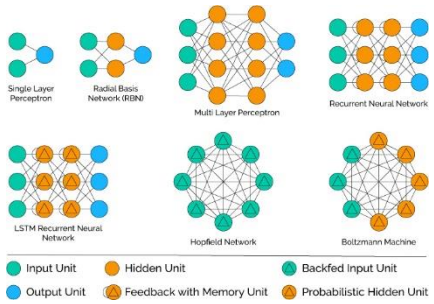
- ONNX is an open format built to represent ML models.
- ONNX defines a common set of operators - the building blocks of ML and DL models - and a common file format to enable AI developers to use models with a variety of frameworks, tools, runtimes, and compilers.
- ONNX Runtime: library to optimize and accelerate ML inferencing
  - Take model, export ML model to ONNX format, do inferencing in many different languages.

Commonly used in ML community.

https://onnx.ai/ / https://onnxruntime.ai/

From data to FMU:

Create your ML model → Save as ONNX file → Prepare FMU interface specification file (.json) → Compile FMU from ONNX and json files → Run FMU



ONNX

{JSON}

FMU

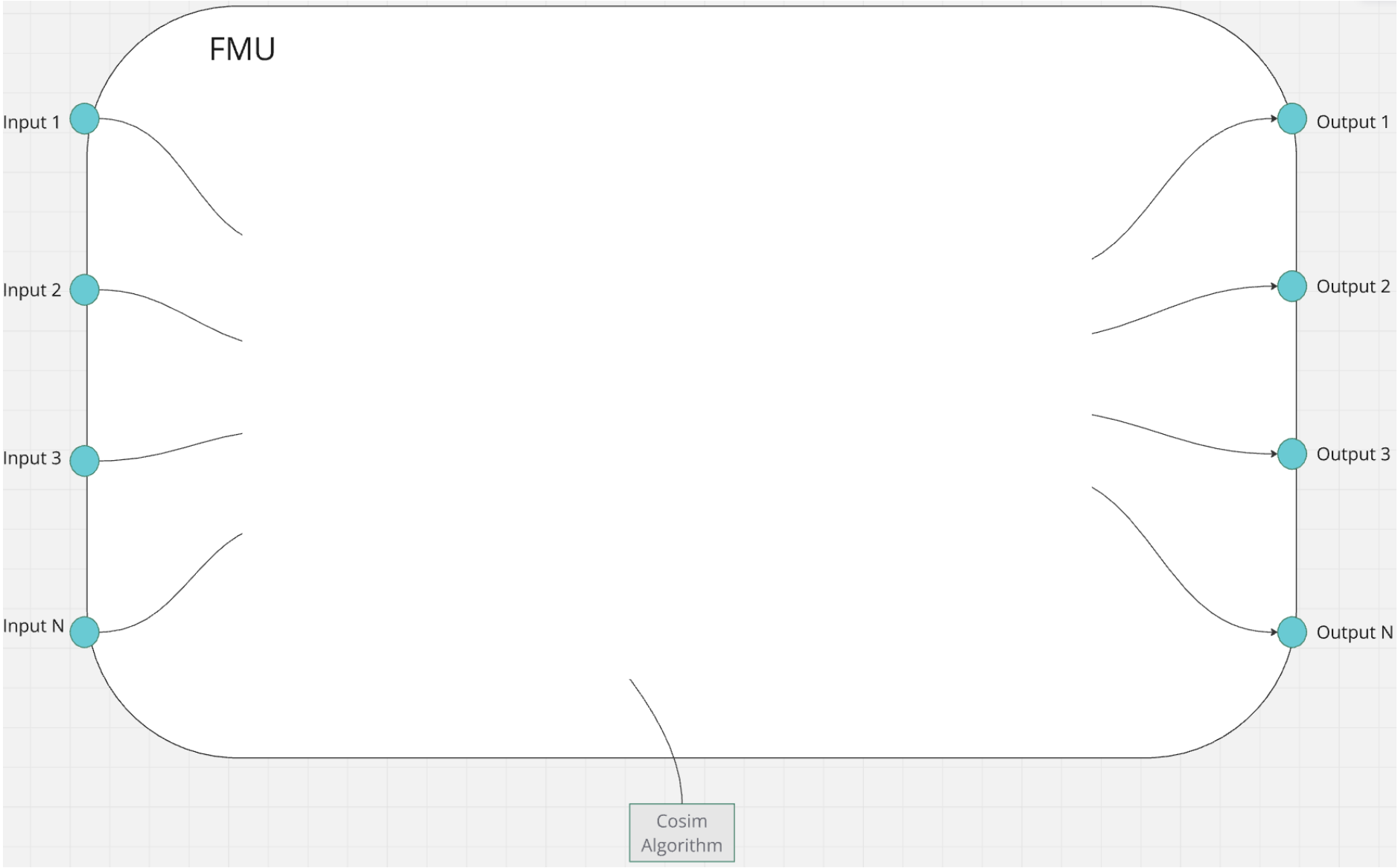
fmi

DNV

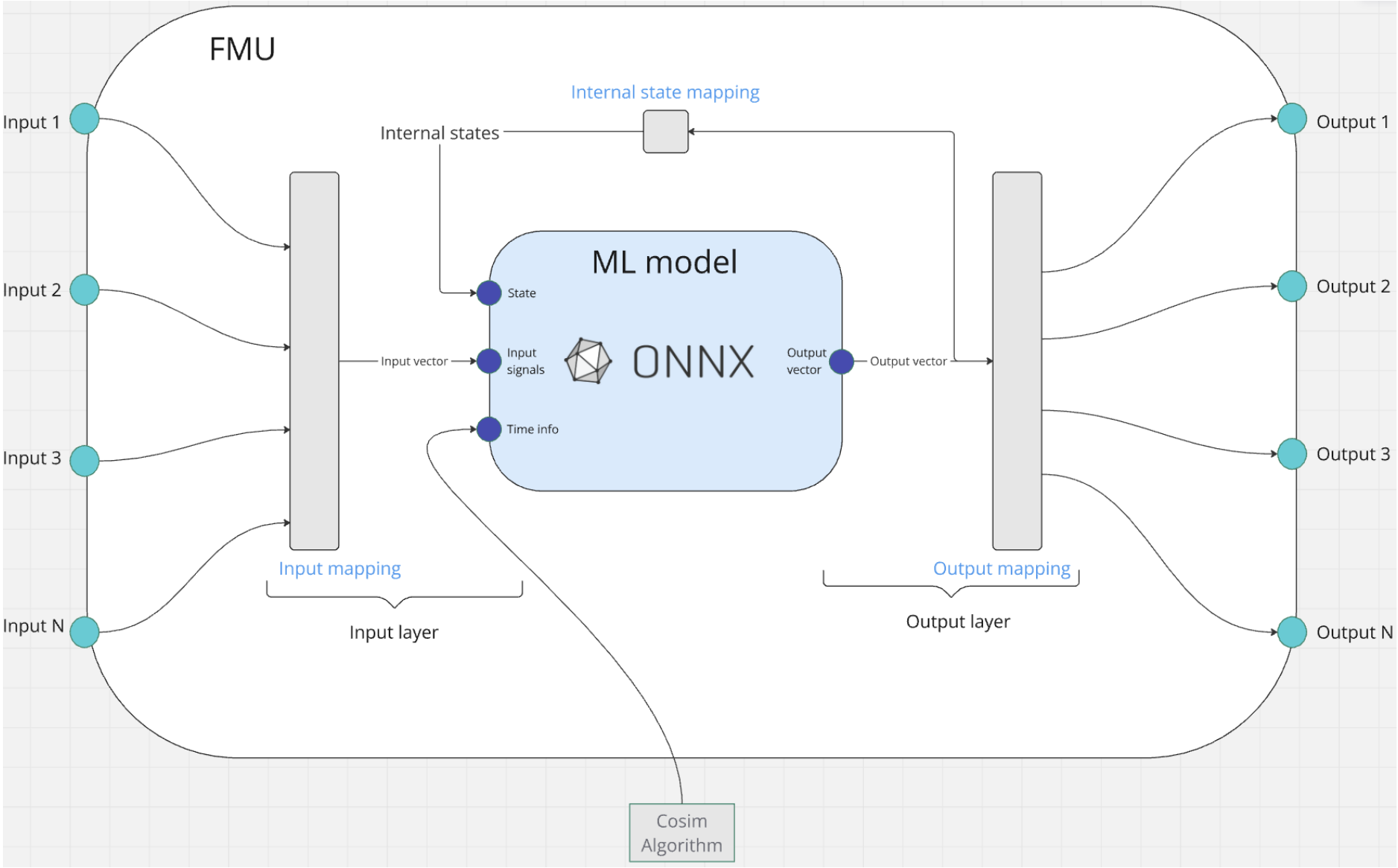
MLFMU:
From ONNX to FMU

DNV

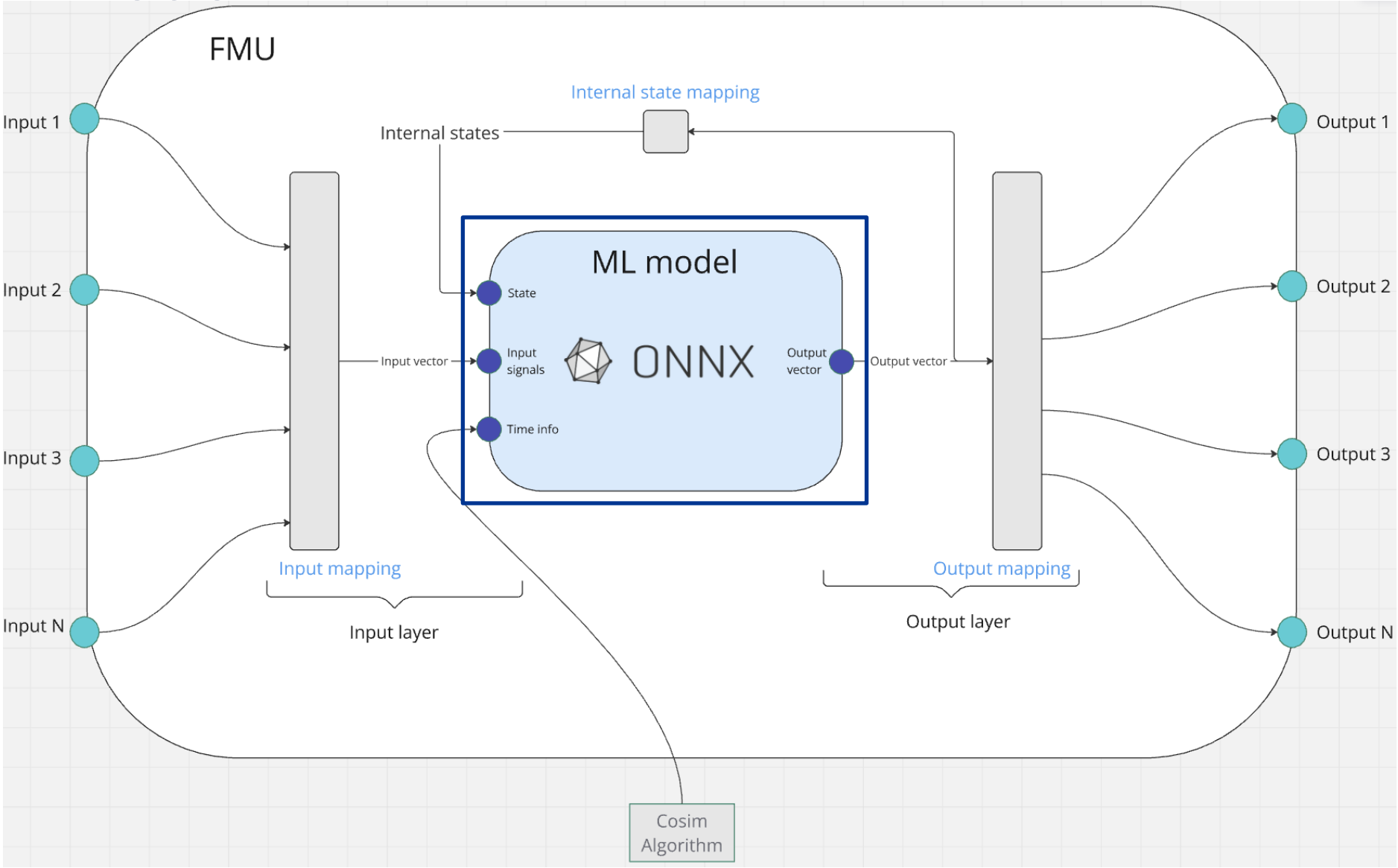
FMU


FMU
Input 1
Input 2
Input 3
Input N
Output 1
Output 2
Output 3
Output N
Cosim
Algorithm

FMU


FMU
Internal state mapping
Internal states
Input 1
Input 2
Input 3
Input N
ML model
State
Input signals
Time info
ONNX
Output vector
Input vector
Output vector
Output 1
Output 2
Output 3
Output N
Input mapping
Input layer
Output mapping
Output layer
Cosim Algorithm

