Process Model to Predict Nondeterministic Behavior of IoT Systems

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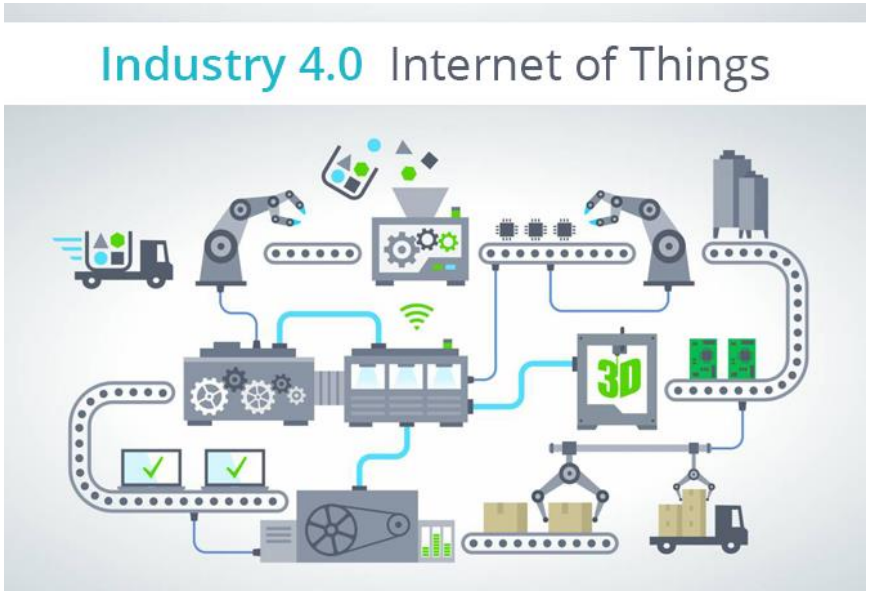
Contents

1. Overview

Internet of Things

- Definition
  - Network of physical devices, vehicles, buildings and other items that enable these objects to collect and exchange data[1]
- Applications
  - Media
  - Healthcare systems
  - Industry 4.0
  - …
- Challenges
  - Safety
  - Security
  - Correctness
  - Complex dependencies
  - Cyber-Physical-Systems
- Requirements
  - Specification
  - Verification



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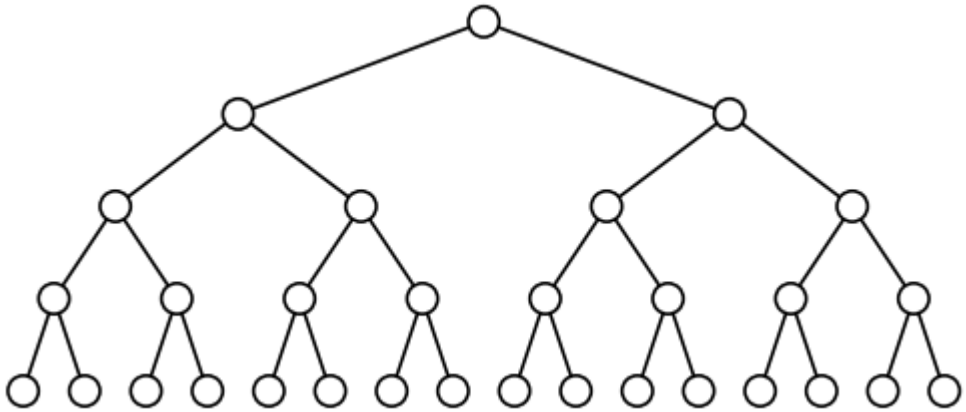
1 https://en.wikipedia.org/wiki/Internet_of_things
2 https://www.mobinius.com/industry-4-0-iot/

Motivation

- Probability in IoT
  - Nondeterministic behavior of each devices
    - Complex
    - Non-predictable
  - Analysis and design are difficult



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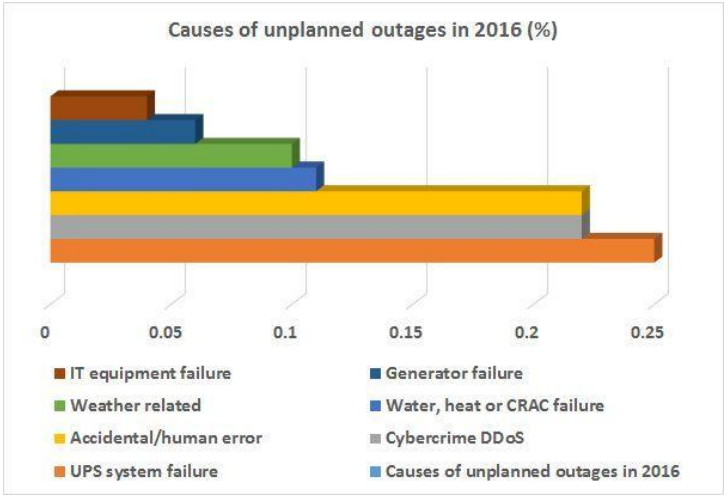
1 https://www.acmicpc.net/problem/13405

Motivation

- Probability in IoT
  - Probability
    - In design step, statistics data is used
      - Error occurred
      - Route selection
    - Probability is used to analyze
      - Risk management
      - Behavior prediction



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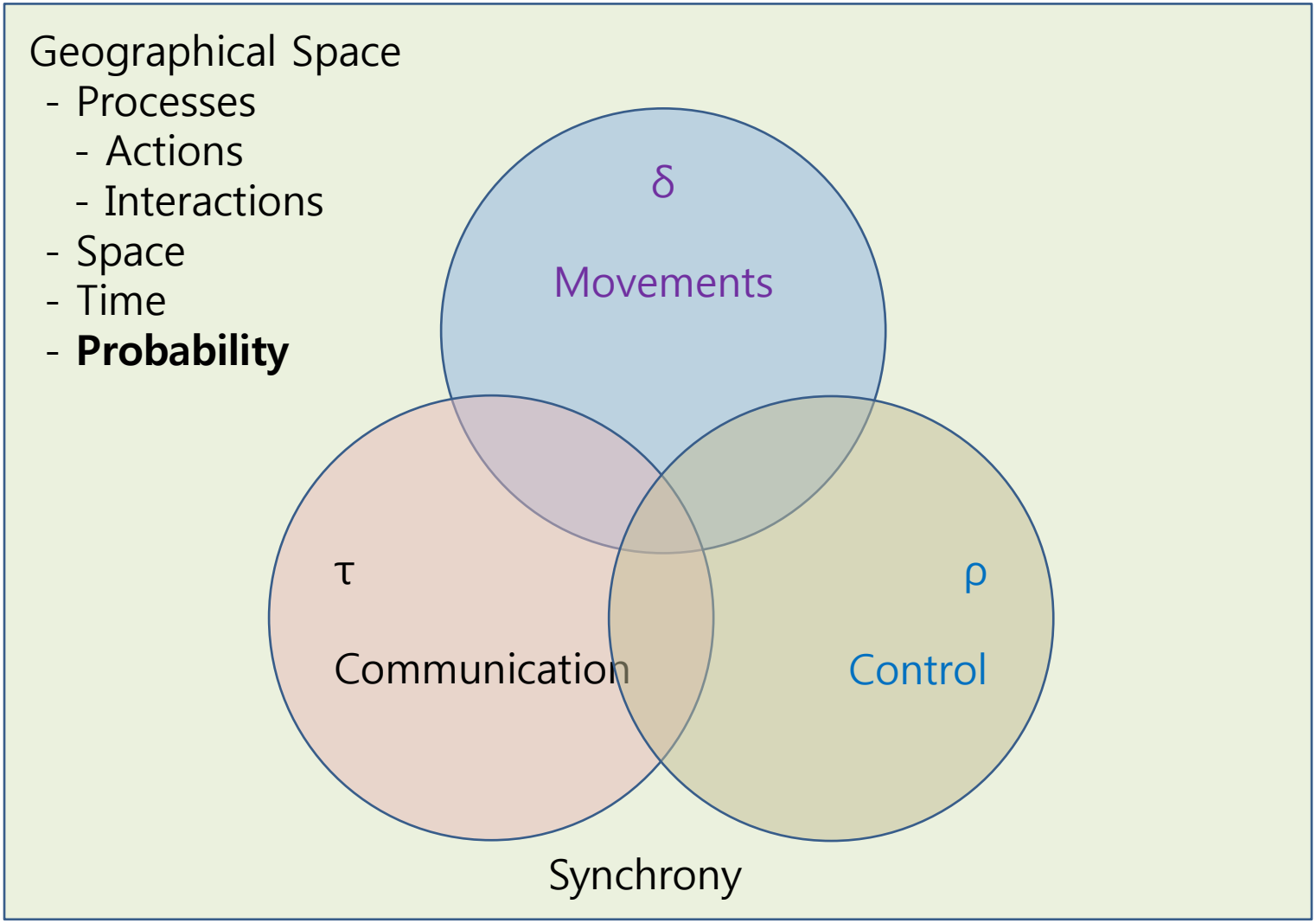
1 https://blog.storagecraft.com/business-continuity-statistics-tech/

Approach

- Process algebra
  - Specify IoT systems
  - Analyze IoT systems
  - Specify probability density function
  - Probabilistic analysis

2. dTP-Calculus

dTP-Calculus



Syntax

$P ::= A$	Action
$\mid A^{p,n}_{[r,to,e,d]}$	Timed action
$\mid P^{p,n}_{[r,to,e,d]}$	Timed process
$\mid P_{(n)}$	Priority
$\mid P[Q]$	Nesting
$\mid P\langle r \rangle$	Channel
$\mid P + Q$	Choice
$\mid P\{c\} +_F Q\{c\}$	Probabilistic choice
$\mid P \parallel Q$	Parallel
$\mid P \backslash \mathrm{E}$	Exception
$\mid A \cdot P$	Sequence
$F ::= D$	Discrete distribution
$\mid N(\mu, \sigma)$	Normal distribution
$\mid E(\lambda)$	Exponential distribution
$\mid U(l, u)$	Uniform distribution

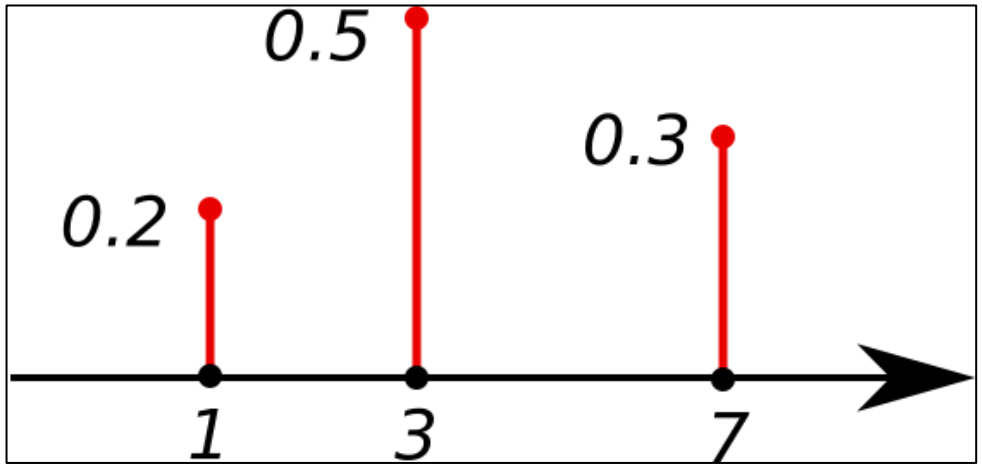
$A ::= \emptyset$	Empty
$\mid r(\overline{msg})$	Send
$\mid r(msg)$	Receive
$\mid M$	Movement action
$\mid C$	Control action
$M ::= m^p(k)\ P$	Movement request
$\mid P\ m(k)$	Movement permission
$m ::= in$	In movement
$\mid out$	Out movement
$\mid get$	Get movement
$\mid put$	Put movement
$C ::= new\ P$	Create process
$\mid kill\ P$	Kill process
$\mid exit$	Exit process

Syntax

- Probability
  - Probabilities specification
    - Discrete distribution
  - Probability density function specification
    - Normal distribution
    - Exponential distribution
    - Uniform distribution

Syntax

- Probabilistic choice
  - Discrete distribution
    - $P\{c\} +_D Q\{c\}$
      - c : Probability
    - Example
      - $P\{0.2\} +_D Q\{0.5\} +_D R\{0.3\}$



