

A digital twin method for automated behavior analysis of large-scale distributed lot systems

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An initiative of industry, academia and TNO



Outline

Challenge

Digital twin method

Use-case

Conclusions

Example Lighting System Behavior

1. There is no one in the room
2. One of the sensors in the room detects presence
3. As long as presence is detected
4. When presence is no longer detected for T seconds

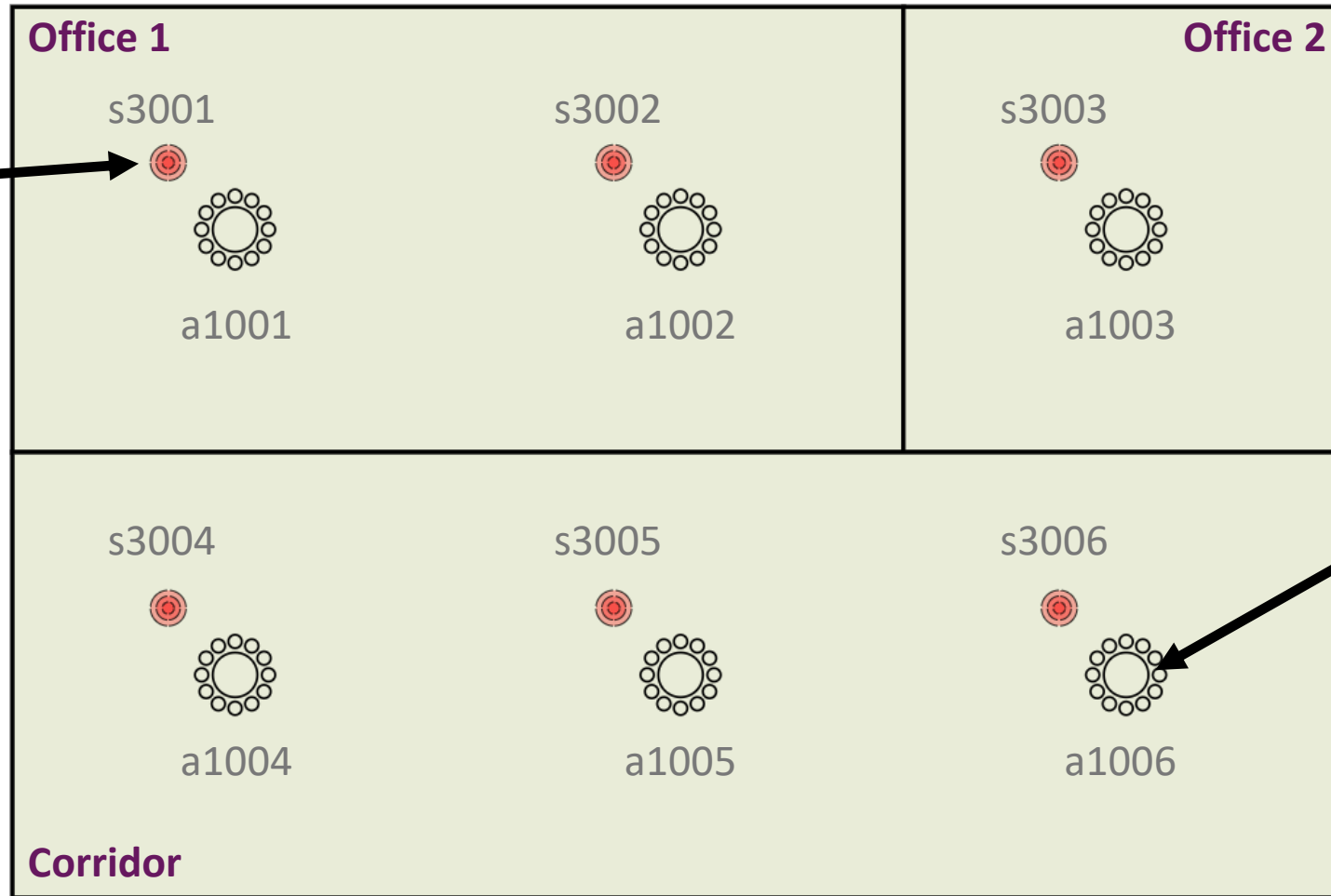


Lights off

Topology of a simple building

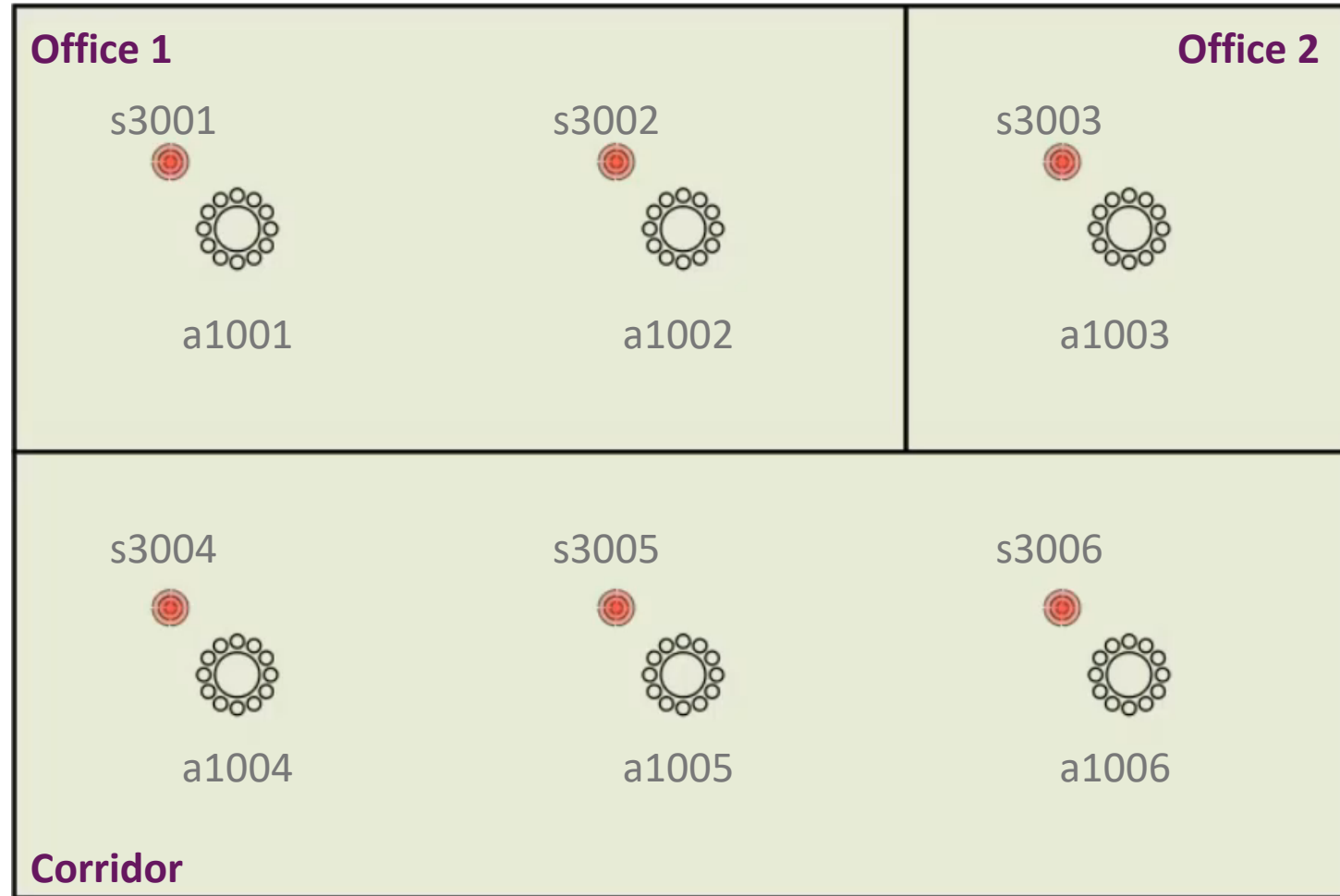
Presence Sensor

red: no presence
green: presence

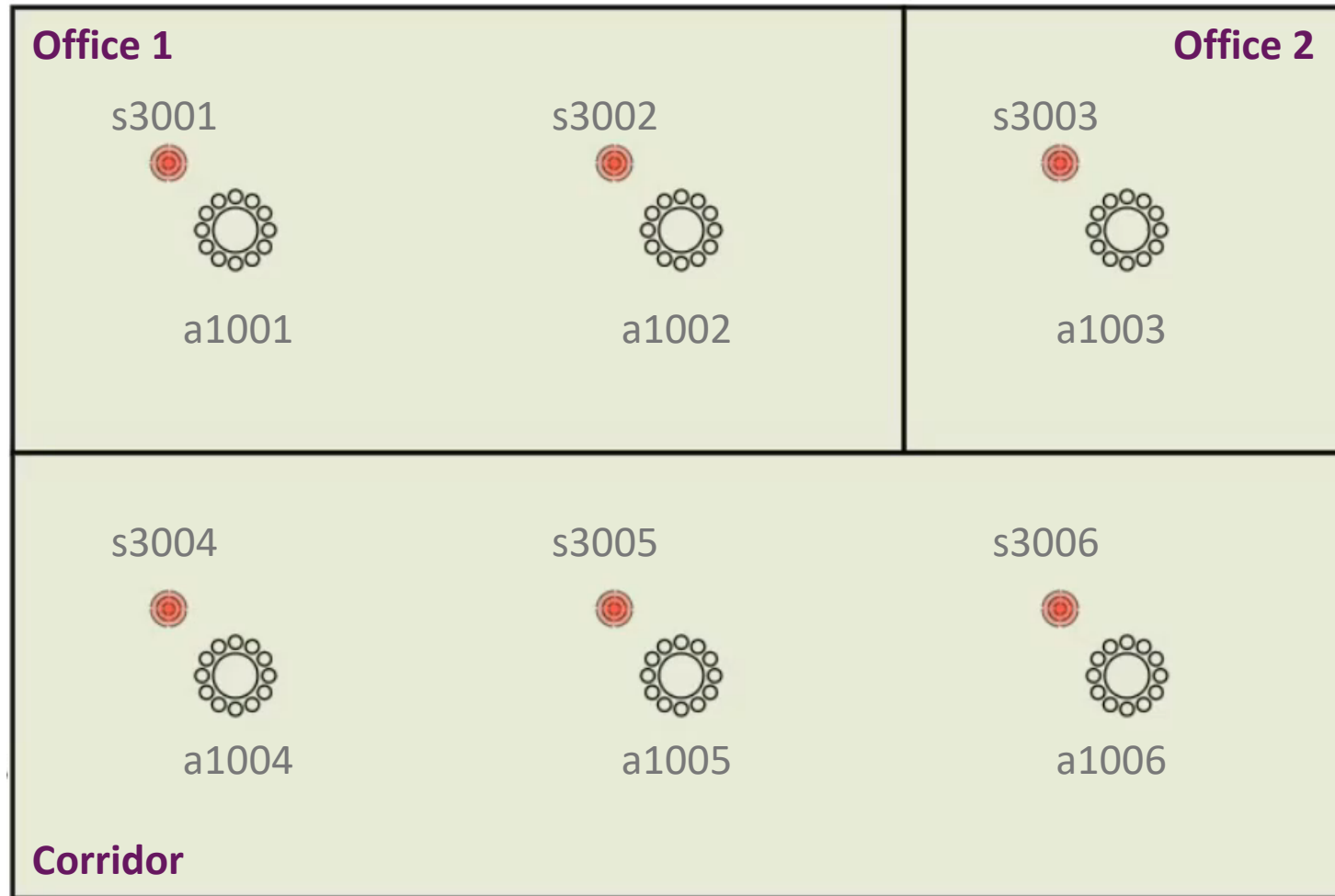


Actuator

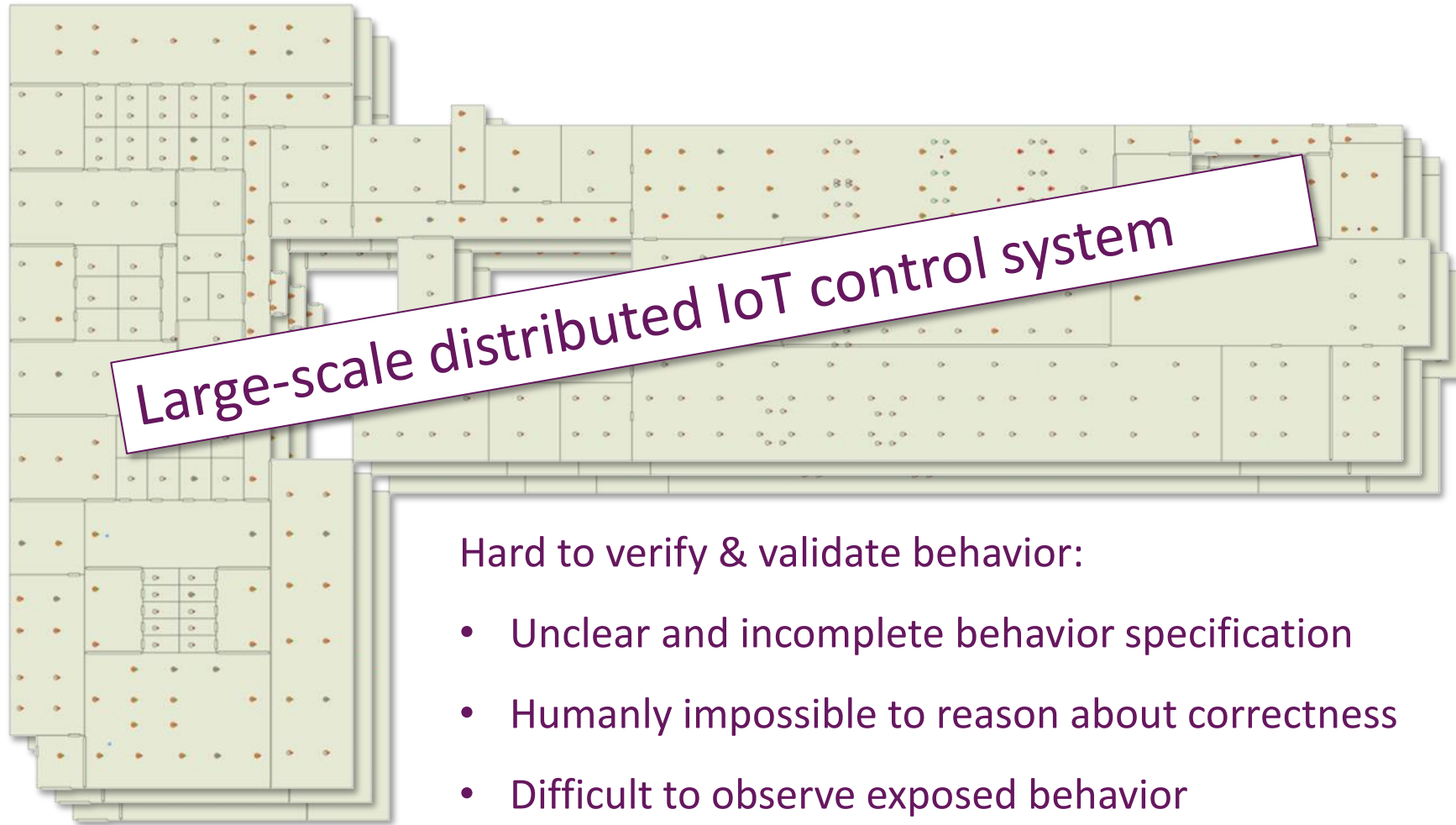
Intended lighting system behavior



Observed lighting system behavior



Topology of a multi-floor building



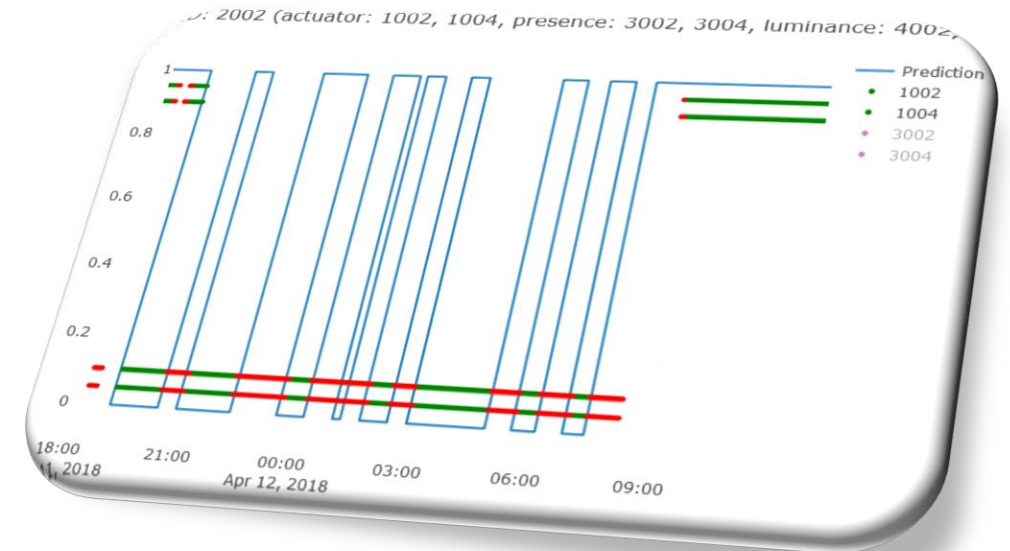
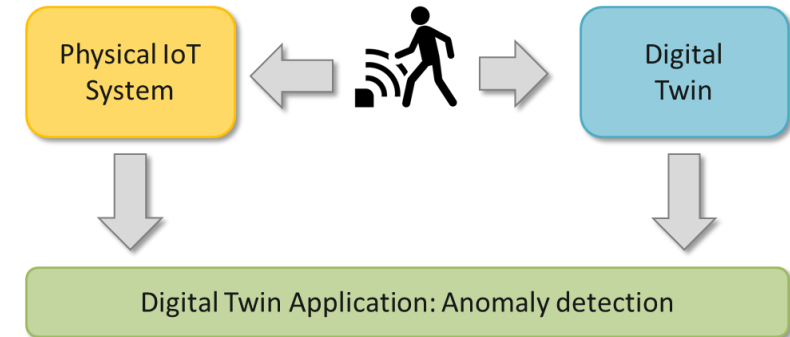