ONNX model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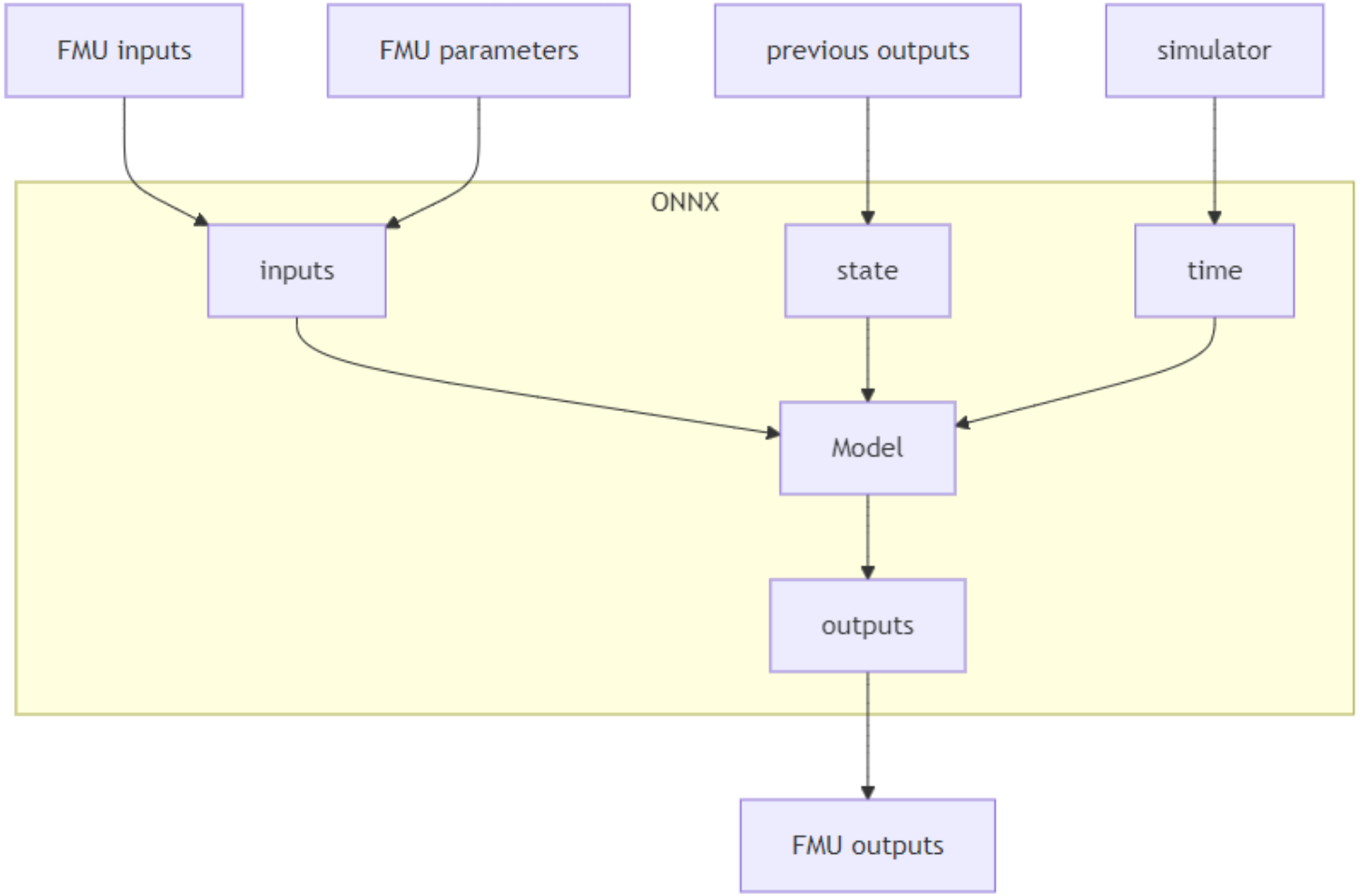
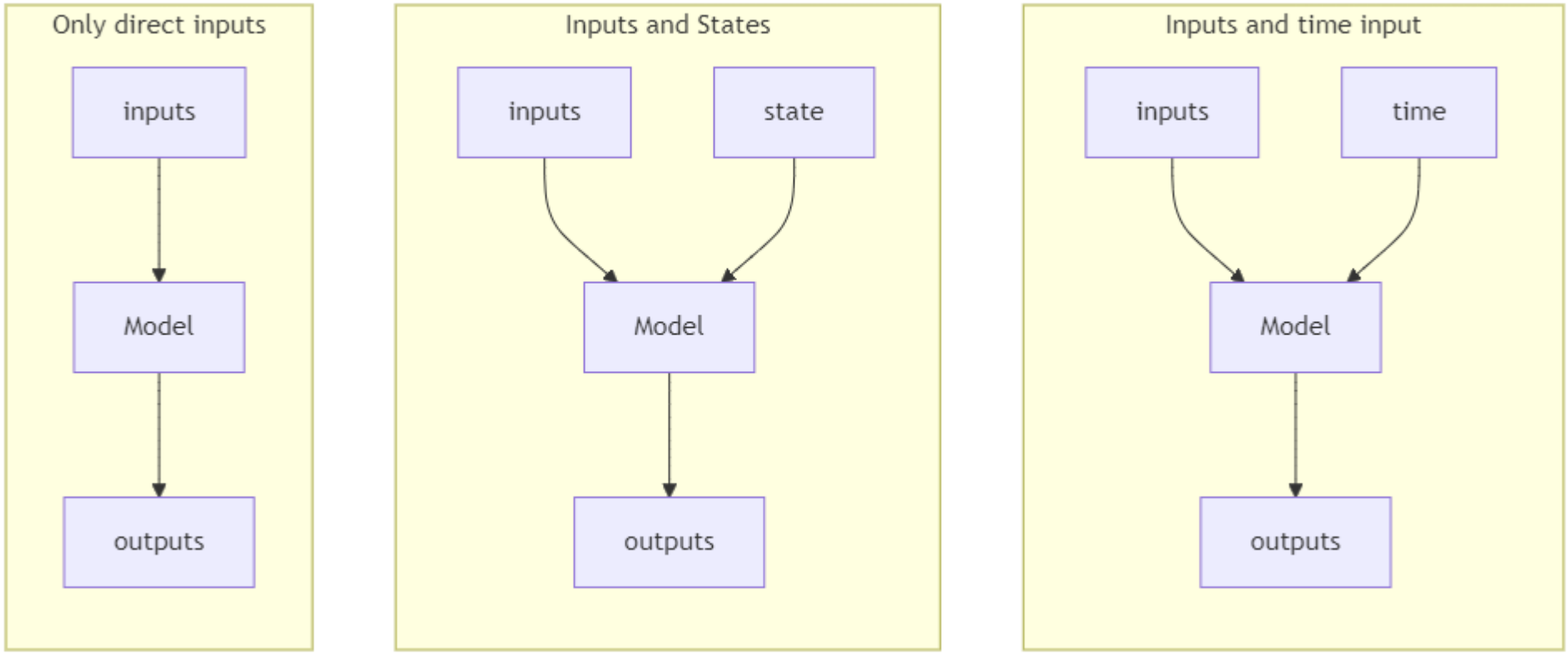
Cosim Algorithm