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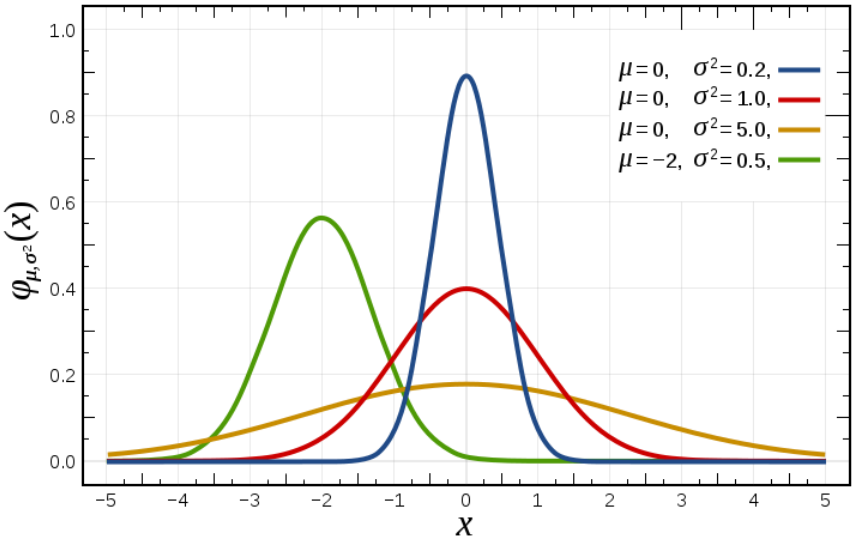
1 https://en.wikipedia.org/wiki/Probability_distribution

Syntax

- Probabilistic choice
  - Normal distribution
    - $P\{c\} +_{N(\mu,\sigma)} Q\{c\}$
      - c : Variable area (Condition)
      - μ : Mean
      - σ : Standard deviation
    - Example
      - $P\{v > 52\} +_{N(50,5)} Q\{v \leq 52\}$



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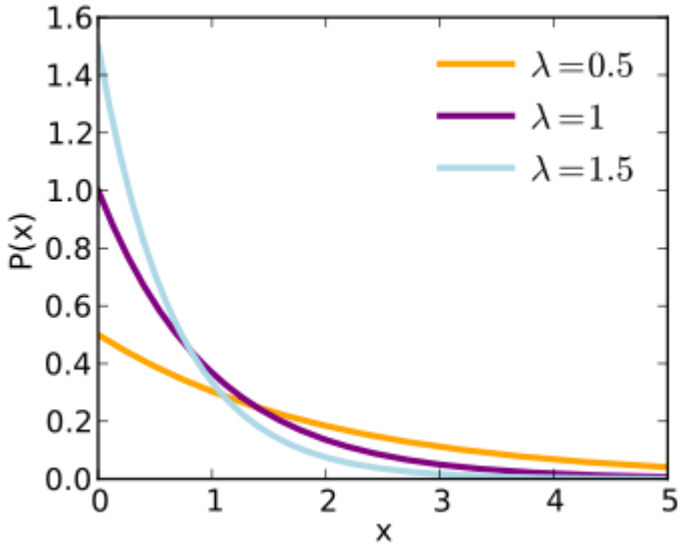
1 https://en.wikipedia.org/wiki/Normal_distribution

Syntax

- Probabilistic choice
  - Exponential distribution
    - $P\{c\} +_{E(\lambda)} Q\{c\}$
      - c : Variable area (Condition)
      - λ : Frequency
    - Example
      - $P\{v > 2.5\} +_{E(0.33)} Q\{v \leq 2.5\}$



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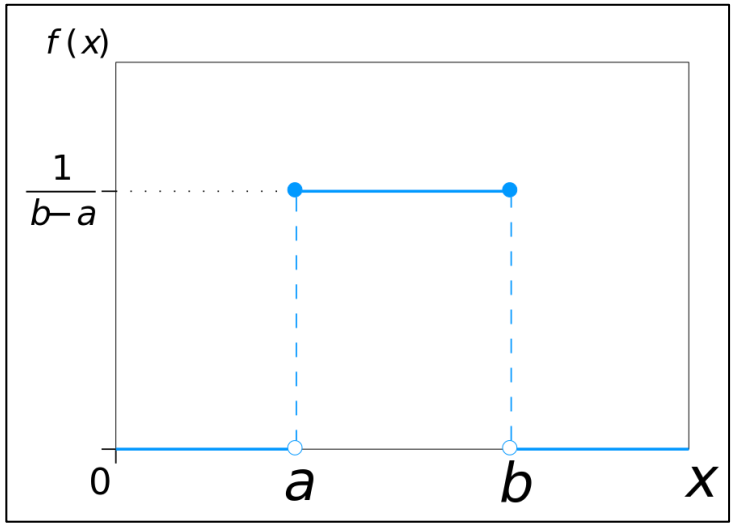
1 https://en.wikipedia.org/wiki/Exponential_distribution

Syntax

- Probabilistic choice
  - Uniform distribution
    - $P\{c\} +_{U(l,u)} Q\{c\}$
      - c : Variable area (Condition)
      - l : Lower bound
      - u : Upper bound
    - Example
      - $P\{v > 5\} +_{U(3,7)} Q\{v \leq 5\}$



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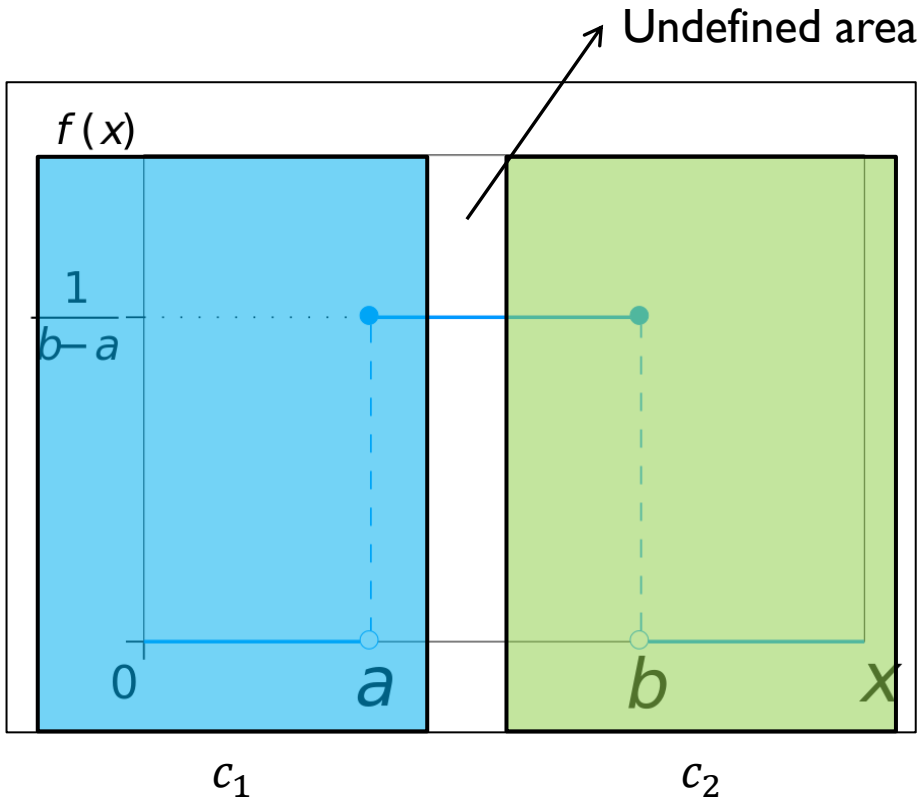
1 https://en.wikipedia.org/wiki/Uniform_distribution_(continuous)

Syntax

- Probabilistic choice
  - Summation of the probabilities should be 1
  - Discrete distribution
    - $P_1\{c_1\} +_D P_2\{c_2\} +_D \cdots +_D P_n\{c_n\}$
      - $\sum_{i=1}^{n} c_i = 1$
  - Normal distribution, uniform distribution
    - $P_1\{c_1\} +_F P_2\{c_2\} +_F \cdots +_F P_n\{c_n\}$
      - $\bigcup_{i=1}^{n} c_i = \mathbb{R}$
      - $\forall i, j \in \{x | x \in \mathbb{N}, 1 \leq x \leq n\}\ then\ c_i \cap c_j = \emptyset\ (for\ i \neq j)$
  - Exponential distribution
    - $P_1\{c_1\} +_F P_2\{c_2\} +_F \cdots +_F P_n\{c_n\}$
      - $\bigcup_{i=1}^{n} c_i = \{x \mid x \geq 0,\ x \in \mathbb{R}\}$
      - $\forall i, j \in \{x | x \in \mathbb{N}, 1 \leq x \leq n\}\ then\ c_i \cap c_j = \emptyset\ (for\ i \neq j)$

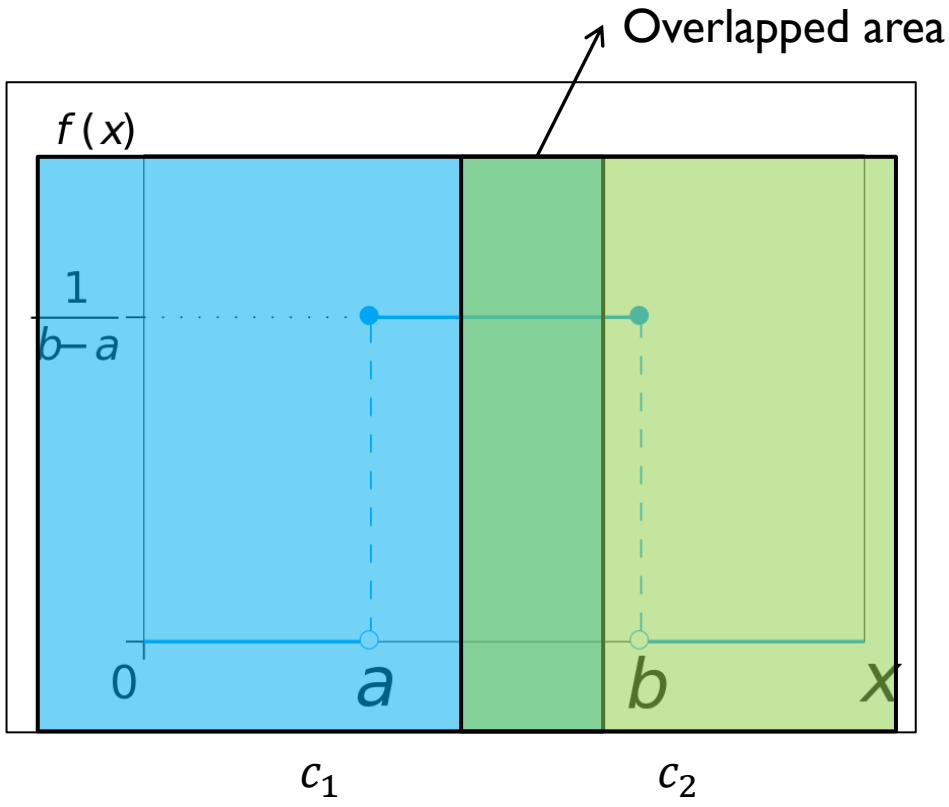
Syntax

- Probabilistic choice
  - Error
    - Summation of the probabilities is less than 1
      - $P\{c_1\} +_F Q\{c_2\}$



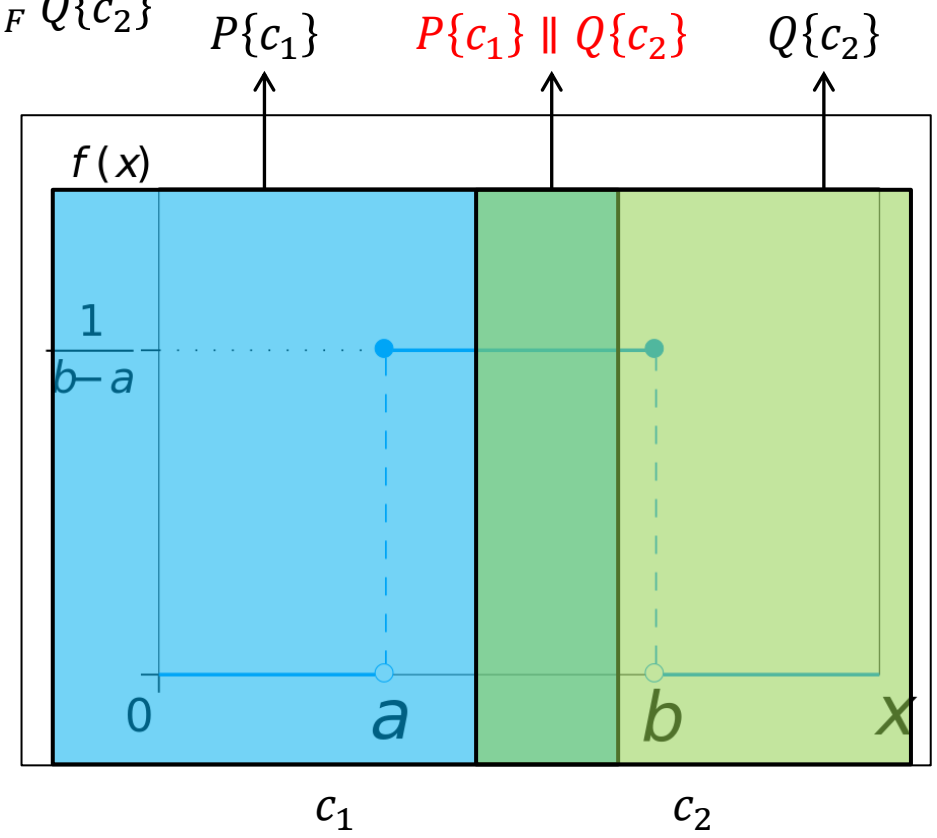
Syntax

- Probabilistic choice
  - Error
    - Summation of the probabilities is greater than 1
      - $P\{c_1\} +_F Q\{c_2\}$