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IoT DSL

Scope

- Distributed control applications
- 1000's of components
- Few component/behaviour types

Out of scope

- Network technology details
- Systems with many unique components/behaviours

What is it used for

Unambiguous/formal specification

- Behaviour
- Topology
- Requirements
- Environment/Scenario

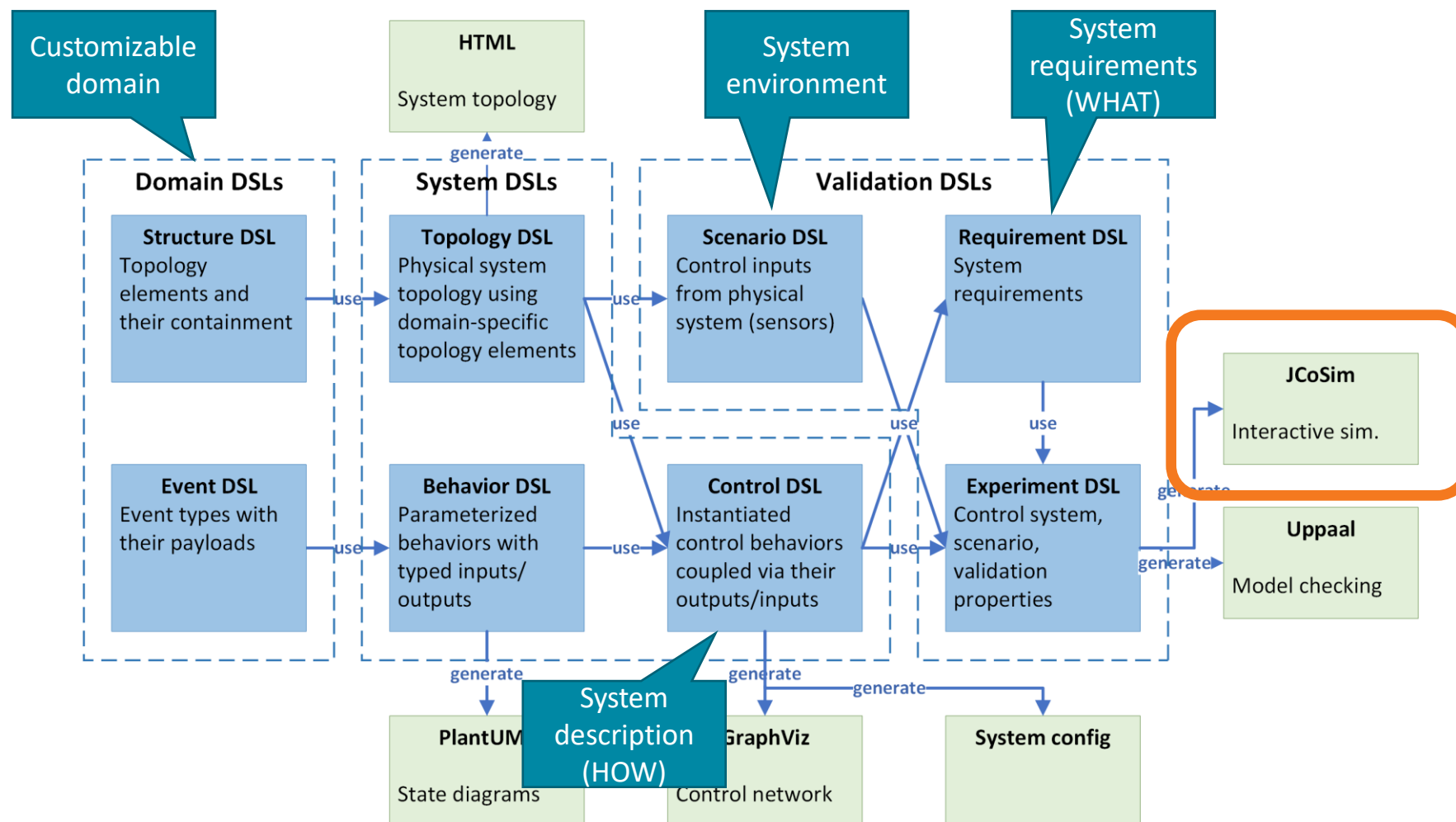
Static Validation:
Specification checking
while specifying