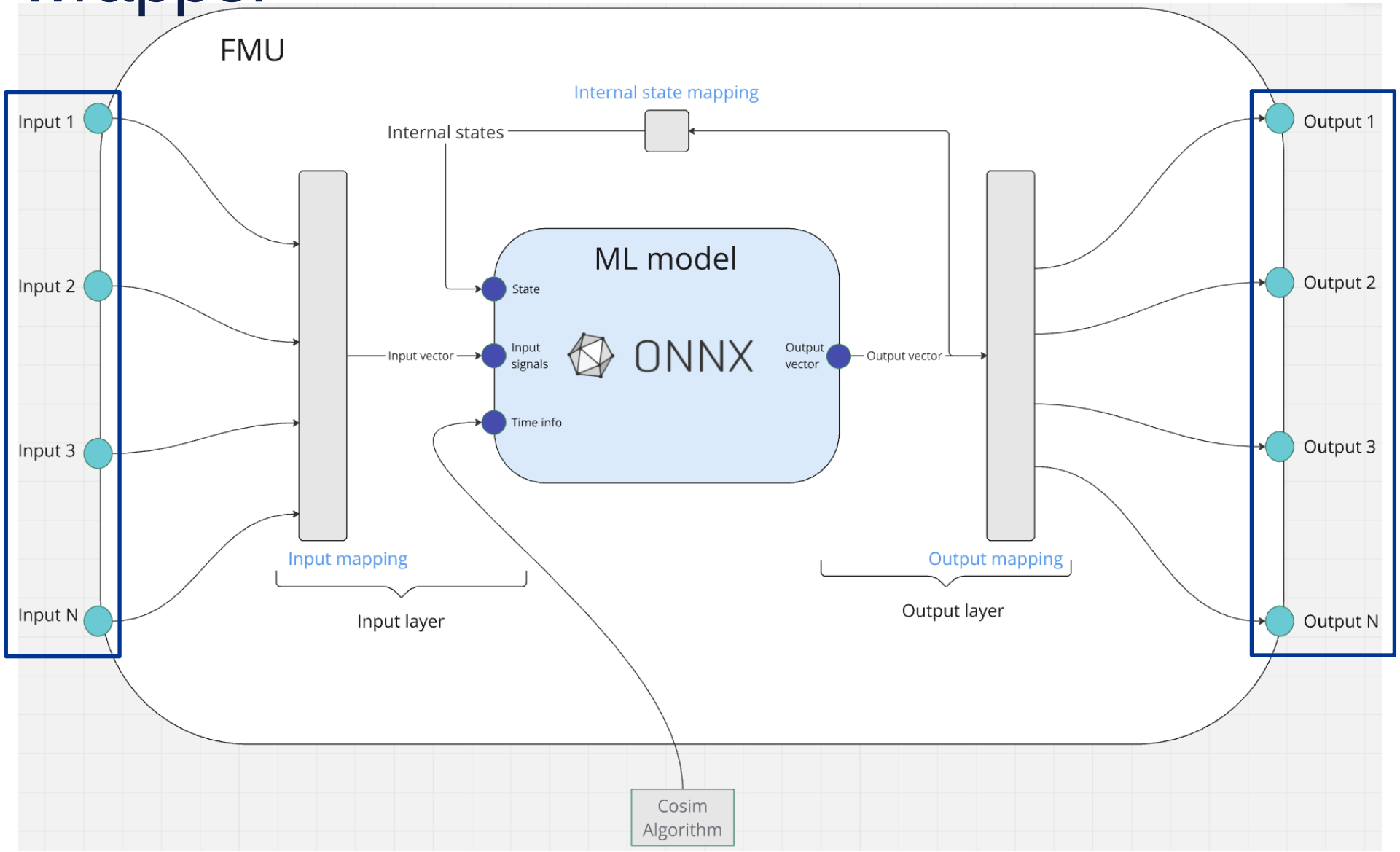
Specifying inputs and outputs



Input options



FMU wrapper


FMU
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Output vector
Output vector
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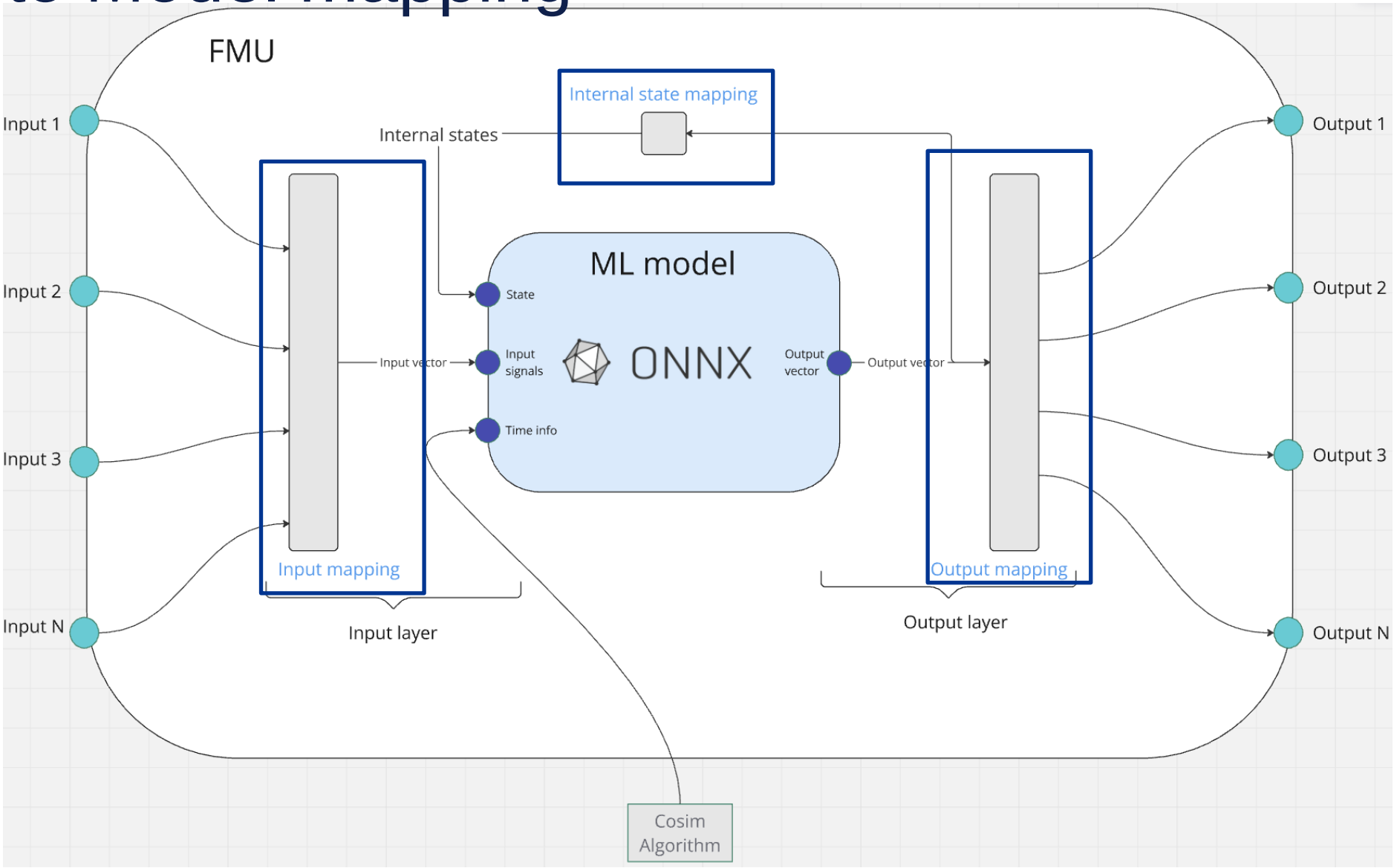
Output N
Input mapping
Input layer
Output mapping
Output layer
Cosim Algorithm

FMU to Model mapping



Interface specification file

```
{
    "name": "WindToPower",
    "description": "A Machine Learning based FMU that outputs the estimated power output of a wind turbine given the wind speed and direction.",
    "inputs": [
        {
            "name": "windSpeed",
            "description": "The speed of the wind",
        },
        {
            "name": "windDirection",
            "description": "The direction of the wind",
        }
    ],
    "parameters": [],
    "outputs": [
        {
            "name": "power",
            "description": "The estimated wind turbine power output",
        }
    ],
    "states": []
}
```

Interface specification file


```
{
    "name": "WindToPower",
    "description": "A Machine Learning based FMU that outputs the estimated power output of a wind turbine given the wind speed and direction.",
    "inputs": [
        {
            "name": "windSpeed",
            "description": "The speed of the wind",
            "agentInputIndexes": [
                "0"
            ]
        },
        {
            "name": "windDirection",
            "description": "The direction of the wind",
            "agentInputIndexes": [
                "1"
            ]
        }
    ],
    "parameters": [],
    "outputs": [
        {
            "name": "power",
            "description": "The estimated wind turbine power output",
            "agentOutputIndexes": [
                "0"
            ]
        }
    ],
    "states": []
}
```

Using arrays

```
"inputs": [
    {
        "name": "position",
        "description": "position with [x, y, z] coordinates",
        "agentInputIndexes": [
            "0:3"
        ],
        "is_array": true,
        "length": 3
    },
    {
        "name": "velocity",
        "description": "velocity in the [x, y, z] directions",
        "agentInputIndexes": [
            "3:6"
        ],
        "is_array": true,
        "length": 3
    }
],
```