Syntax

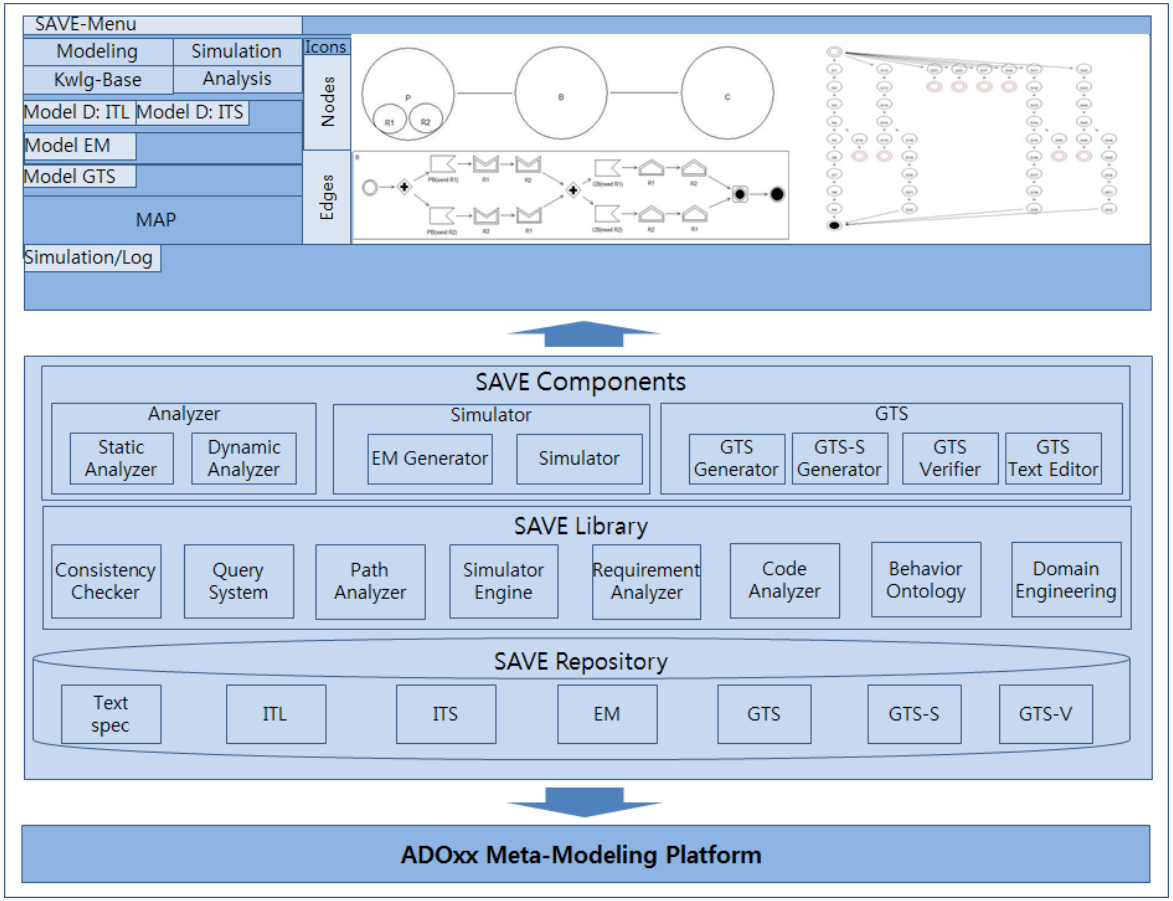
- Probabilistic choice
  - Error
    - Summation of the probabilities is greater than 1
      - $P\{c_1\} +_F Q\{c_2\}$



3. SAVE

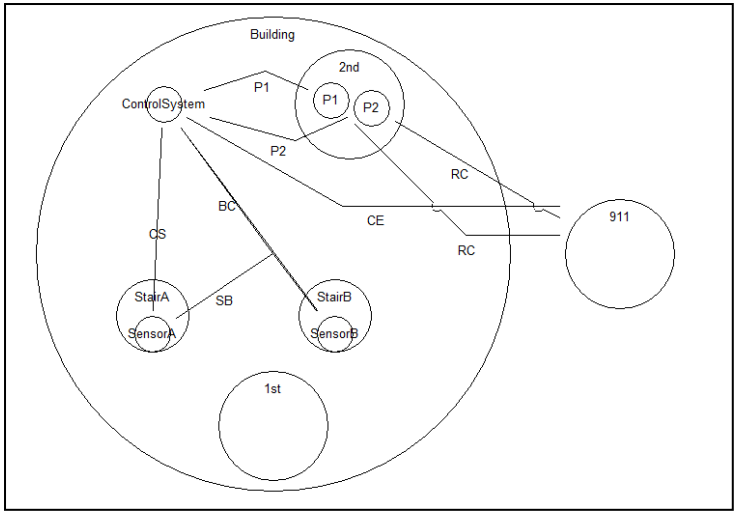
SAVE

- SAVE
  - Specification, Analysis, Verification, and Evaluation
  - Based on ADOxx meta-modeling platform

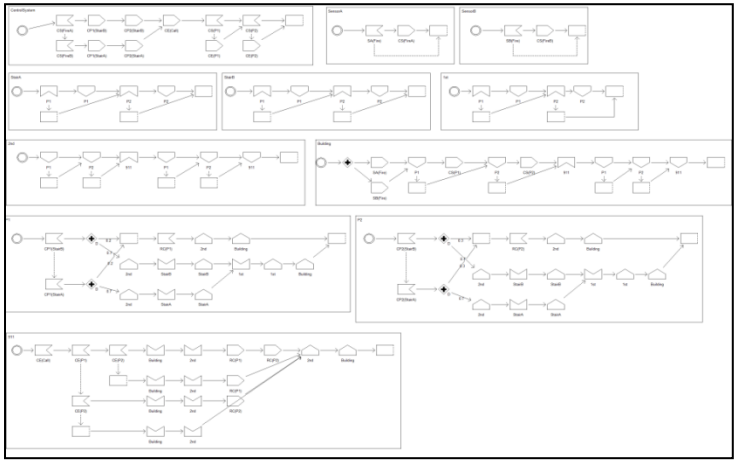


Specification - Visualization

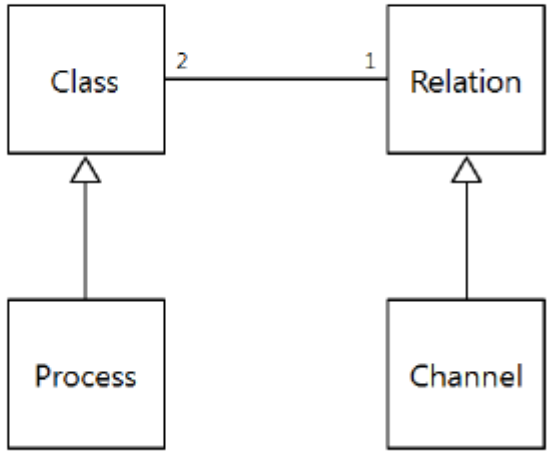
- Graphic language
  - System View
    - In-the-Large (ITL) Model
    - Representation
      - Interactions of each processes



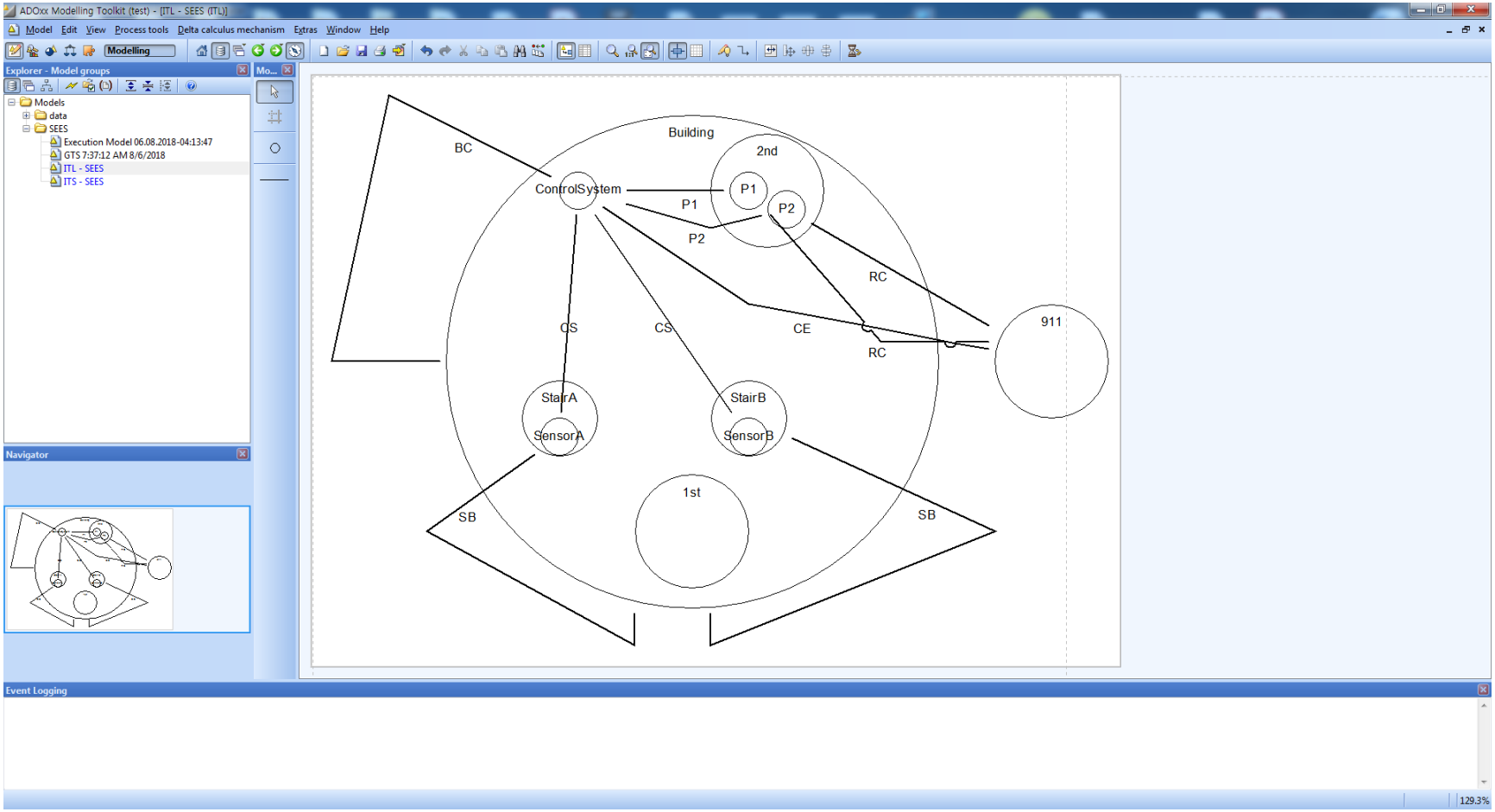
  - Process View
    - In-the-Small (ITS) Model
    - Representation
      - Detailed actions of each processes