System Analysis

- Behaviour
- Performance
- Root Cause Analysis (Digital Twin)

Dynamic Validation:
Requirement checking using
Simulation
Model checking

IoT DSL: Modular system specification



Example: Event DSL

Events SimpleBuilding
Types

```
// Occupancy event (0 = Vacant, 1 = Occupied)
EventType Occupancy (Integer isOccupied range [ 0, 1 ])

// Light level signal (0-100%)
EventType LightLevel (Integer level range [ 0, 100 ])
```

Example: Structure DSL

Structures SimpleBuilding
Types

StructureType Building contains Floor

StructureType Floor contains Room

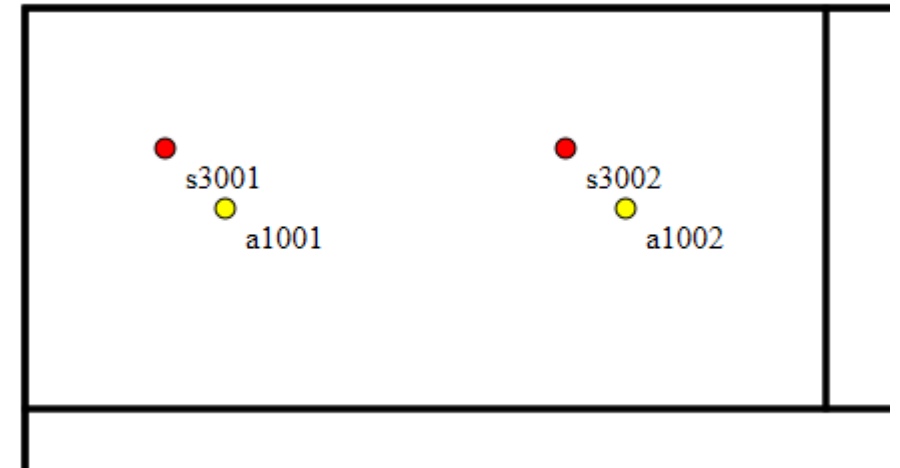
StructureType Room

Example: Topology DSL

```

Topology SimpleBuilding.Building SimpleBuilding
{
    Perimeter ( (0, 0) - (600,0) - (600,400) - (0,400) )
    Sensors
    Actuators
    Structures
        Topology SimpleBuilding.Floor Floor1 {
            Perimeter ( (0,0) - (600,0) - (600,400) - (0,400) )
            Sensors
            Actuators
            Structures
                Topology SimpleBuilding.Room Office1 {
                    Perimeter ( (0,0) - (400,0) - (400,200) - (0,200) )
                    Sensors
                        Sensor s3001 Type SimpleBuilding.OccupancyDetected Coordinates (70,70)
                        Sensor s3002 Type SimpleBuilding.OccupancyDetected Coordinates (270,70)
                    Actuators
                        Actuator a1001 Type SimpleBuilding.SetOutputLevel Coordinates (100,100)
                        Actuator a1002 Type SimpleBuilding.SetOutputLevel Coordinates (300,100)
                    Structures
                }
                Topology SimpleBuilding.Room Office2 {
                    Perimeter ( (400,0) - (600,0) - (600,200) - (400,200) )
                    Sensors
                        Sensor s3003 Type SimpleBuilding.OccupancyDetected Coordinates (470,70)
                    Actuators
                        Actuator a1003 Type SimpleBuilding.SetOutputLevel Coordinates (500,100)
                    Structures
                }
            }
        }
    }
}

```



Example: Behavior DSL

Transitions

```

Transition // Off2On
Source Off
Trigger Input OfficeSensors SimpleBuilding.OccupancyDetected( isOccupied )
Condition isOccupied = 1
Destination On
Updates
Resets
Events
    Output OfficeLuminaires SimpleBuilding.SetOutputLevel( LevelOn )
  
```

```

Transition // On2Hold
Source On
Trigger Input OfficeSensors SimpleBuilding.OccupancyDetected( isOccupied )
Condition isOccupied = 0
Destination Hold
Updates
Resets OfficeSensorsOccupancyTimer
Events
  
```

```

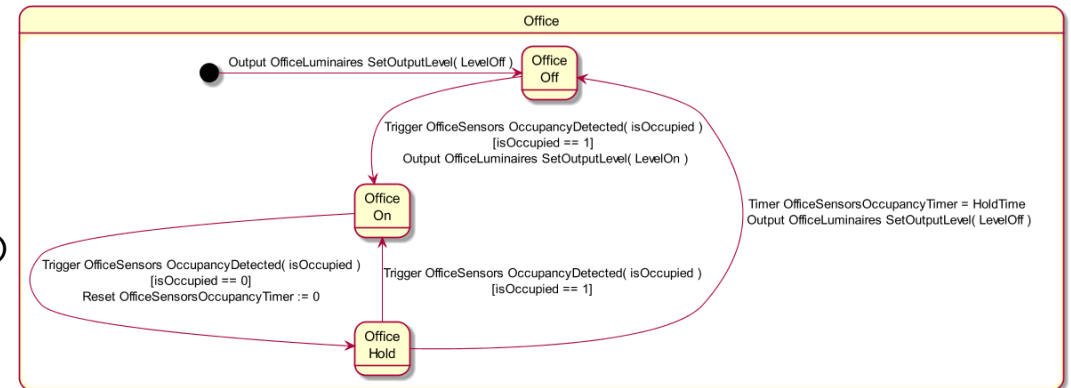
Transition // Hold2On
Source Hold
Trigger Input OfficeSensors SimpleBuilding.OccupancyDetected( isOccupied )
Condition isOccupied = 1
Destination On
Updates
Resets
Events
  
```

```

Transition // Hold2Off
  
```

```

...
  
```



Example: Control DSL

ControlSystem SimpleBuilding
Topology SimpleBuilding

Controllers

Controller ctrlOffice1

Behavior Office

Parameters

Controller ctrlOffice2

Behavior Office

Parameters

Controller ctrlCorridor

Behavior Office

Parameters

Network

Edge SimpleBuilding.OccupancyDetected: SimpleBuilding.Floor1.Office1.s3001 -> ctrlOffice1 Office.OfficeSensors

Edge SimpleBuilding.OccupancyDetected: SimpleBuilding.Floor1.Office1.s3002 -> ctrlOffice1 Office.OfficeSensors