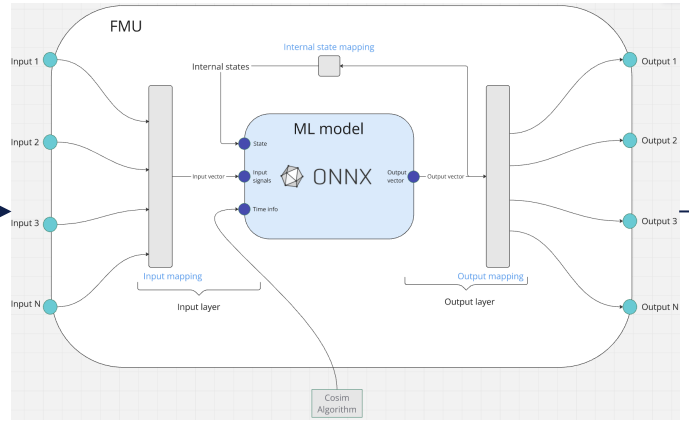

DNV

MLFMU: Compile FMU from .onnx & .json

model.onnx

interface.json

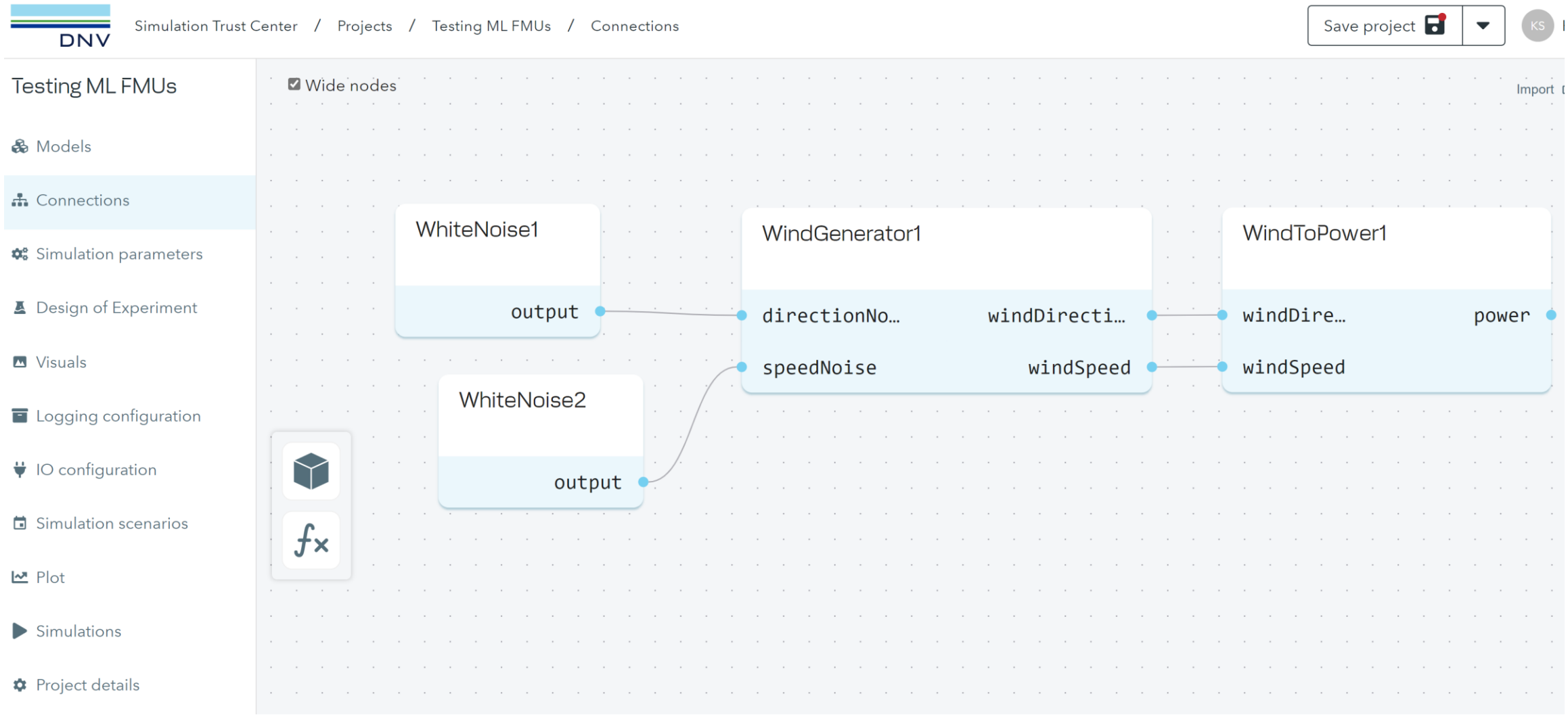
```
> mlfmu build
```



model.fmu

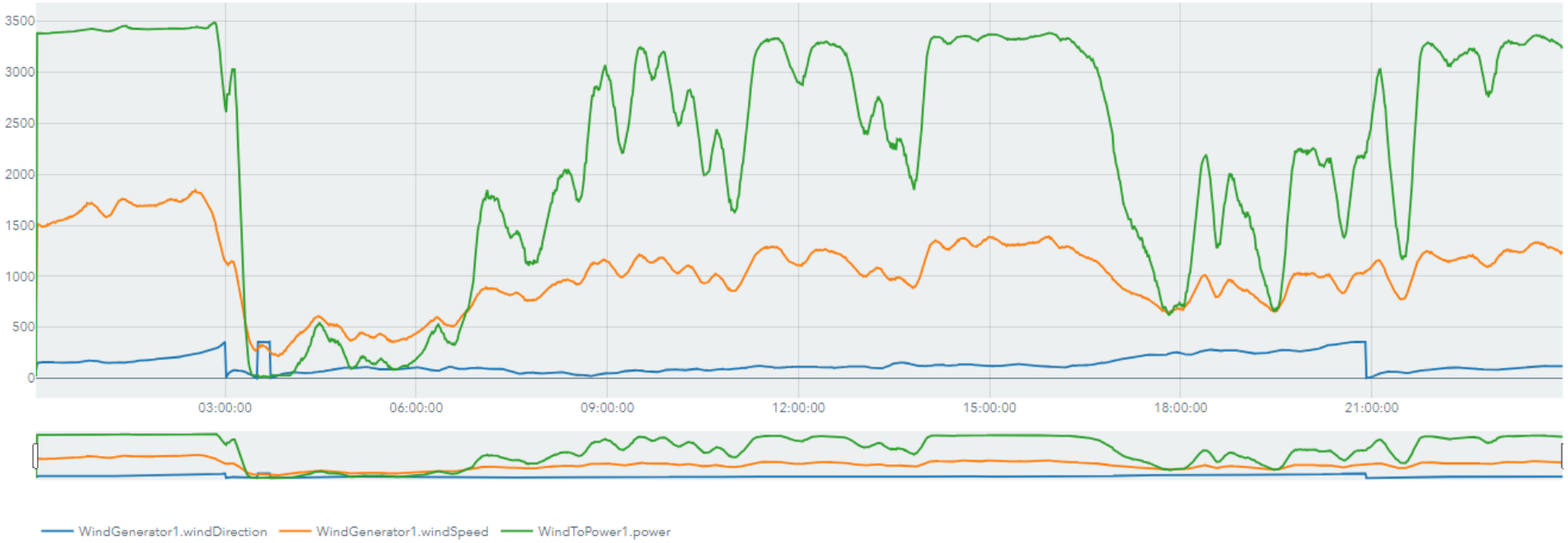
Using the ML FMUs

Example: Run FMUs in the Simulation Trust Center



DNV

STC results



Start time [s] 0

End time [s] 86400 Set max

Window period 60s

Load Data

Variable	Current	Mean	Max	Min	Std dev	Scaling
WindGenerator1.windDirection	117.25	135.29	358.48	0.21	78.31	None
WindGenerator1.windSpeed	1232.38	1039.20	1844.73	217.02	359.91	x 100
WindToPower1.power	3253.65	2242.37	3489.56	11.06	1131.60	None

Recorded models

- WhiteNoise2
- WhiteNoise1
- WindGenerator1
- WindToPower1

Additional functionality

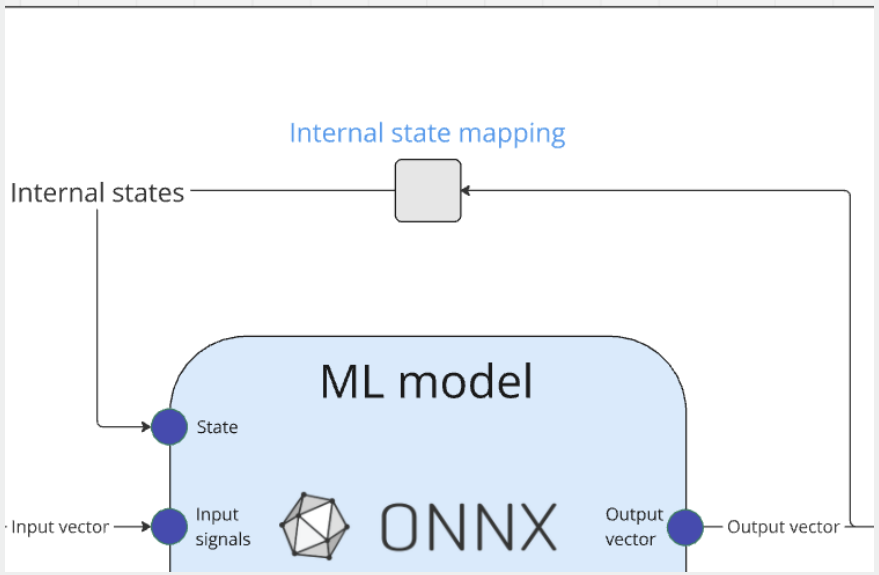
Using state

Why?