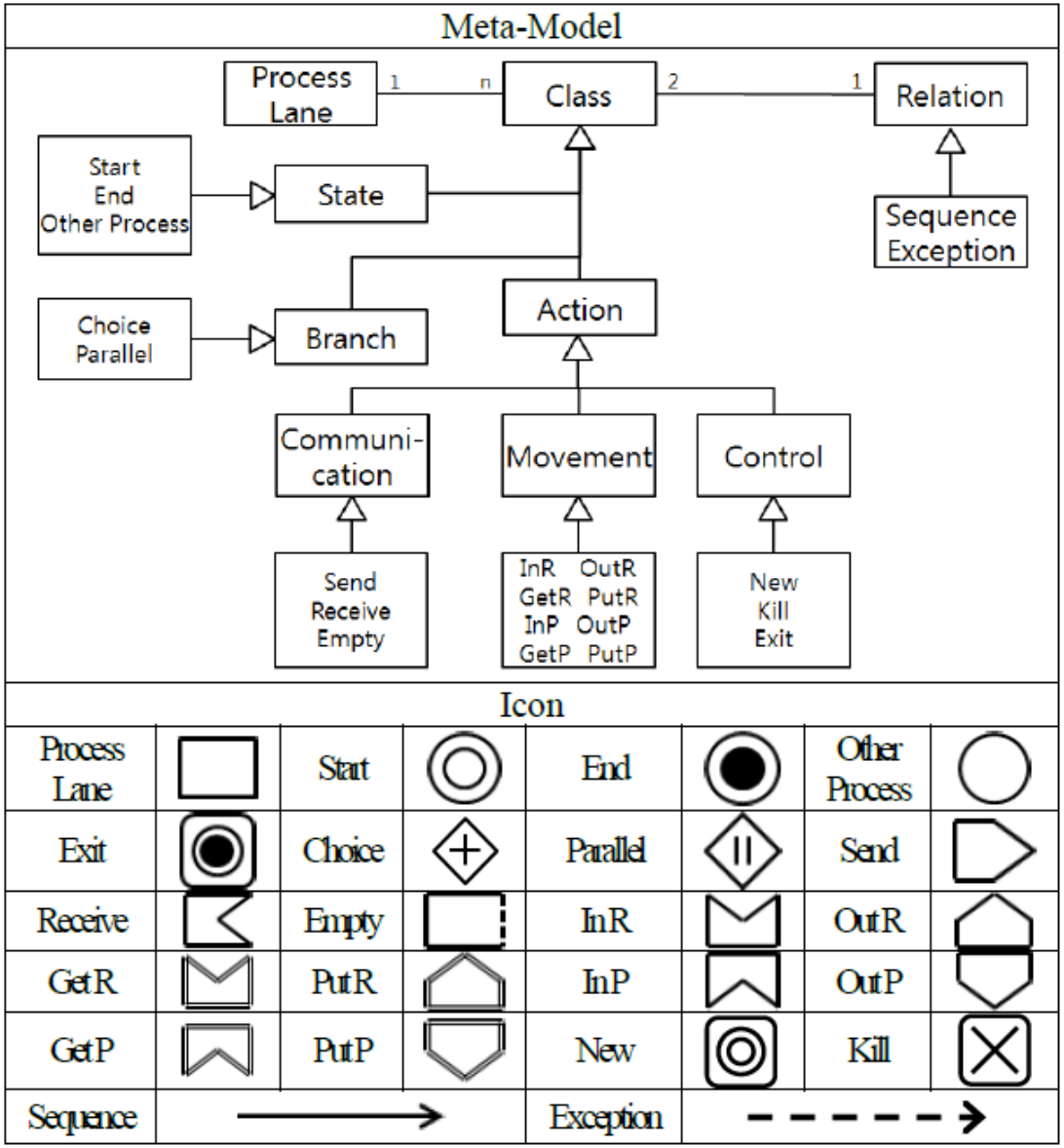
System View

Meta-Model	Icon	
	Process	
	Channel	

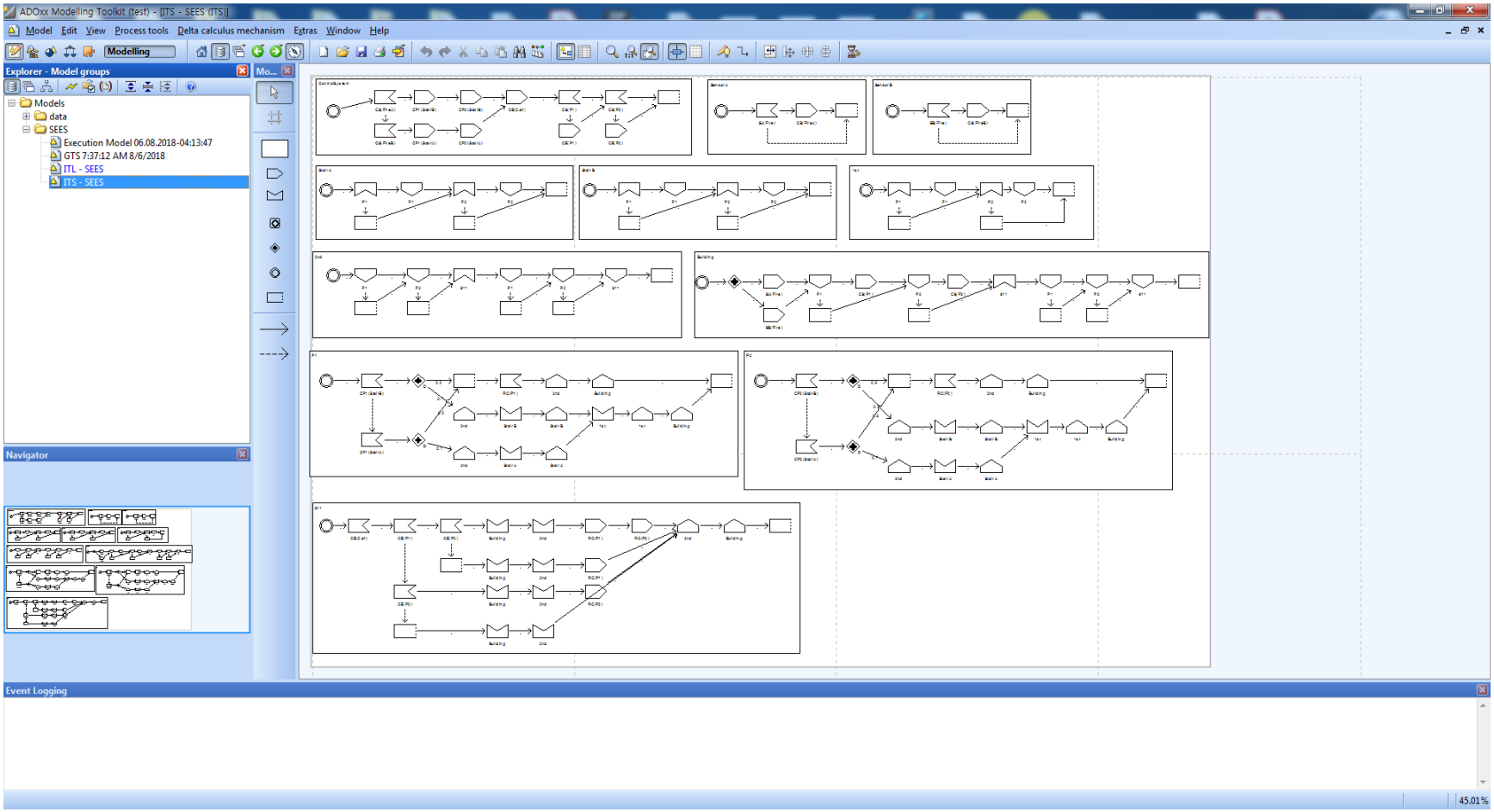
System View


ADOxx Modelling Toolkit (test) - [ITL - SEES (ITL)]
Model Edit View Process tools Delta calculus mechanism Extras Window Help
Modelling
Explorer - Model groups
Models
data
SEES
Execution Model 06.08.2018-04:13:47
GTS 7:37:12 AM 8/6/2018
ITL - SEES
ITS - SEES
Navigator
Building
2nd
BC
ControlSystem
P1
P2
P1
P2
RC
CS
CS
CE
RC
911
StairA
SensorA
StairB
SensorB
1st
SB
SB
Event Logging
129.3%

Process View

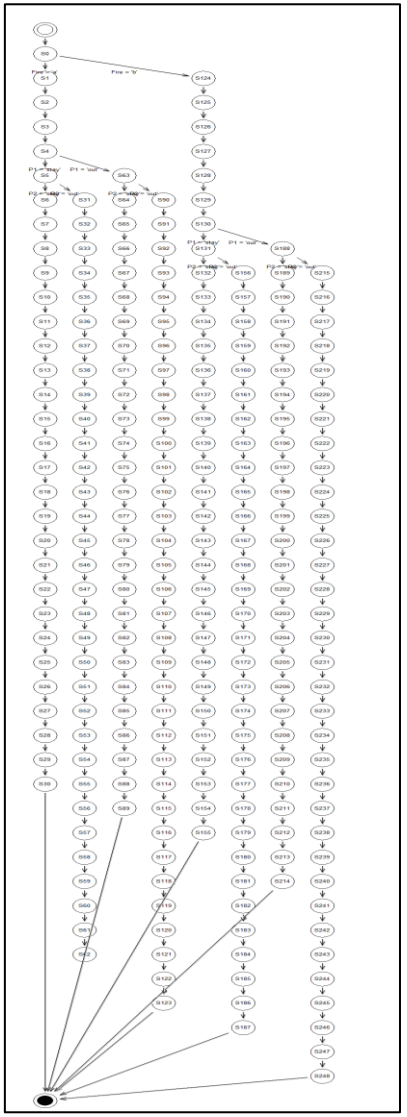


Process View

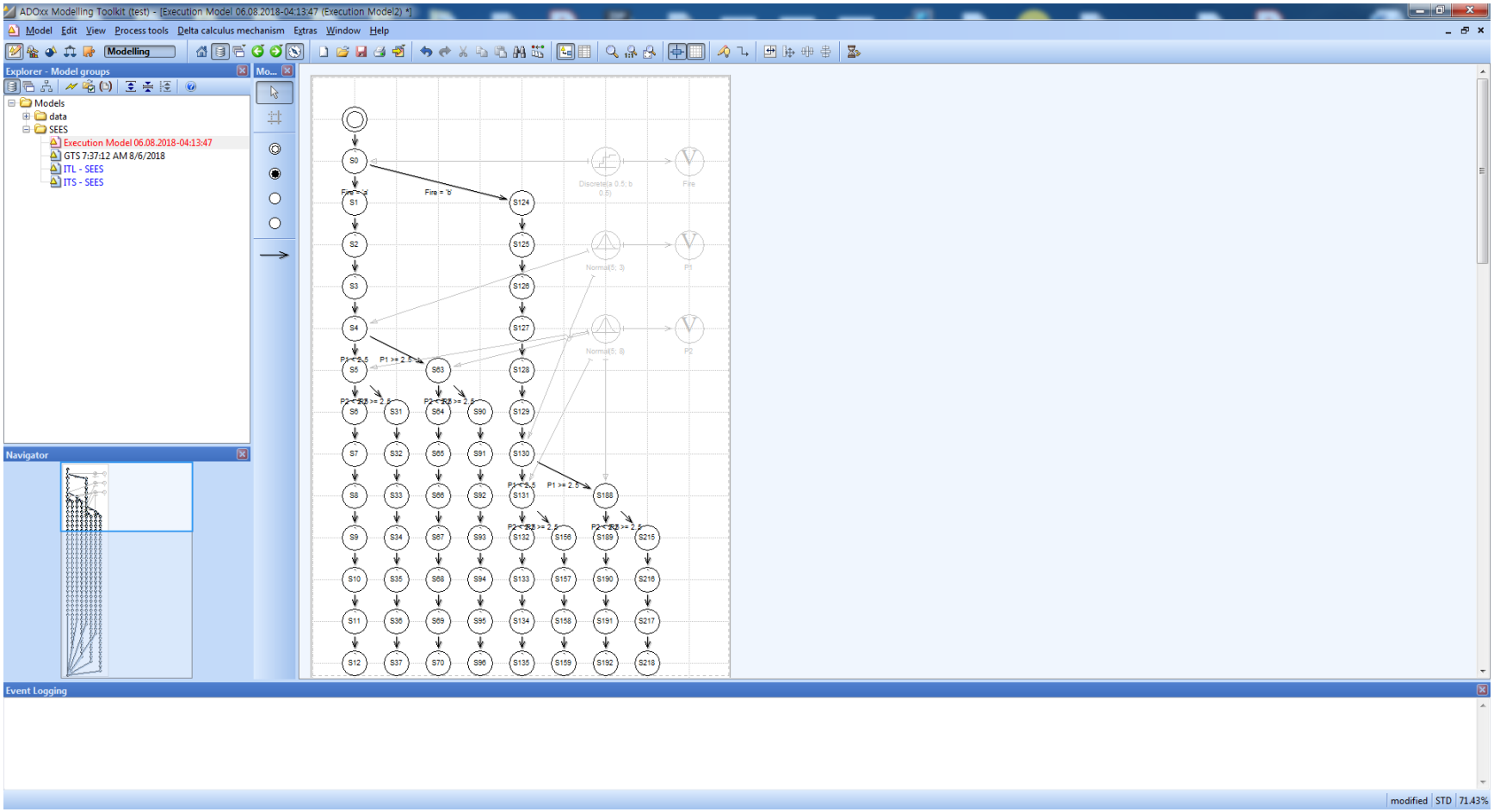


Analysis

- Analysis
  - Path analysis
    - All possible execution path
    - Generate simulation model
  - Simulation
    - Simulate the system based on a path