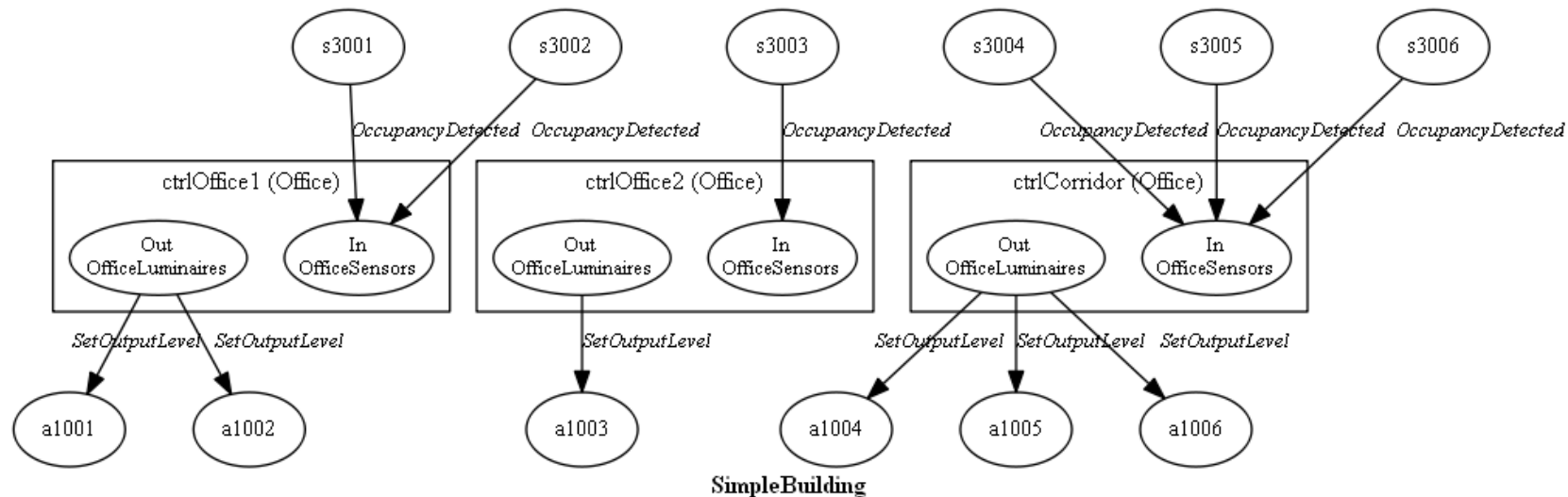
Edge SimpleBuilding.SetOutputLevel: ctrlOffice1 Office.OfficeLuminaires -> SimpleBuilding.Floor1.Office1.a1001

Edge SimpleBuilding.SetOutputLevel: ctrlOffice1 Office.OfficeLuminaires -> SimpleBuilding.Floor1.Office1.a1002

Edge SimpleBuilding.OccupancyDetected: SimpleBuilding.Floor1.Office2.s3003 -> ctrlOffice2 Office.OfficeSensors

Edge SimpleBuilding.SetOutputLevel: ctrlOffice2 Office.OfficeLuminaires -> SimpleBuilding.Floor1.Office2.a1003

...

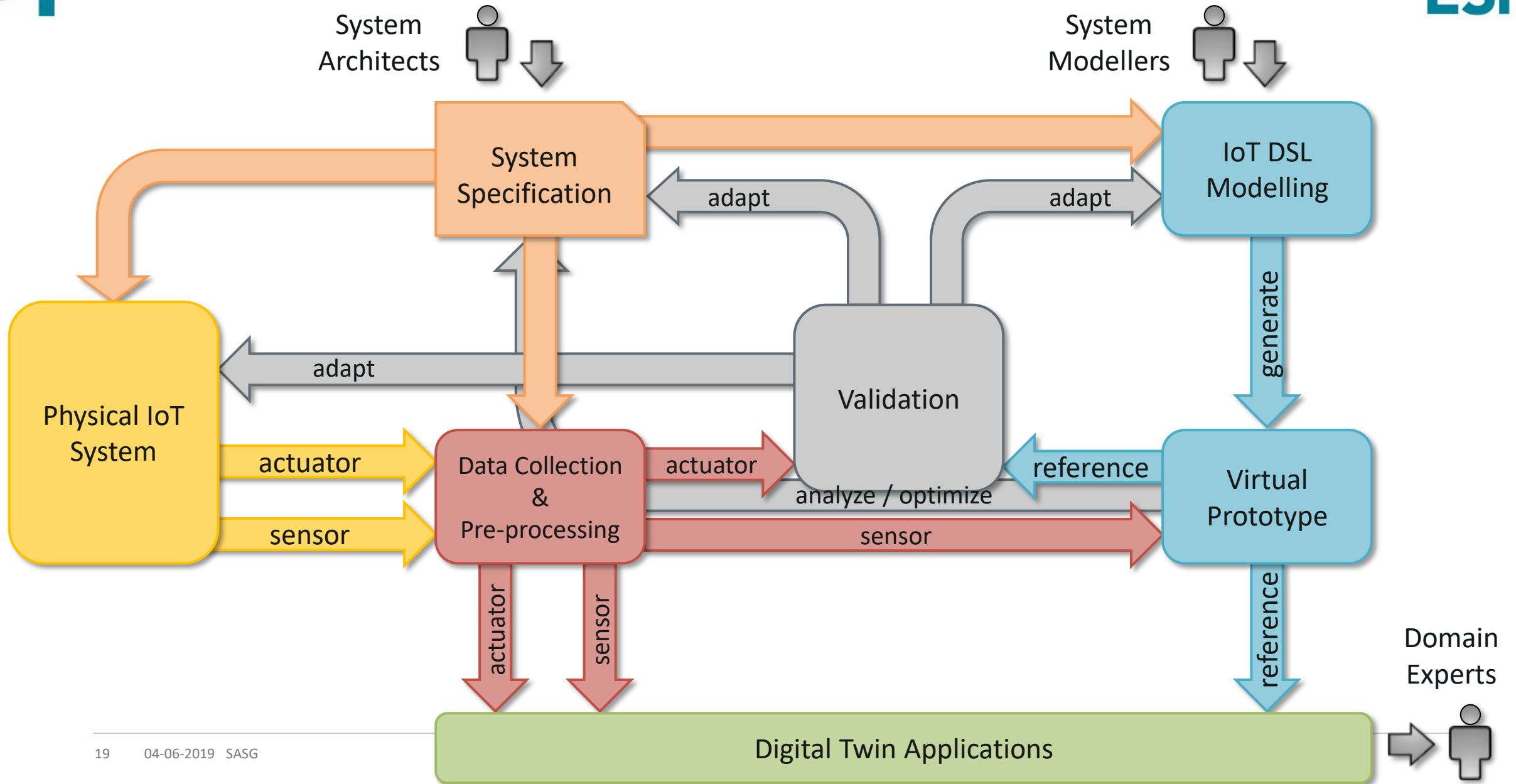


Example: Scenario DSL

```
Scenario SimpleBuilding
Topology SimpleBuilding
Sensor SimpleBuilding.Floor1.Office1.s3001
    Time 10 seconds SimpleBuilding.OccupancyDetected( 1 )
    Time 1000 seconds SimpleBuilding.OccupancyDetected( 0 )
Sensor SimpleBuilding.Floor1.Corridor.s3004
    Time 600 seconds SimpleBuilding.OccupancyDetected( 1 )
    Time 800 seconds SimpleBuilding.OccupancyDetected( 0 )
```