- Remember signals in the past
- Internal states to the ML model

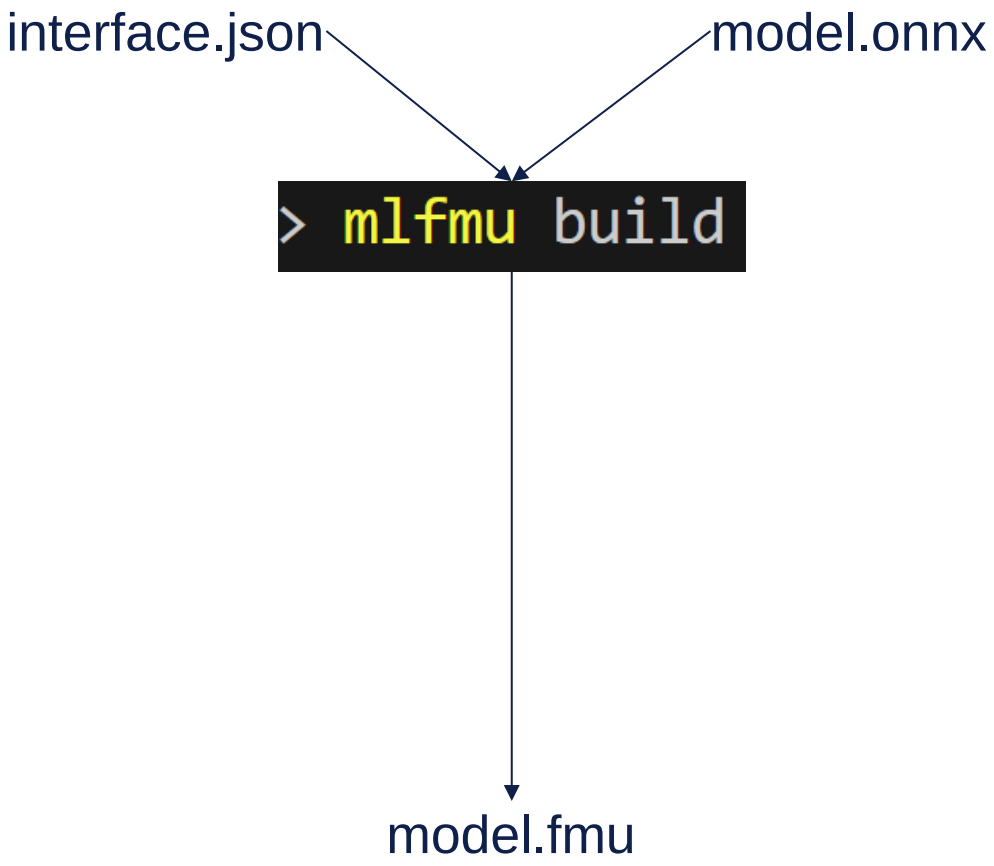
How?

- Needs to be outputted from the ML model
  - Some used for FMU outputs
  - Others used as states
  - Or both
- Modify existing ML model with a wrapper

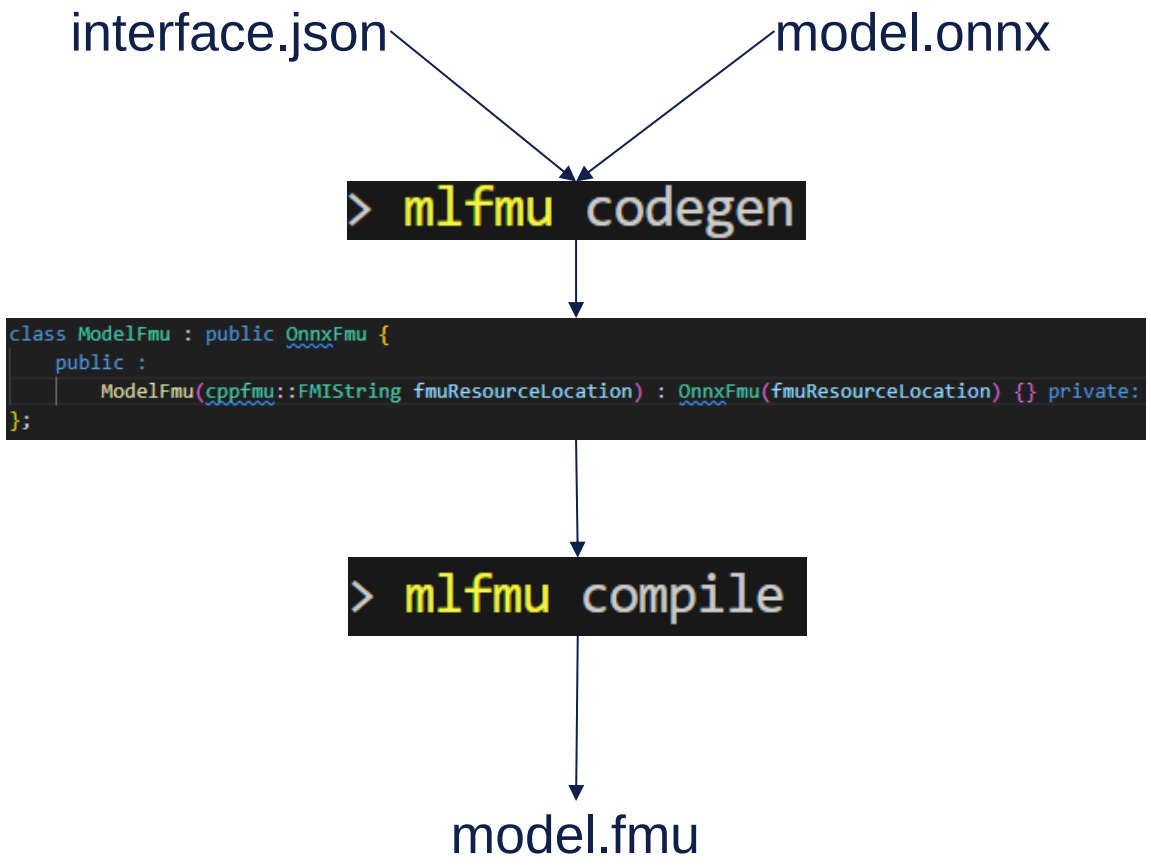



```
"states": [
    {
        "name": "previousOutput",
        "agentOutputIndexes": [
            "0:3"
        ]
    },
    {
        "name": "previousPosition",
        "agentOutputIndexes": [
            "3:6"
        ]
    },
    {
        "name": "previousVelocity",
        "agentOutputIndexes": [
            "6:9"
        ]
    },
    {
        "name": "statesForModel",
        "agentOutputIndexes": [
            "9:42"
        ]
    }
```