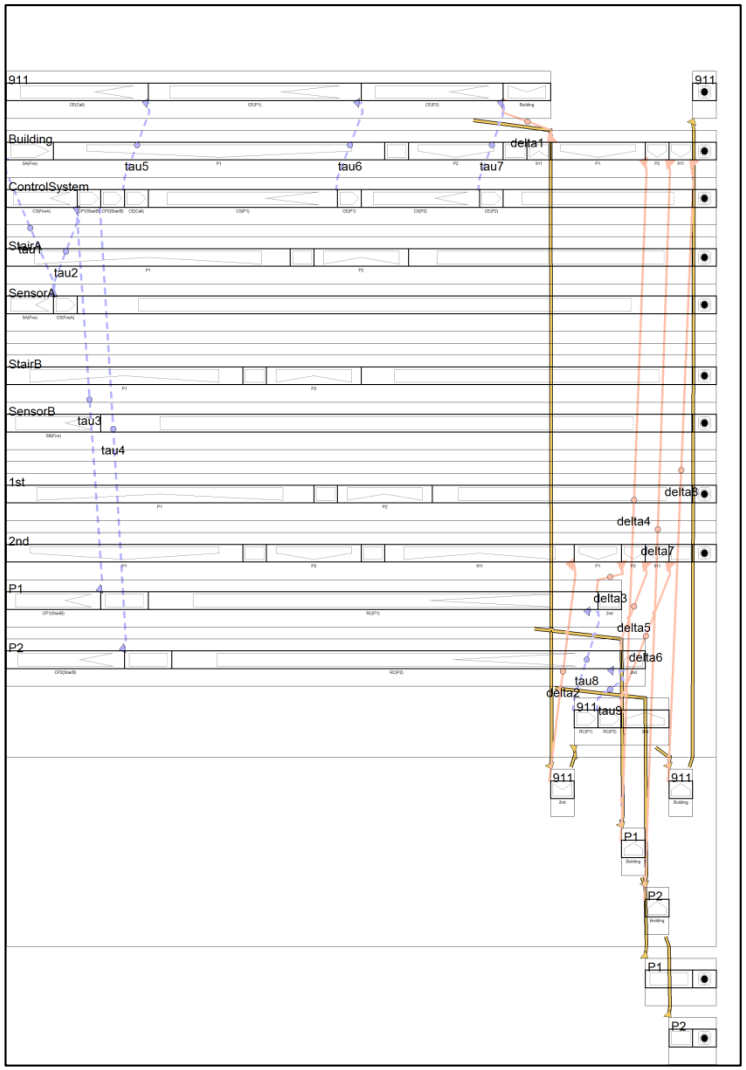


Simulation model

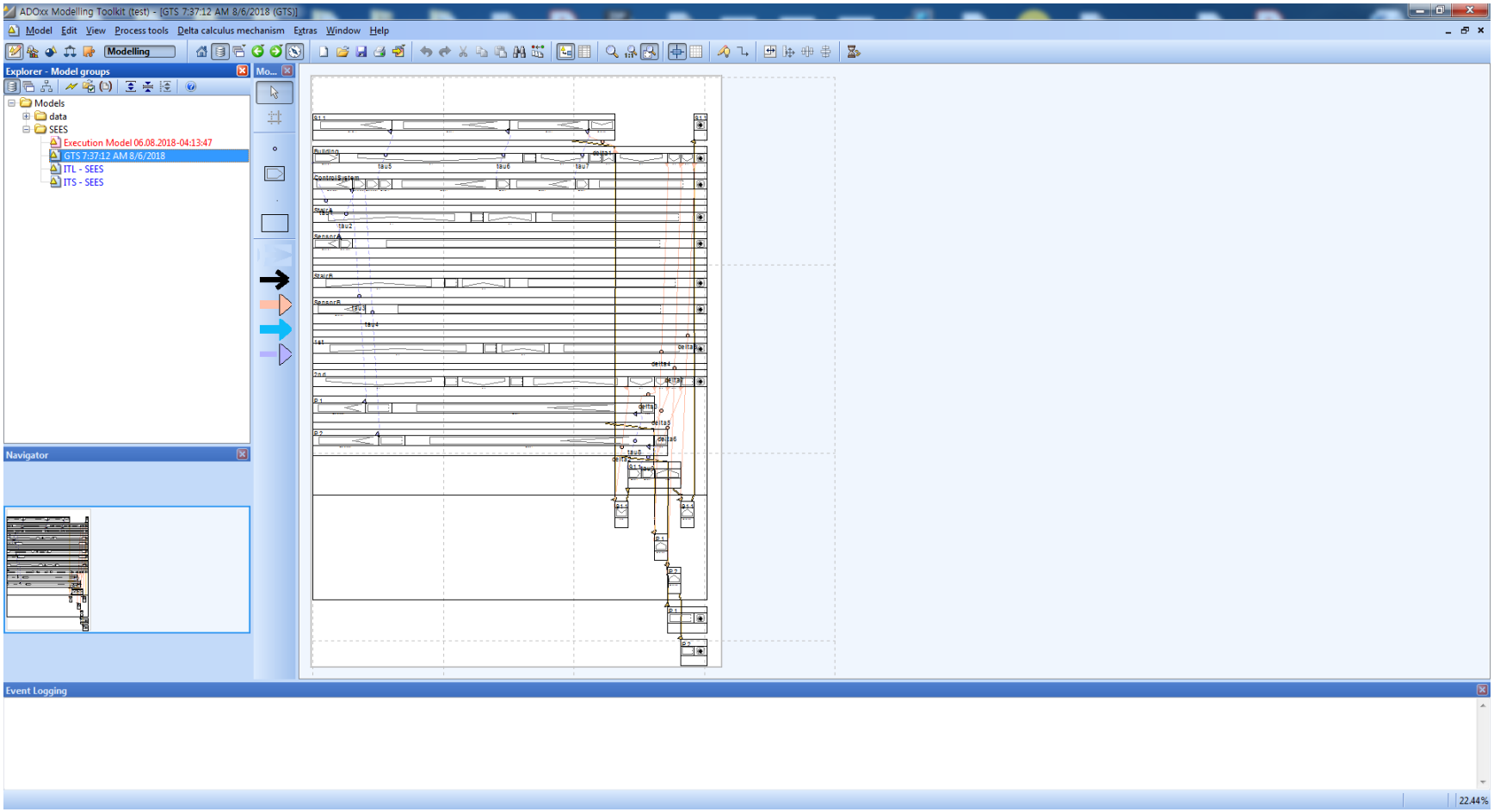


Verification

- Verification
  - Behavior analysis
    - Analyze the system behavior
    - Generate geo-temporal space model
  - Requirements Verification
    - Verify a set of system requirements



Analysis model



4. Example

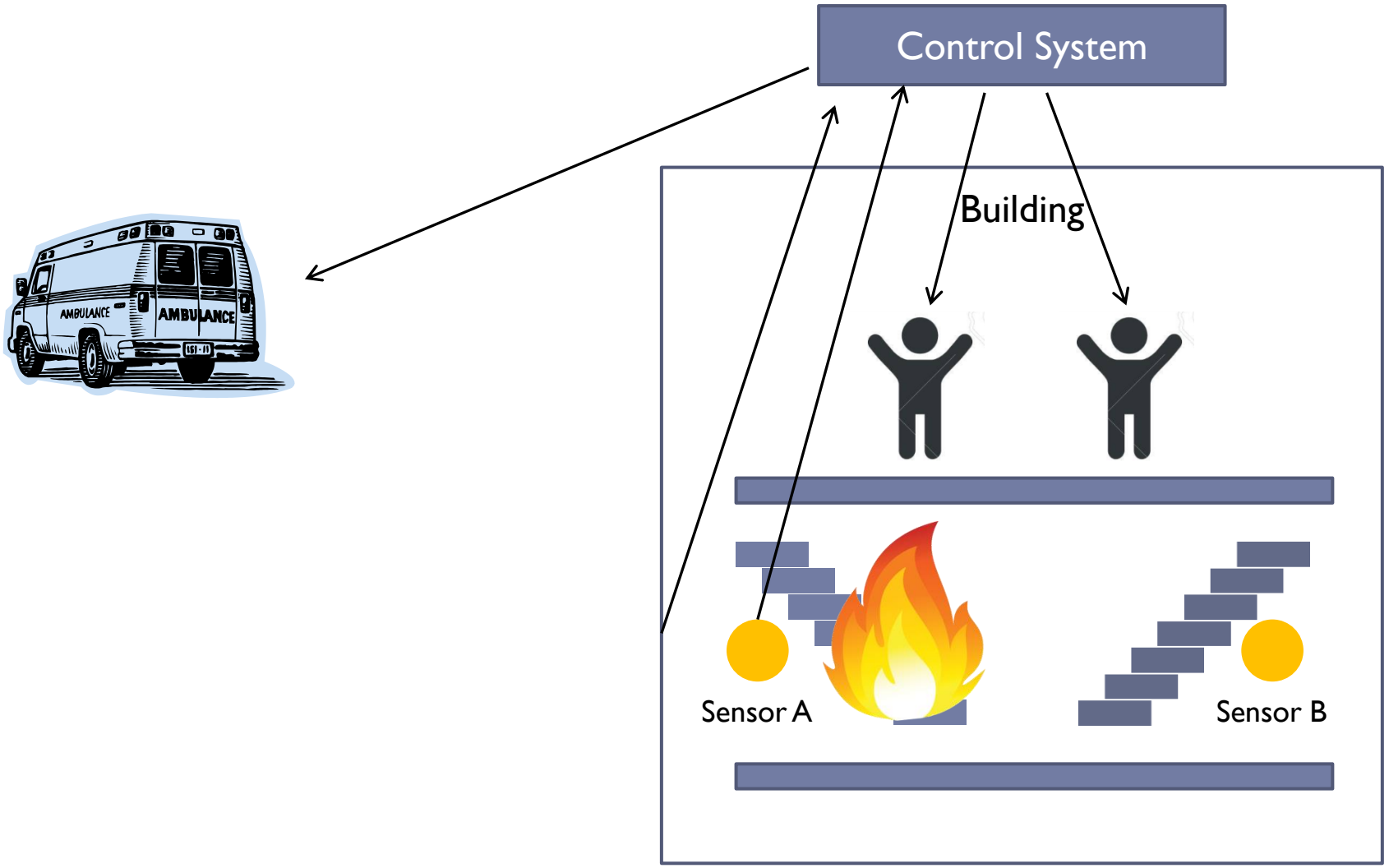
Example

- Smart Emergency Evacuation System
  - Sensors
    - Fire detection
  - Control System
    - Evacuation alarm
    - Rescue request
    - Evacuation route notification

[1]