Example: Experiment DSL

Experiment SimpleBuilding
System SimpleBuilding
Scenario SimpleBuilding



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OpenAIS Smart Lighting Case

Witte Dame building

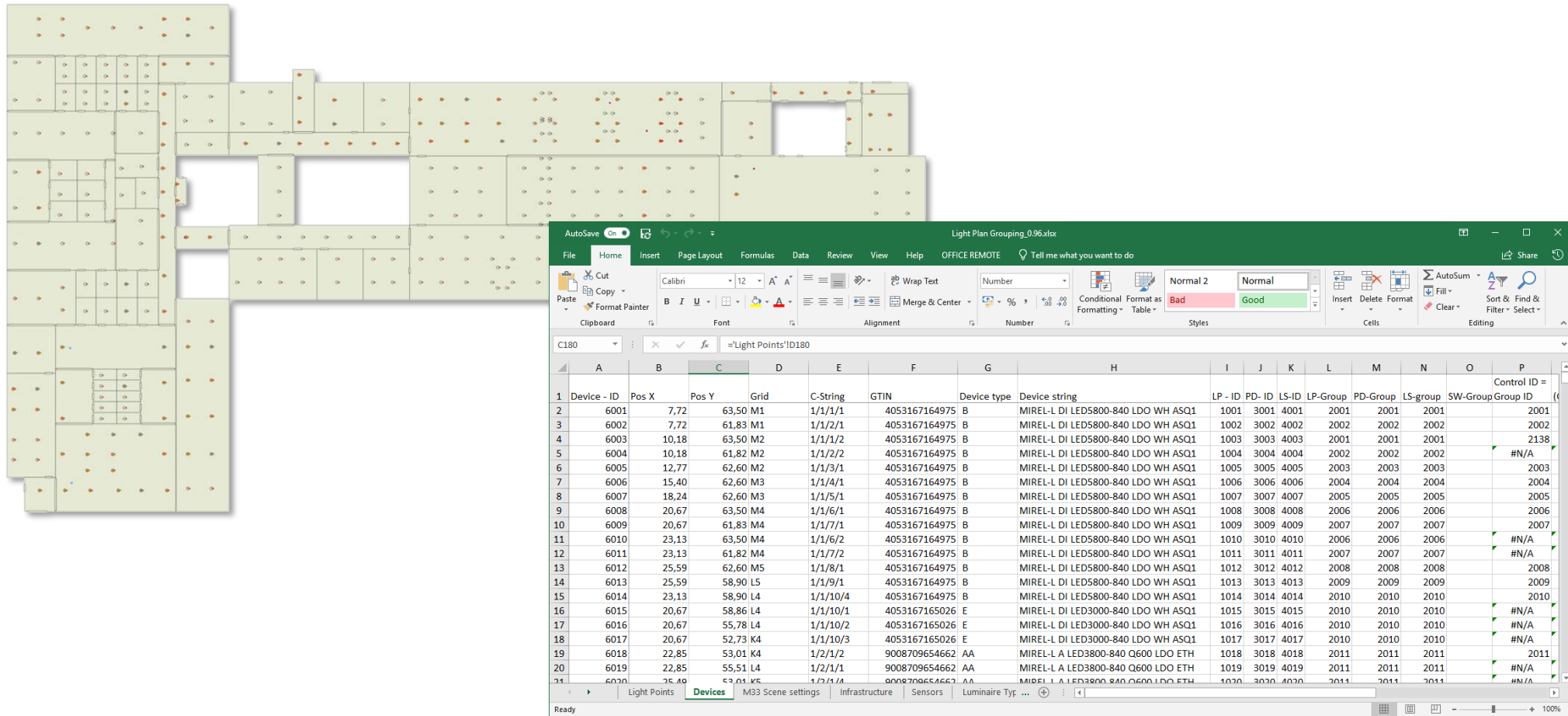
- Landmark historical building
- Former lighting factory

Smart lighting system

- Complete 5th floor
- 367 light points
- More than 1,300 devices
- 12 behavior types



OpenAIS lighting system specification



IoT DSL modelling

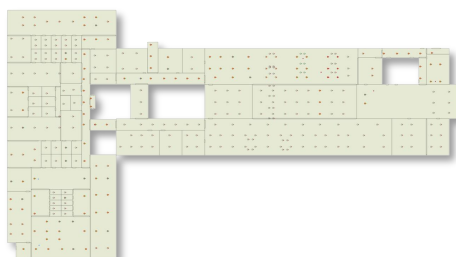
Manual

Event model

Structure model

Behavior model

System specification



Generate

Generated

Topology model

Generate

Virtual
prototype

Generate

Control model

Device ID	Pos X	Pos Y	Grid	C-String	GTN	Device type	Device string	IP ID	PD ID	LS ID	IP-Group	PD-Group	LS-Group	SW-Group	Group ID
6001	7.72	63.50	M1	1/1/1/1	4053167164975	B	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1001	1001	1001	2001	2001	2001	2001	2001
6002	7.72	61.83	M1	1/1/2/1	4053167164975	B	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1002	1002	1002	2002	2002	2002	2002	2002
6003	10.18	63.50	M2	1/1/1/2	4053167164975	B	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1003	1003	1003	2003	2003	2003	2003	2118
6004	10.18	61.82	M2	1/1/2/2	4053167164975	B	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1004	1004	1004	2002	2002	2002	2002	2002
6005	12.77	62.60	M2	1/1/3/1	4053167164975	B	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1005	1005	1005	2003	2003	2003	2003	2003
6006	15.40	62.60	M3	1/1/4/1	4053167164975	B	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1006	1006	1006	2004	2004	2004	2004	2004
6007	18.24	62.60	M3	1/1/5/1	4053167164975	B	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1007	1007	1007	2005	2005	2005	2005	2005
6008	20.67	63.50	M4	1/1/6/1	4053167164975	B	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1008	1008	1008	2006	2006	2006	2006	2006
6009	20.67	61.83	M4	1/1/7/1	4053167164975	B	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1009	1009	1009	2007	2007	2007	2007	2007
6010	23.13	63.50	M4	1/1/8/2	4053167164975	B	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1010	1010	1010	2006	2006	2006	2006	2006
6011	23.13	61.83	M4	1/1/9/2	4053167164975	B	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1011	1011	1011	2007	2007	2007	2007	2007
6012	25.59	62.60	M5	1/1/8/1	4053167164975	B	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1012	1012	1012	2008	2008	2008	2008	2008
6013	25.59	58.90	L3	1/1/9/1	4053167164975	B	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1013	1013	1013	2009	2009	2009	2009	2009
6014	28.13	58.90	L4	1/1/10/4	4053167164975	B	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1014	1014	1014	2010	2010	2010	2010	2010
6015	20.67	58.96	L4	1/1/10/1	4053167165026	F	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1015	1015	1015	2010	2010	2010	2010	2010
6016	20.67	55.78	L4	1/1/10/2	4053167165026	F	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1016	1016	1016	2010	2010	2010	2010	2010
6017	20.67	52.73	K4	1/1/10/3	4053167165026	F	MIRELL-DI-LED5800-840-LOO-WH-A0G3	1017	1017	1017	2010	2010	2010	2010	2010
6018	22.85	55.01	K4	1/1/1/1	9008708054662	AA	MIRELL-A-LED5800-840-0600-LOO-ETH	1018	1018	1018	2011	2011	2011	2011	2011
6019	22.85	55.51	L4	1/1/1/1	9008708054662	AA	MIRELL-A-LED5800-840-0600-LOO-ETH	1019	1019	1019	2011	2011	2011	2011	2011
6020	25.40	55.51	L4	1/1/1/1	9008708054662	AA	MIRELL-A-LED5800-840-0600-LOO-ETH	1020	1020	1020	2011	2011	2011	2011	2011

Errors revealed using static and dynamic validation

Light Plan Grouping_0.96.xlsx

File Home Insert Page Layout Formulas Data Review View Help OFFICE REMOTE Tell me what you want to do