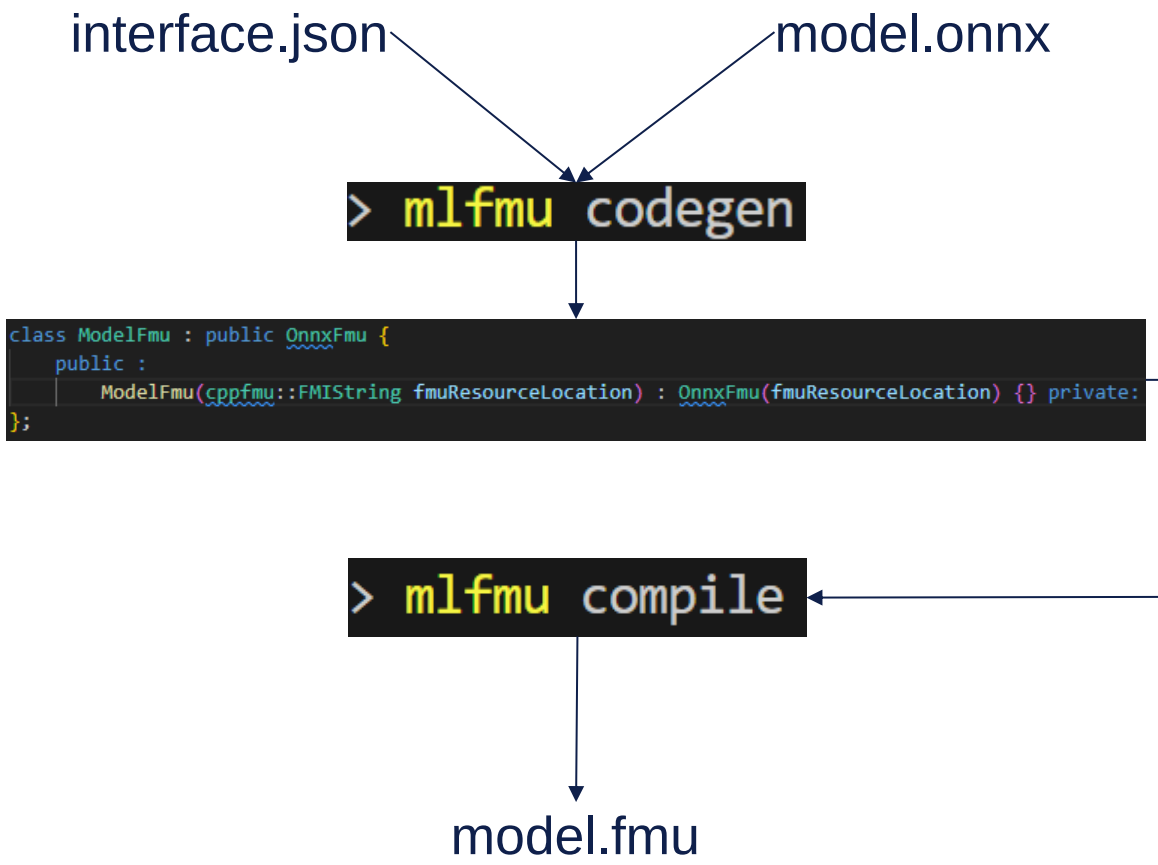
Altering C++ source code



Split up build command



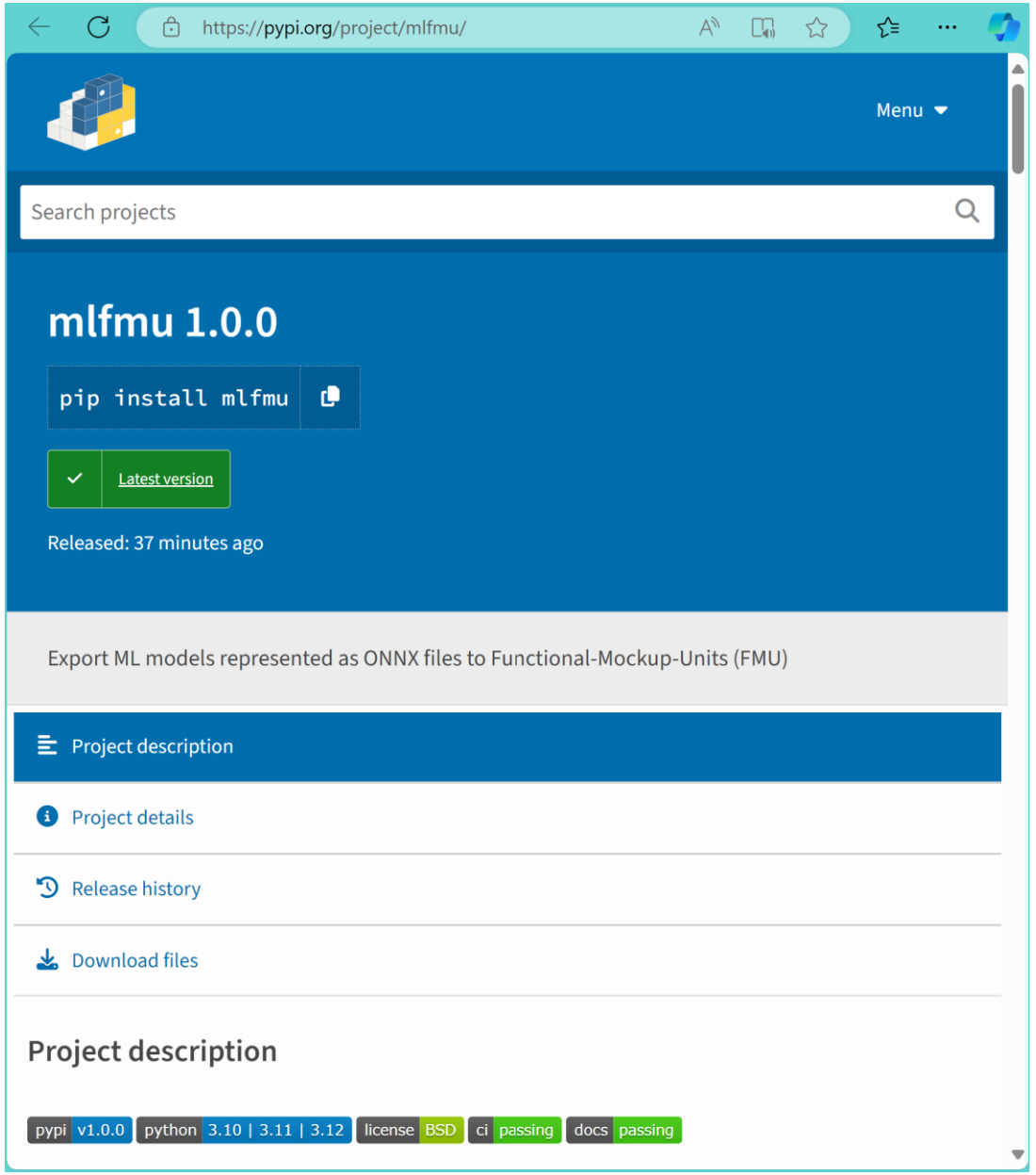
Implement custom behaviour before and after DoStep




```cpp
class ModelFmu : public OnnxFmu
{
public:
    ModelFmu(cppfmu::FMIString fmuResourceLocation)
        : OnnxFmu(fmuResourceLocation)
    { }

    bool DoStep(
        cppfmu::FMIReal currentCommunicationPoint,
        cppfmu::FMIReal dt,
        cppfmu::FMIBoolean newStep,
        cppfmu::FMIReal& endOfStep) override
    {
        // Implement custom behaviour here ...

        // Modify inputs and parameters

        // Call the OnnxFmu::DoStep function
        bool onnxDoStepSuccessful = OnnxFmu::DoStep(
            currentCommunicationPoint,
            dt,
            newStep,
            endOfStep);

        if (!onnxDoStepSuccessful) {
            return false;
        }

        // Modify outputs

        return true;
    }

private:
};
```

Future developments

- It is published as a package: mlfmu · PyPI
  - `pip install mlfmu`
- The code is open source: https://www.github.com/dnv-opensource/mlfmu
- Version 1.0 is not the final version
  - No “one size fits all”
  - We tried to make it generic and easy to use.
  - Just try to use it, find what is missing, and let us know!