[1] http://www.arpel.com/business-services/fire-detection/

Example


Control System
Building
AMBULANCE
AMBULANCE
Sensor A
Sensor B

Example

- Textual Specification

$$Sys := Building[Control\ System|StairA[SensorA]|StairB[SensorB]\ |1st\ floor|2nd\ floor[P1|P2]]|\ 911;$$

$$Control\ System := (CS(FireA)_{[0,-,1,3]} \cdot P1(\overline{StairB}) \cdot P2(\overline{StairB}))\backslash(CS(FireB) \cdot P1(\overline{StairA}) \cdot P2(\overline{StairA}))$$
$$\cdot CE(\overline{Call}) \cdot CS(P1)_{[0,-,1,7]}\backslash CE(\overline{P1}) \cdot CS(P2)_{[0,-,1,4]}\backslash CE(\overline{P2});$$

$$SensorA := \left(SA(\overline{Fire})_{[0,-,1,2]} \cdot CS(\overline{FireA})\right)\backslash\emptyset_3;$$

$$SensorB := \left(SB(\overline{Fire})_{[0,-,1,2]} \cdot CS(\overline{FireB})\right)\backslash\emptyset_3;$$

$$P1 := (P1(StairB)_{[0,-,1,3]} \cdot (\emptyset.RC(P1).out\ 2nd.out\ Building\{v < 2.5\} +_{N(5,3)} out\ 2nd.in\ StairB.out\ StairB.in\ 1st.out\ 1st.out\ Building\{v \geq 2.5\}))$$
$$\backslash(P1(StairA) \cdot (\emptyset.RC(P1).out\ 2nd.out\ Building\{v < 2.5\} +_{N(5,3)} out\ 2nd.in\ StairA.out\ StairA.in\ 1st.out\ 1st.out\ Building\{v \geq 2.5\}));$$

$$P2 := (P2(StairB)_{[0,-,1,4]} \cdot (\emptyset.RC(P2).out\ 2nd.out\ Building\{v < 2.5\} +_{N(5,8)} out\ 2nd.in\ StairB.out\ StairB.in\ 1st.out\ 1st.out\ Building\{v \geq 2.5\}))$$
$$\backslash(P2(StairA) \cdot (\emptyset.RC(P2).out\ 2nd.out\ Building\{v < 2.5\} +_{N(5,8)} out\ 2nd.in\ StairA.out\ StairA.in\ 1st.out\ 1st.out\ Building\{v \geq 2.5\}));$$

$$StairA := (P1\ in_{[0,-,1,10]} \cdot P1\ out)\backslash\emptyset \cdot (P2\ in_{[0,-,1,3]} \cdot P2\ out)\backslash\emptyset;$$

$$StairB := (P1\ in_{[0,-,1,8]} \cdot P1\ out)\backslash\emptyset \cdot (P2\ in_{[0,-,1,3]} \cdot P2\ out)\backslash\emptyset;$$

$$1st\ floor := (P1\ in_{[0,-,1,11]} \cdot P1\ out)\backslash\emptyset \cdot (P2\ in_{[0,-,1,3]} \cdot P2\ out)\backslash\emptyset;$$

$$2nd\ floor := P1\ out_{[0,-,1,8]}\backslash\emptyset \cdot P2\ out_{[0,-,1,3]}\backslash\emptyset \cdot 911\ in \cdot P1\ out_{[0,-,1,5]}\backslash\emptyset \cdot P2\ out_{[0,-,1,3]}\backslash\emptyset \cdot 911\ out;$$

$$Building := (SA(\overline{Fire})\{0.5\} +_D SB(\overline{Fire})\{0.5\}) \cdot \left(P1\ out_{[0,-,1,13]} \cdot CS(\overline{P1})\right)\backslash\emptyset \cdot \left(P2\ out_{[0,-,1,3]} \cdot CS(\overline{P2})\right)\backslash\emptyset$$
$$\cdot 911\ in \cdot P1\ out_{[0,-,1,5]}\backslash\emptyset \cdot P2\ out_{[0,-,1,3]}\backslash\emptyset \cdot 911\ out;$$

$$911 := Ce(Call) \cdot CE(P1)_{[0,-,1,10]}\backslash((CE(P2)_{[0,-,1,3]} \cdot in\ Building \cdot in\ 2nd \cdot RC(\overline{P2}) \cdot out\ 2nd \cdot out\ Building)$$
$$\backslash in\ Building \cdot in\ 2nd \cdot out\ 2nd \cdot out\ Building)$$
$$\cdot \left(CE(P2)_{[0,-,1,8]} \cdot in\ Building \cdot in\ 2nd \cdot RC(\overline{P1}) \cdot RC(\overline{P2}) \cdot out\ 2nd \cdot out\ Building\right)$$
$$\backslash(in\ Building \cdot in\ 2nd \cdot RC(\overline{P1}) \cdot out\ 2nd \cdot out\ Building)$$

Example

- Textual Specification

$$Sys := Building[Control\ System|StairA[SensorA]|StairB[SensorB]\ |1st\ floor|2nd\ floor[P1|P2]]|\ 911;$$

$$Control\ System := (CS(FireA)_{[0,-,1,3]} \cdot P1(\overline{StairB}) \cdot P2(\overline{StairB}))\backslash(CS(FireB) \cdot P1(\overline{StairA}) \cdot P2(\overline{StairA}))$$
$$\cdot CE(\overline{Call}) \cdot CS(P1)_{[0,-,1,7]}\backslash CE(\overline{P1}) \cdot CS(P2)_{[0,-,1,4]}\backslash CE(\overline{P2});$$

$$SensorA := \left(SA(\overline{Fire})_{[0,-,1,2]} \cdot CS(\overline{FireA})\right)\backslash\emptyset_3;$$

$$SensorB := \left(SB(\overline{Fire})_{[0,-,1,2]} \cdot CS(\overline{FireB})\right)\backslash\emptyset_3;$$

$$P1 := (P1(StairB)_{[0,-,1,3]} \cdot (\emptyset.RC(P1).out\ 2nd.out\ Building\{v < 2.5\} +_{N(5,3)} out\ 2nd.in\ StairB.out\ StairB.in\ 1st.out\ 1st.out\ Building\{v \geq 2.5\}))$$
$$\backslash(P1(StairA) \cdot (\emptyset.RC(P1).out\ 2nd.out\ Building\{v < 2.5\} +_{N(5,3)} out\ 2nd.in\ StairA.out\ StairA.in\ 1st.out\ 1st.out\ Building\{v \geq 2.5\}));$$

$$P2 := (P2(StairB)_{[0,-,1,4]} \cdot (\emptyset.RC(P2).out\ 2nd.out\ Building\{v < 2.5\} +_{N(5,8)} out\ 2nd.in\ StairB.out\ StairB.in\ 1st.out\ 1st.out\ Building\{v \geq 2.5\}))$$
$$\backslash(P2(StairA) \cdot (\emptyset.RC(P2).out\ 2nd.out\ Building\{v < 2.5\} +_{N(5,8)} out\ 2nd.in\ StairA.out\ StairA.in\ 1st.out\ 1st.out\ Building\{v \geq 2.5\}));$$

$$StairA := (P1\ in_{[0,-,1,10]} \cdot P1\ out)\backslash\emptyset \cdot (P2\ in_{[0,-,1,3]} \cdot P2\ out)\backslash\emptyset;$$

$$StairB := (P1\ in_{[0,-,1,8]} \cdot P1\ out)\backslash\emptyset \cdot (P2\ in_{[0,-,1,3]} \cdot P2\ out)\backslash\emptyset;$$

$$1st\ floor := (P1\ in_{[0,-,1,11]} \cdot P1\ out)\backslash\emptyset \cdot (P2\ in_{[0,-,1,3]} \cdot P2\ out)\backslash\emptyset;$$

$$2nd\ floor := P1\ out_{[0,-,1,8]}\backslash\emptyset \cdot P2\ out_{[0,-,1,3]}\backslash\emptyset \cdot 911\ in \cdot P1\ out_{[0,-,1,5]}\backslash\emptyset \cdot P2\ out_{[0,-,1,3]}\backslash\emptyset \cdot 911\ out;$$

$$Building := (\mathbf{SA(\overline{Fire})\{0.5\} +_D SB(\overline{Fire})\{0.5\}}) \cdot \left(P1\ out_{[0,-,1,13]} \cdot CS(\overline{P1})\right)\backslash\emptyset \cdot \left(P2\ out_{[0,-,1,3]} \cdot CS(\overline{P2})\right)\backslash\emptyset$$
$$\cdot 911\ in \cdot P1\ out_{[0,-,1,5]}\backslash\emptyset \cdot P2\ out_{[0,-,1,3]}\backslash\emptyset \cdot 911\ out;$$

$$911 := Ce(Call) \cdot CE(P1)_{[0,-,1,10]}\backslash((CE(P2)_{[0,-,1,3]} \cdot in\ Building \cdot in\ 2nd \cdot RC(\overline{P2}) \cdot out\ 2nd \cdot out\ Building)$$
$$\backslash in\ Building \cdot in\ 2nd \cdot out\ 2nd \cdot out\ Building)$$
$$\cdot \left(CE(P2)_{[0,-,1,8]} \cdot in\ Building \cdot in\ 2nd \cdot RC(\overline{P1}) \cdot RC(\overline{P2}) \cdot out\ 2nd \cdot out\ Building\right)$$
$$\backslash(in\ Building \cdot in\ 2nd \cdot RC(\overline{P1}) \cdot out\ 2nd \cdot out\ Building)$$

Example

- Textual Specification

$$Sys := Building[Control\,System|StairA[SensorA]|StairB[SensorB]\,|1st\,floor|2nd\,floor[P1|P2]]|\,911;$$

$$Control\,System := (CS(FireA)_{[0,-,1,3]} \cdot P1(\overline{StairB}) \cdot P2(\overline{StairB}))\backslash(CS(FireB) \cdot P1(\overline{StairA}) \cdot P2(\overline{StairA}))$$
$$\cdot CE(\overline{Call}) \cdot CS(P1)_{[0,-,1,7]}\backslash CE(\overline{P1}) \cdot CS(P2)_{[0,-,1,4]}\backslash CE(\overline{P2});$$

$$SensorA := \left(SA(\overline{Fire})_{[0,-,1,2]} \cdot CS(\overline{FireA})\right)\backslash\emptyset_3;$$

$$SensorB := \left(SB(\overline{Fire})_{[0,-,1,2]} \cdot CS(\overline{FireB})\right)\backslash\emptyset_3;$$

$$P1 := (P1(StairB)_{[0,-,1,3]} \cdot (\emptyset.\mathbf{RC(P1).out\ 2nd.out\ Building}\{v < 2.5\} +_{N(5,3)} \mathbf{out\ 2nd.in\ StairB.out\ StairB.in\ 1st.out\ 1st.out\ Building}\{v \geq 2.5\}))$$
$$\backslash(P1(StairA) \cdot (\emptyset.\mathbf{RC(P1).out\ 2nd.out\ Building}\{v < 2.5\} +_{N(5,3)} \mathbf{out\ 2nd.in\ StairA.out\ StairA.in\ 1st.out\ 1st.out\ Building}\{v \geq 2.5\}));$$

$$P2 := (P2(StairB)_{[0,-,1,4]} \cdot (\emptyset.RC(P2).\,out\ 2nd.out\ Building\{v < 2.5\} +_{N(5,8)} out\ 2nd.in\ StairB.out\ StairB.in\ 1st.out\ 1st.\,out\ Building\{v \geq 2.5\}))$$
$$\backslash(P2(StairA) \cdot (\emptyset.\,RC(P2).out\ 2nd.out\ Building\{v < 2.5\} +_{N(5,8)} out\ 2nd.in\ StairA.out\ StairA.in\ 1st.out\ 1st.out\ Building\{v \geq 2.5\}));$$

$$StairA := (P1\ in_{[0,-,1,10]} \cdot P1\ out)\backslash\emptyset \cdot (P2\ in_{[0,-,1,3]} \cdot P2\ out)\backslash\emptyset;$$

$$StairB := (P1\ in_{[0,-,1,8]} \cdot P1\ out)\backslash\emptyset \cdot (P2\ in_{[0,-,1,3]} \cdot P2\ out)\backslash\emptyset;$$

$$1st\ floor := (P1\ in_{[0,-,1,11]} \cdot P1\ out)\backslash\emptyset \cdot (P2\ in_{[0,-,1,3]} \cdot P2\ out)\backslash\emptyset;$$

$$2nd\ floor := P1\ out_{[0,-,1,8]}\backslash\emptyset \cdot P2\ out_{[0,-,1,3]}\backslash\emptyset \cdot 911\ in \cdot P1\ out_{[0,-,1,5]}\backslash\emptyset \cdot P2\ out_{[0,-,1,3]}\backslash\emptyset \cdot 911\ out;$$

$$Building := (SA(\overline{Fire})\{0.5\} +_D SB(\overline{Fire})\{0.5\}) \cdot \left(P1\ out_{[0,-,1,13]} \cdot CS(\overline{P1})\right)\backslash\emptyset \cdot \left(P2\ out_{[0,-,1,3]} \cdot CS(\overline{P2})\right)\backslash\emptyset$$
$$\cdot 911\ in \cdot P1\ out_{[0,-,1,5]}\backslash\emptyset \cdot P2\ out_{[0,-,1,3]}\backslash\emptyset \cdot 911\ out;$$

$$911 := Ce(Call) \cdot CE(P1)_{[0,-,1,10]}\backslash((CE(P2)_{[0,-,1,3]} \cdot in\ Building \cdot in\ 2nd \cdot RC(\overline{P2}) \cdot out\ 2nd \cdot out\ Building)$$
$$\backslash in\ Building \cdot in\ 2nd \cdot out\ 2nd \cdot out\ Building)$$
$$\cdot \left(CE(P2)_{[0,-,1,8]} \cdot in\ Building \cdot in\ 2nd \cdot RC(\overline{P1}) \cdot RC(\overline{P2}) \cdot out\ 2nd \cdot out\ Building\right)$$
$$\backslash(in\ Building \cdot in\ 2nd \cdot RC(\overline{P1}) \cdot out\ 2nd \cdot out\ Building)$$