Clipboard Font Alignment Number Styles Cells Editing

Wrong device position

Wrong behavior assignment

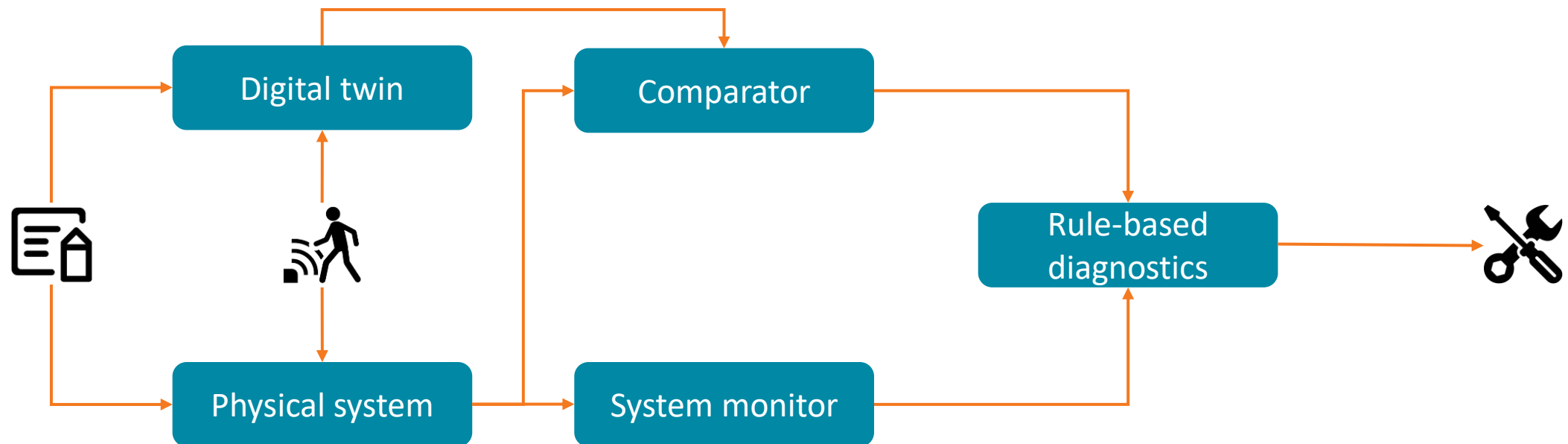
Duplicate device names

Wrong group assignment

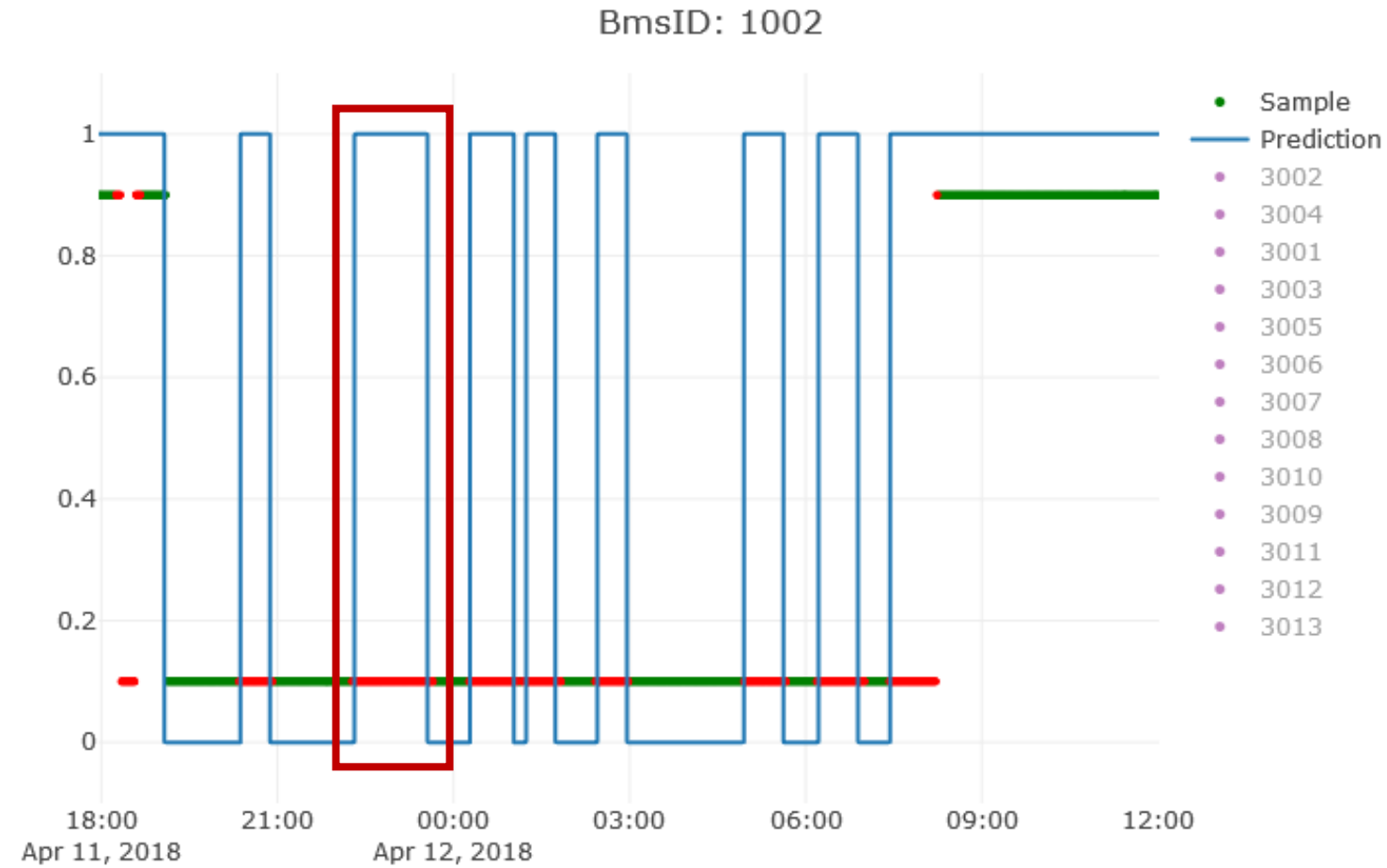
Device - ID	Pos X	Pos Y	Grid	C-String	GTIN	Device type	Device string	LP - ID	PD - ID	LS	Control ID =	Group Group ID
6001	7,72	63,50	M1	1/1/1/1	4053167164975	B	MIREL-L DI LED5800-840 LDO WH ASQ1	1001	3001	4001	2001	2001
6002	7,72	61,83	M1	1/1/2/1	4053167164975	B	MIREL-L DI LED5800-840 LDO WH ASQ1	1002	3002	4002	2002	2002
6003	10,18	63,50	M2	1/1/1/2	4053167164975	B	MIREL-L DI LED5800-840 LDO WH ASQ1	1003	3003	4003	2001	2001
6004	10,18	61,82	M2	1/1/2/2	4053167164975	B	MIREL-L DI LED5800-840 LDO WH ASQ1	1004	3004	4004	2002	2002
6005	12,77	62,60	M2	1/1/3/1	4053167164975	B	MIREL-L DI LED5800-840 LDO WH ASQ1	1005	3005	4005	2003	2003
6006	15,40	62,60	M3	1/1/4/1	4053167164975	B	MIREL-L DI LED5800-840 LDO WH ASQ1	1006	3006	4006	2004	2004
6007	18,24	62,60	M3	1/1/5/1	4053167164975	B	MIREL-L DI LED5800-840 LDO WH ASQ1	1007	3007	4007	2005	2005
6008	20,67	63,50	M4	1/1/6/1	4053167164975	B	MIREL-L DI LED5800-840 LDO WH ASQ1	1008	3008	4008	2006	2006
6009	20,67	61,83	M4	1/1/7/1	4053167164975	B	MIREL-L DI LED5800-840 LDO WH ASQ1	1009	3009	4009	2007	2007
6010	23,13	63,50	M4	1/1/6/2	4053167164975	B	MIREL-L DI LED5800-840 LDO WH ASQ1	1010	3010	4010	2006	2006
6011	23,13	61,83	M4	1/1/7/2	4053167164975	B	MIREL-L DI LED5800-840 LDO WH ASQ1	1011	3011	4011	2007	2007
6012	23,13	62,60	M5	1/1/8/1	4053167164975	B	MIREL-L DI LED5800-840 LDO WH ASQ1	1012	3012	4012	2008	2008
6013	23,13	63,50	L5	1/1/9/1	4053167164975	B	MIREL-L DI LED5800-840 LDO WH ASQ1	1013	3013	4013	2009	2009
6014	23,13	58,90	L4	1/1/10/4	4053167164975	B	MIREL-L DI LED5800-840 LDO WH ASQ1	1014	3014	4014	2010	2010
6015	20,67	58,86	L4	1/1/10/1	4053167165026	E	MIREL-L DI LED3000-840 LDO WH ASQ1	1015	3015	4015	2010	2010
6016	20,67	55,78	L4	1/1/10/2	4053167165026	E	MIREL-L DI LED3000-840 LDO WH ASQ1	1016	3016	4016	2010	2010
6017	20,67	52,73	K4	1/1/10/3	4053167165026	E	MIREL-L DI LED3000-840 LDO WH ASQ1	1017	3017	4017	2010	2010
6018	22,85	53,01	K4	1/2/1/2	9008709654662	AA	MIREL-L A LED3800-840 Q600 LDO ETH	1018	3018	4018	2011	2011
6019	22,85	55,51	L4	1/2/1/1	9008709654662	AA	MIREL-L A LED3800-840 Q600 LDO ETH	1019	3019	4019	2011	2011
6020	25,40	53,01	K5	1/2/1/4	9008709654662	AA	MIREL-L A LED3800-840 Q600 LDO ETH	1020	3020	4020	2011	2011