Thank you!

https://pypi.org/project/mlfmu/
https://www.github.com/dnv-opensource/mlfmu

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Simulation Technologies team, DNV

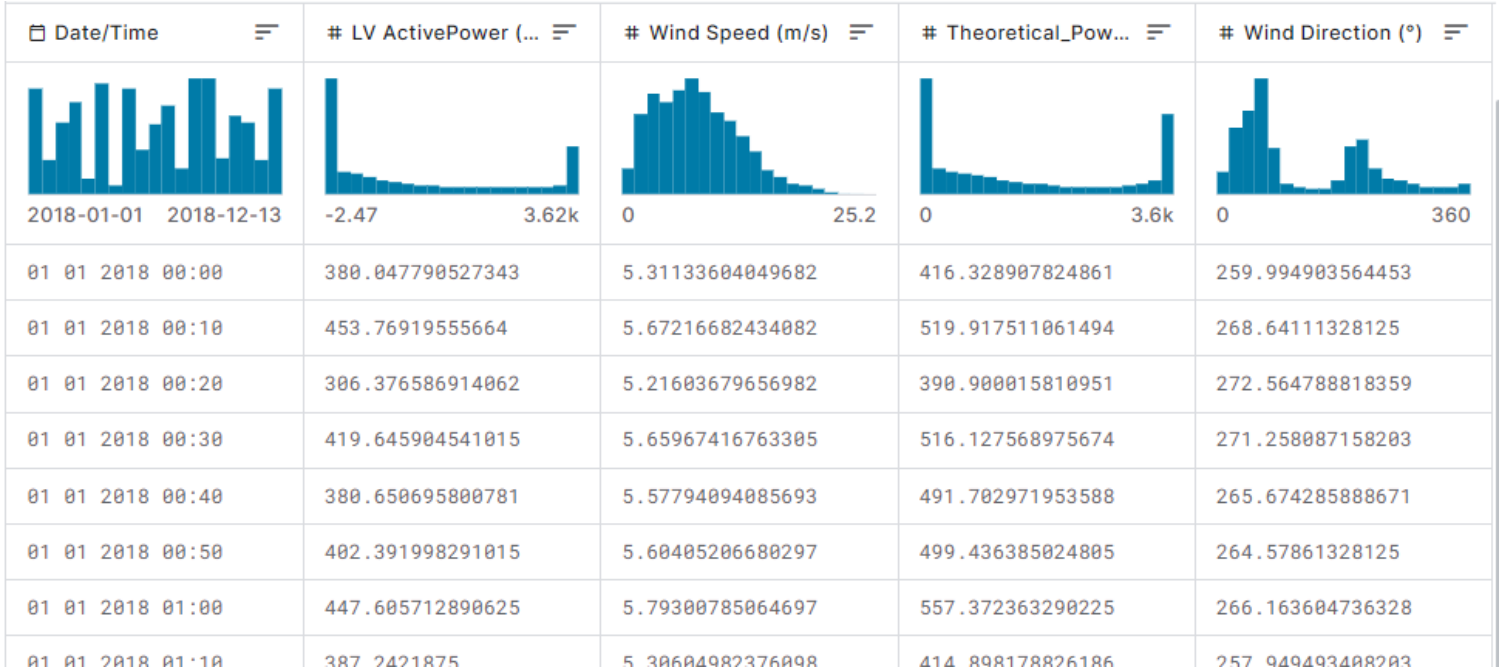
www.dnv.com

Example: The data

Example: https://www.kaggle.com/datasets/berkerisen/wind-turbine-scada-dataset/data

Data:

- recorded date/time,
- active power generated by the turbine for that moment,
- wind speed,
- theoretical power curve values that the turbine generates given the wind speed,
- wind direction.



Date/Time	# LV ActivePower (...	# Wind Speed (m/s)	# Theoretical_Pow...	# Wind Direction (°)
2018-01-01 2018-12-13	-2.47 3.62k	0 25.2	0 3.6k	0 360
01 01 2018 00:00	380.047790527343	5.31133604049682	416.328907824861	259.994903564453
01 01 2018 00:10	453.76919555664	5.67216682434082	519.917511061494	268.64111328125
01 01 2018 00:20	306.376586914062	5.21603679656982	390.900015810951	272.564788818359
01 01 2018 00:30	419.645904541015	5.65967416763305	516.127568975674	271.258087158203
01 01 2018 00:40	380.650695800781	5.57794094085693	491.702971953588	265.674285888671
01 01 2018 00:50	402.391998291015	5.60405206680297	499.436385024805	264.57861328125
01 01 2018 01:00	447.605712890625	5.79300785064697	557.372363290225	266.163604736328
01 01 2018 01:10	387.2421875	5.30604982376098	414.898178826186	257.949493408203

Example: Create a simple ML model

Goal: train a simple neural network to predict the active power production (model output), given a certain wind speed and wind direction (model input).

```
# 2 hidden layers, 32 units each
self.dense1 = tf.keras.layers.Dense(32, activation=tf.nn.relu)
self.dense2 = tf.keras.layers.Dense(32, activation=tf.nn.relu)
# output layer
self.dense3 = tf.keras.layers.Dense(1, activation=None)

power_model.fit(train_power, validation_data=val_power, epochs=num_epochs_power)
```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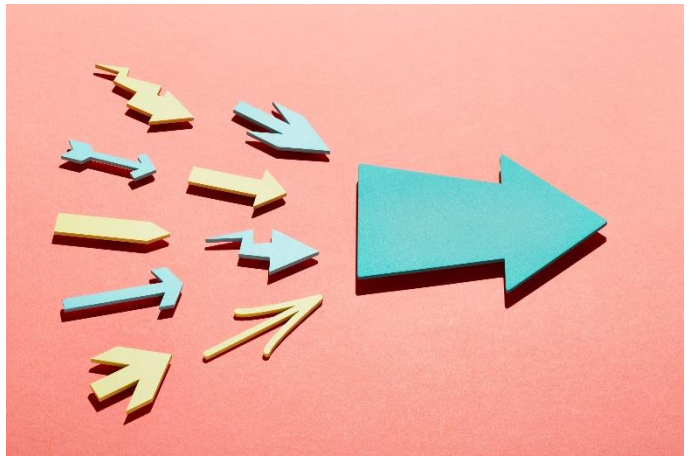
Example: Convert to ONNX

Use the appropriate converting library:

- sklearn-onnx: converts models from scikit-learn,
- tf2onnx: converts models from tensorflow,
- onnxmltools: converts models from lightgbm, xgboost, pyspark, libsvm
- torch.onnx: converts model from pytorch.



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Altering C++ source code - Detailed example

interface.json

model.onnx

```
> mlfmu codegen
```

```
class ModelFmu : public OnnxFmu {
    public :
        ModelFmu(cppfmu::FMIString fmuResourceLocation) : OnnxFmu(fmuResourceLocation) {} private:
};
```

```
> mlfmu compile
```

model.fmu

```
class ModelFmu : public OnnxFmu
{
public:
    ModelFmu(cppfmu::FMIString fmuResourceLocation)
        : OnnxFmu(fmuResourceLocation)
    { }

    bool DoStep(cppfmu::FMIReal currentCommunicationPoint, cppfmu::FMIReal dt, cppfmu::FMIBoolean newStep,
        cppfmu::FMIReal& endOfStep) override
    {
        // Modify the inputs or parameters before the onnx model is run

        // Get the values needed for modification
        const cppfmu::FMIReal values[1] = {0.0};
        const cppfmu::FMIValueReference value_references[1] = {0};
        GetReal(value_references, 1, values);

        // Modify the values as needed

        // Set the modified values
        SetReal(value_references, 1, values);

        bool onnxDoStepSuccess = OnnxFmu::DoStep(currentCommunicationPoint, dt, newStep, endOfStep);
        if (!onnxDoStepSuccess) {
            return false;
        }

        // Modify the outputs or states after the onnx model is run

        // Get the values needed for modification
        const cppfmu::FMIValueReference output_value_references[1] = {1};
        cppfmu::FMIReal output_values[1] = {0.0};
        GetReal(output_value_references, 1, output_values);

        // Modify the values as needed

        // Set the modified values
        SetReal(output_value_references, 1, output_values);

        // Complete the modification by saving any changes to the states as well
        SetOnnxStates();

        return true;
    }

private:
};
```


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