Example

- Textual Specification

$$Sys := Building[Control\ System|StairA[SensorA]|StairB[SensorB]\ |1st\ floor|2nd\ floor[P1|P2]]|\ 911;$$

$$Control\ System := (CS(FireA)_{[0,-,1,3]} \cdot P1(\overline{StairB}) \cdot P2(\overline{StairB}))\backslash(CS(FireB) \cdot P1(\overline{StairA}) \cdot P2(\overline{StairA}))$$
$$\cdot CE(\overline{Call}) \cdot CS(P1)_{[0,-,1,7]}\backslash CE(\overline{P1}) \cdot CS(P2)_{[0,-,1,4]}\backslash CE(\overline{P2});$$

$$SensorA := \left(SA(\overline{Fire})_{[0,-,1,2]} \cdot CS(\overline{FireA})\right)\backslash\emptyset_3;$$

$$SensorB := \left(SB(\overline{Fire})_{[0,-,1,2]} \cdot CS(\overline{FireB})\right)\backslash\emptyset_3;$$

$$P1 := (P1(StairB)_{[0,-,1,3]} \cdot (\emptyset.RC(P1).out\ 2nd.out\ Building\{v < 2.5\} +_{N(5,3)} out\ 2nd.in\ StairB.out\ StairB.in\ 1st.out\ 1st.out\ Building\{v \geq 2.5\}))$$
$$\backslash(P1(StairA) \cdot (\emptyset.RC(P1).out\ 2nd.out\ Building\{v < 2.5\} +_{N(5,3)} out\ 2nd.in\ StairA.out\ StairA.in\ 1st.out\ 1st.out\ Building\{v \geq 2.5\}));$$

$$P2 := (P2(StairB)_{[0,-,1,4]} \cdot (\emptyset.\mathbf{RC(P2).out\ 2nd.out\ Building\{v < 2.5\} +_{N(5,8)} out\ 2nd.in\ StairB.out\ StairB.in\ 1st.out\ 1st.out\ Building\{v \geq 2.5\}}))$$
$$\backslash(P2(StairA) \cdot (\emptyset.\mathbf{RC(P2).out\ 2nd.out\ Building\{v < 2.5\} +_{N(5,8)} out\ 2nd.in\ StairA.out\ StairA.in\ 1st.out\ 1st.out\ Building\{v \geq 2.5\}}));$$

$$StairA := (P1\ in_{[0,-,1,10]} \cdot P1\ out)\backslash\emptyset \cdot (P2\ in_{[0,-,1,3]} \cdot P2\ out)\backslash\emptyset;$$

$$StairB := (P1\ in_{[0,-,1,8]} \cdot P1\ out)\backslash\emptyset \cdot (P2\ in_{[0,-,1,3]} \cdot P2\ out)\backslash\emptyset;$$

$$1st\ floor := (P1\ in_{[0,-,1,11]} \cdot P1\ out)\backslash\emptyset \cdot (P2\ in_{[0,-,1,3]} \cdot P2\ out)\backslash\emptyset;$$

$$2nd\ floor := P1\ out_{[0,-,1,8]}\backslash\emptyset \cdot P2\ out_{[0,-,1,3]}\backslash\emptyset \cdot 911\ in \cdot P1\ out_{[0,-,1,5]}\backslash\emptyset \cdot P2\ out_{[0,-,1,3]}\backslash\emptyset \cdot 911\ out;$$

$$Building := (SA(\overline{Fire})\{0.5\} +_D SB(\overline{Fire})\{0.5\}) \cdot \left(P1\ out_{[0,-,1,13]} \cdot CS(\overline{P1})\right)\backslash\emptyset \cdot \left(P2\ out_{[0,-,1,3]} \cdot CS(\overline{P2})\right)\backslash\emptyset$$
$$\cdot 911\ in \cdot P1\ out_{[0,-,1,5]}\backslash\emptyset \cdot P2\ out_{[0,-,1,3]}\backslash\emptyset \cdot 911\ out;$$

$$911 := Ce(Call) \cdot CE(P1)_{[0,-,1,10]}\backslash((CE(P2)_{[0,-,1,3]} \cdot in\ Building \cdot in\ 2nd \cdot RC(\overline{P2}) \cdot out\ 2nd \cdot out\ Building)$$
$$\backslash in\ Building \cdot in\ 2nd \cdot out\ 2nd \cdot out\ Building)$$
$$\cdot \left(CE(P2)_{[0,-,1,8]} \cdot in\ Building \cdot in\ 2nd \cdot RC(\overline{P1}) \cdot RC(\overline{P2}) \cdot out\ 2nd \cdot out\ Building\right)$$
$$\backslash(in\ Building \cdot in\ 2nd \cdot RC(\overline{P1}) \cdot out\ 2nd \cdot out\ Building)$$

Example

- Probabilistic choice
  - Building
    - $SA(\overline{Fire})\{0.5\} +_D SB(\overline{Fire})\{0.5\}$
    - Discrete distribution
  - P1
    - $\emptyset \cdot \ \ldots \cdot \{v < 2.5\} +_{N(5,3)} out\ 2nd \cdot \ \ldots \cdot \{v \geq 2.5\}$
    - Normal distribution
  - P2
    - $\emptyset \cdot \ \ldots \cdot \{v < 2.5\} +_{N(5,8)} out\ 2nd \cdot \ \ldots \cdot \{v \geq 2.5\}$
    - Normal distribution

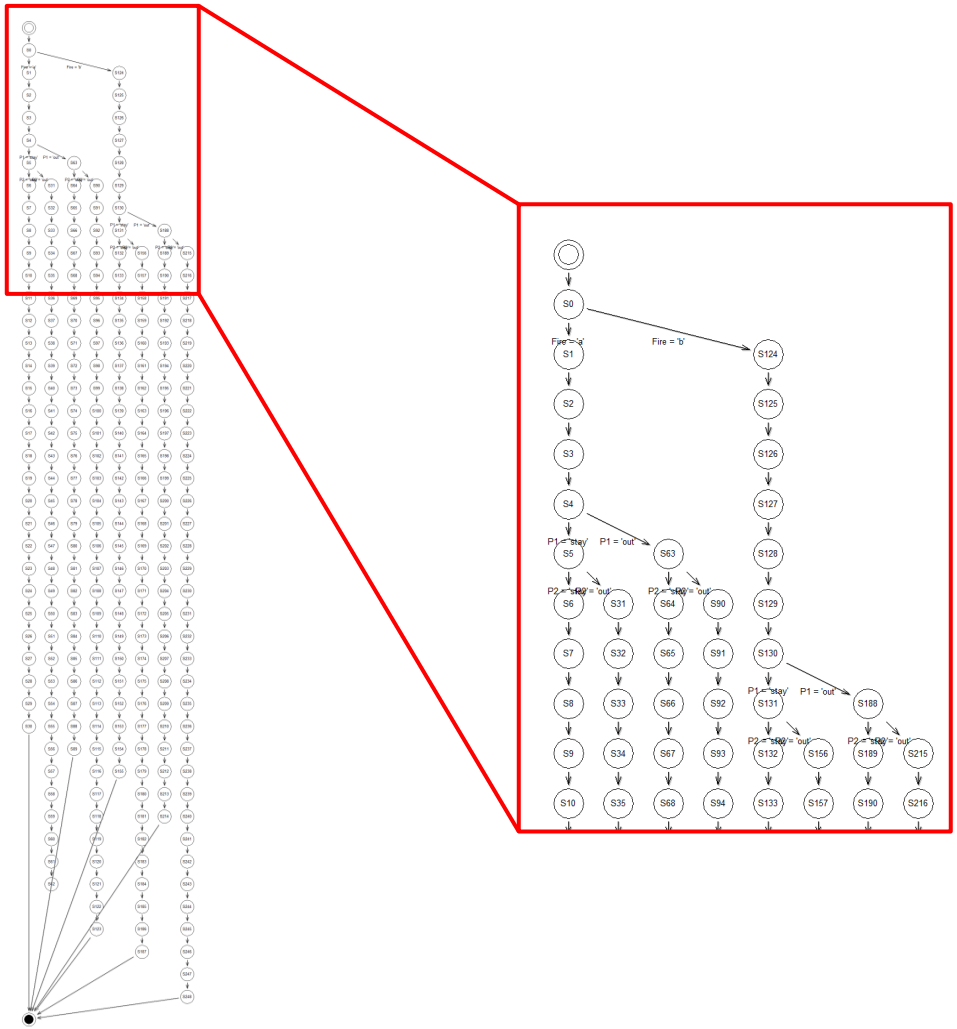
Example

- Probabilistic choice
  - Building
    - $SA(\overline{Fire})\{0.5\} +_D SB(\overline{Fire})\{0.5\}$
    - Discrete distribution
  - P1
    - $\emptyset \cdot \ \ldots \cdot \{v < 2.5\} +_{N(5,\mathbf{3})} out\ 2nd \cdot \ \ldots \cdot \{v \geq 2.5\}$
    - Normal distribution
  - P2
    - $\emptyset \cdot \ \ldots \cdot \{v < 2.5\} +_{N(5,\mathbf{8})} out\ 2nd \cdot \ \ldots \cdot \{v \geq 2.5\}$
    - Normal distribution
  - P1 and P2 have same type's choice, but parameters are different.

5. Analysis

Analysis

- Execution path
  - 8 paths



Analysis

- Execution path
  - 8 paths
    - Fire: The location where the fire occurred
    - Stay: P1 or P2, confined in Building
    - Out: P1 or P2, escaped from Building

	Path 1	Path 2	Path 3	Path 4	Path 5	Path 6	Path 7	Path 8
Fire	Stair A	Stair A	Stair A	Stair A	Stair B	Stair B	Stair B	Stair B
P1	Stay	Stay	Out	Out	Stay	Stay	Out	Out
P2	Stay	Out	Stay	Out	Stay	Out	Stay	Out

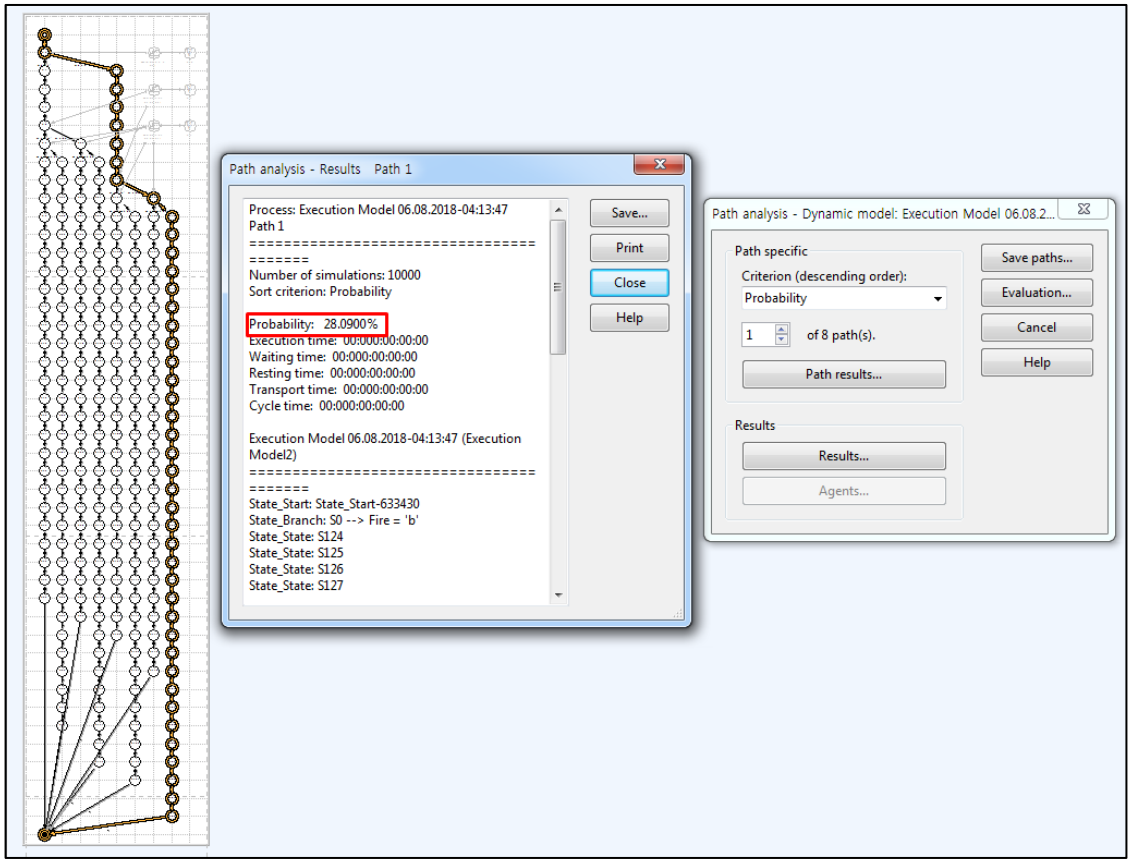
Analysis

- Probability
  - Mathematical analysis
    - Calculate the probability
      - $\emptyset \cdot \ \ldots \cdot \{v < 2.5\} +_{N(5,3)} out\ 2nd \cdot \ \ldots \cdot \{v \geq 2.5\}$
        - $\emptyset \cdot \ \ldots \cdot \{0.2023\} +_{D} out\ 2nd \cdot \ \ldots \cdot \{0.7977\}$
      - $\emptyset \cdot \ \ldots \cdot \{v < 2.5\} +_{N(5,8)} out\ 2nd \cdot \ \ldots \cdot \{v \geq 2.5\}$
        - $\emptyset \cdot \ \ldots \cdot \{0.3773\} +_{D} out\ 2nd \cdot \ \ldots \cdot \{0.6227\}$