Light Points Devices M33 Scene settings Infrastructure Sensors Luminaire Typ ...

Root Cause Analysis for Smart Lighting



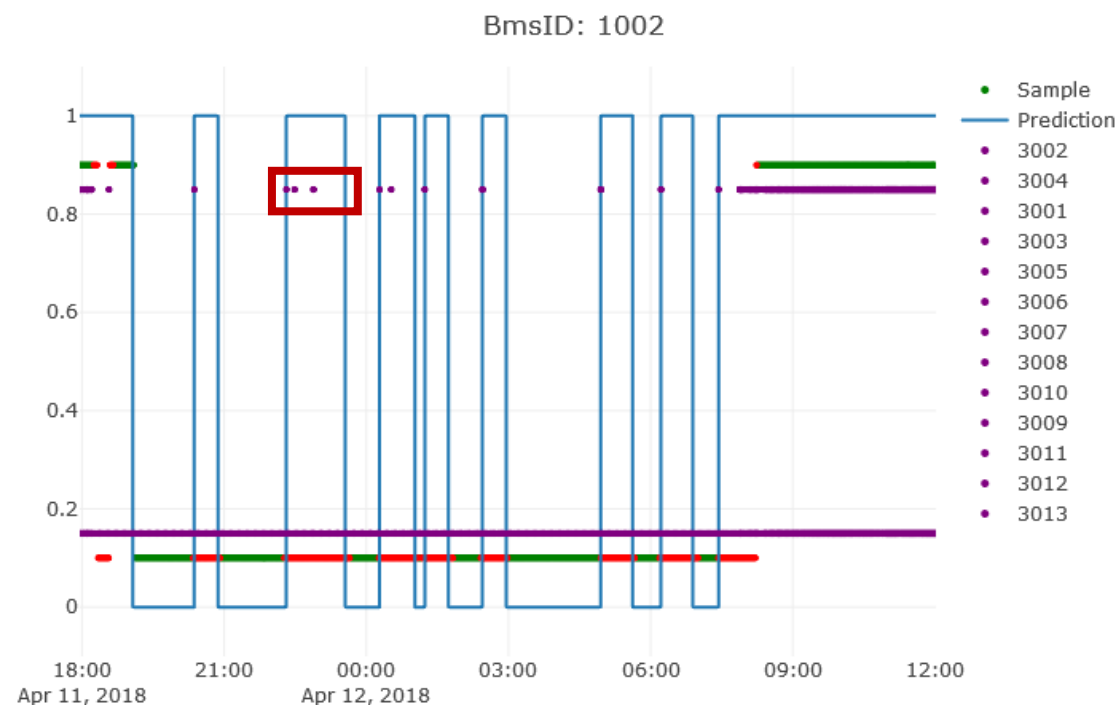
Anomaly detection





Diagnostics: Rule 1

1	Correctness of digital twin behavior	Is a sensor in the group reporting occupancy?	2	3	Is the digital twin behaving correctly?
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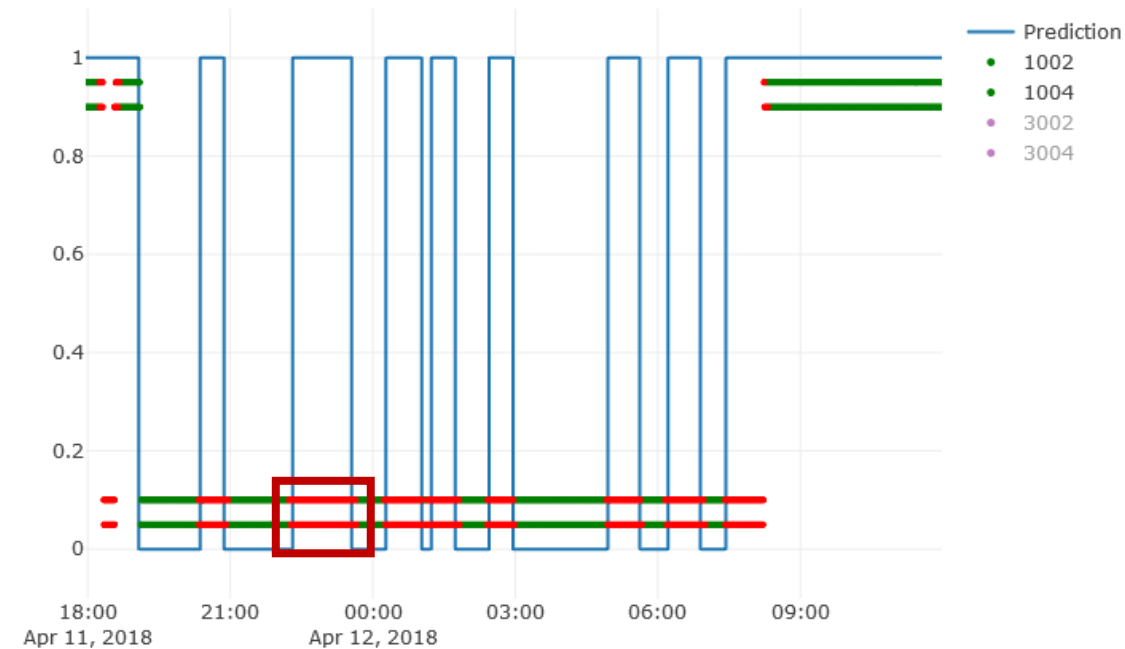




Diagnostics: Rule 2

2	Group problem	Do other light points in the same group behave identically?	4	5	Is it an individual or group problem?
---	---------------	---	---	---	---------------------------------------

cupID: 2002 (actuator: 1002, 1004, presence: 3002, 3004, luminance: 4002, 4004)





Diagnostics: Rule 3

4	Commissioning error	Have all behaviors of group 2002 been commissioned?	5		Commissioning error
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Method applicable to a broad range of distributed IoT systems

- Many components
- Few behaviors

IoT DSL model used as the core of the virtual system

Aspects to transform virtual prototype into digital twin

Method successfully applied to a real-life use-case

QUESTIONS