	Path 1	Path 2	Path 3	Path 4	Path 5	Path 6	Path 7	Path 8
%	3.82	6.3	15.05	24.83	3.82	6.3	15.05	24.83

Analysis

- Simulation
  - Simulate the system based on the probabilities



Analysis

- Simulation
  - Simulate the system based on the probabilities

Number of Simulation	Probability							
	Path 1	Path 2	Path 3	Path 4	Path 5	Path 6	Path 7	Path 8
1,000	3.5	6.2	14.2	25	3.5	7.5	14.4	25.7
1,000,000	3.79	6.32	15.04	24.86	3.82	6.32	14.98	24.87

Analysis

- Simulation
  - Simulate the system based on the probabilities

Number of Simulation	Probability							
	Path 1	Path 2	Path 3	Path 4	Path 5	Path 6	Path 7	Path 8
1,000	3.5	6.2	14.2	25	3.5	7.5	14.4	25.7
1,000,000	3.79	6.32	15.04	24.86	3.82	6.32	14.98	24.87

Simulation results

	Path 1	Path 2	Path 3	Path 4	Path 5	Path 6	Path 7	Path 8
%	3.82	6.3	15.05	24.83	3.82	6.3	15.05	24.83

Mathematical analysis

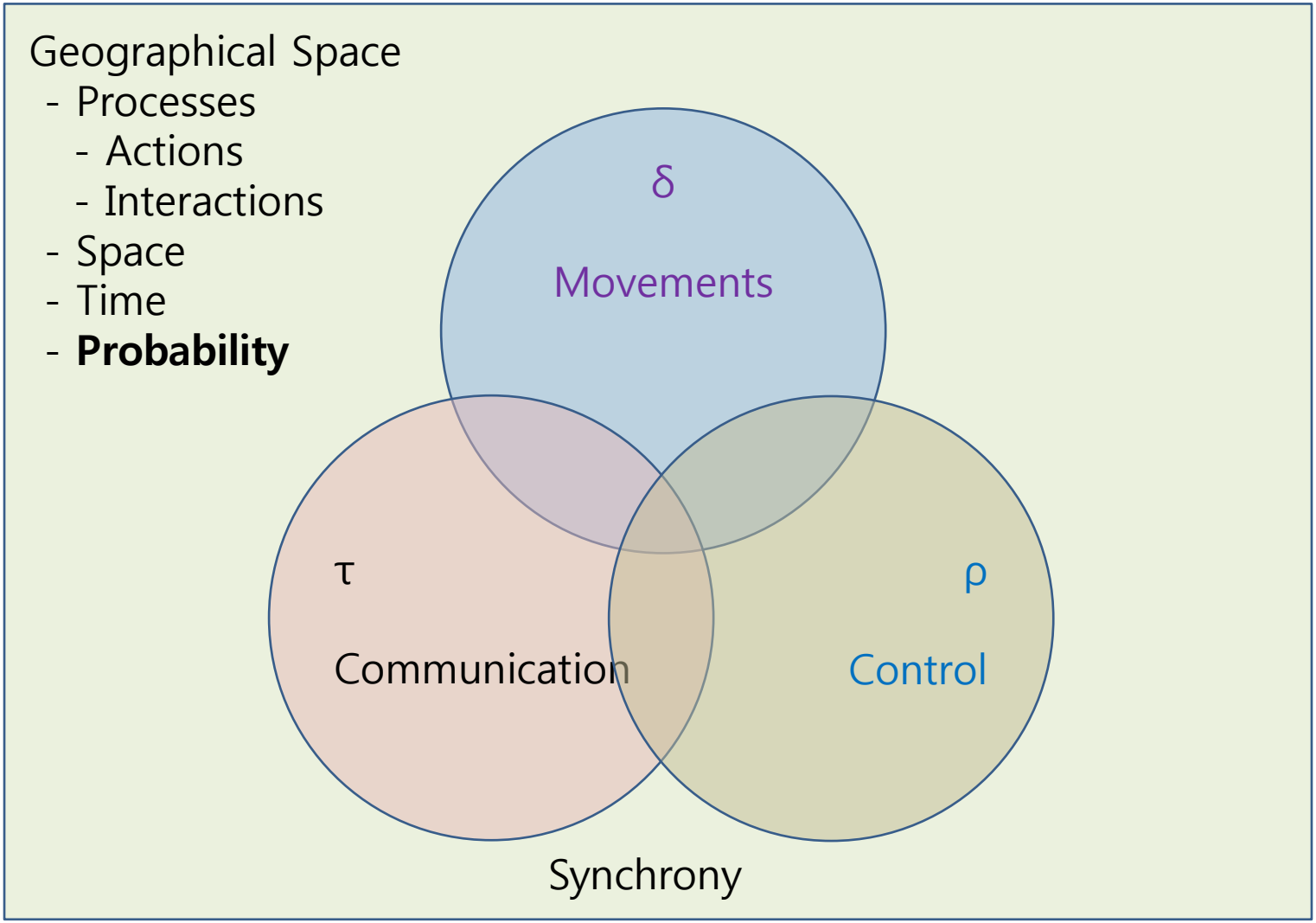
Analysis

- Prediction of occurrence probability
  - In complex system, mathematical analysis is difficult.
  - Through the simulation, paths and probabilities are derived.

- Automation
  - SAVE tool
    - Specify and analyze the system
    - Generate all possible paths
    - Simulation based on probability

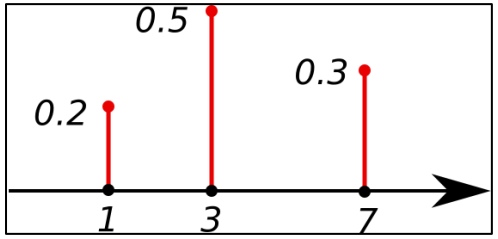
6. Conclusions

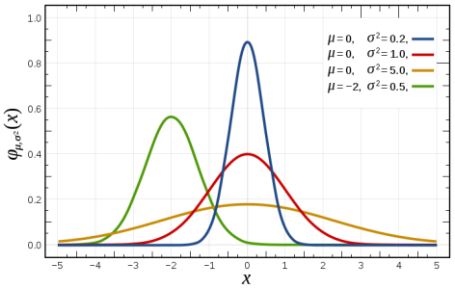
Approach

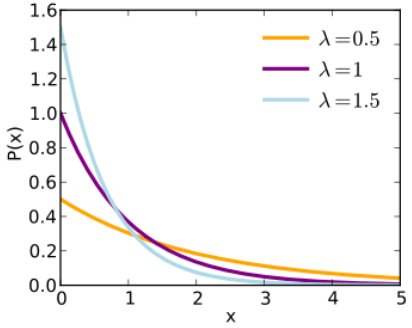

Geographical Space
- Processes
- Actions
- Interactions
- Space
- Time
- **Probability**
δ
Movements
τ
Communication
ρ
Control
Synchrony

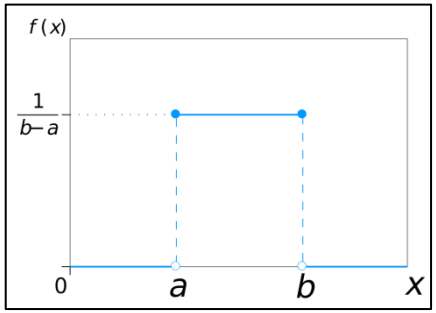
Approach

- Various probability specification
  - Discrete distribution
  - Normal distribution
  - Exponential distribution
  - Uniform distribution

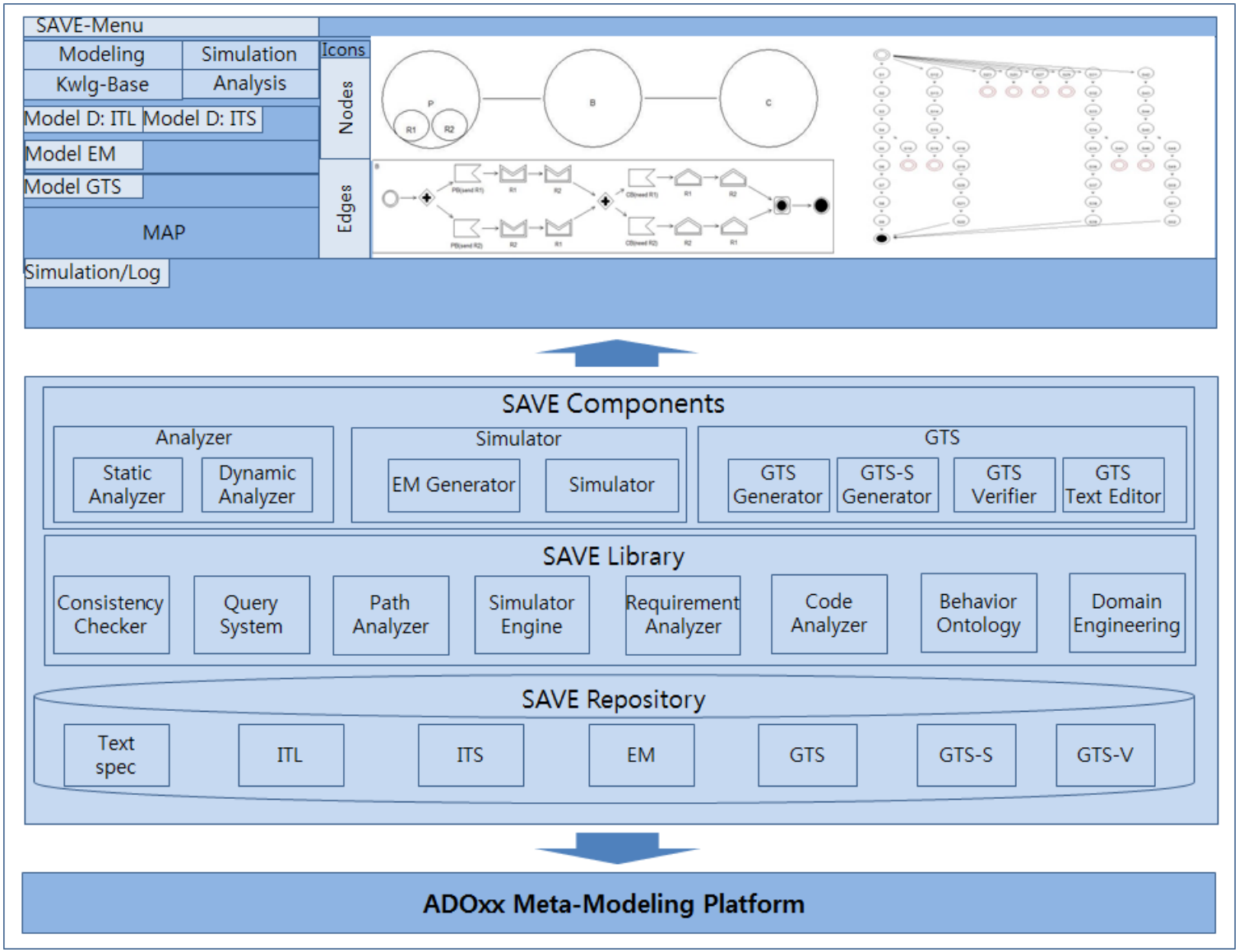






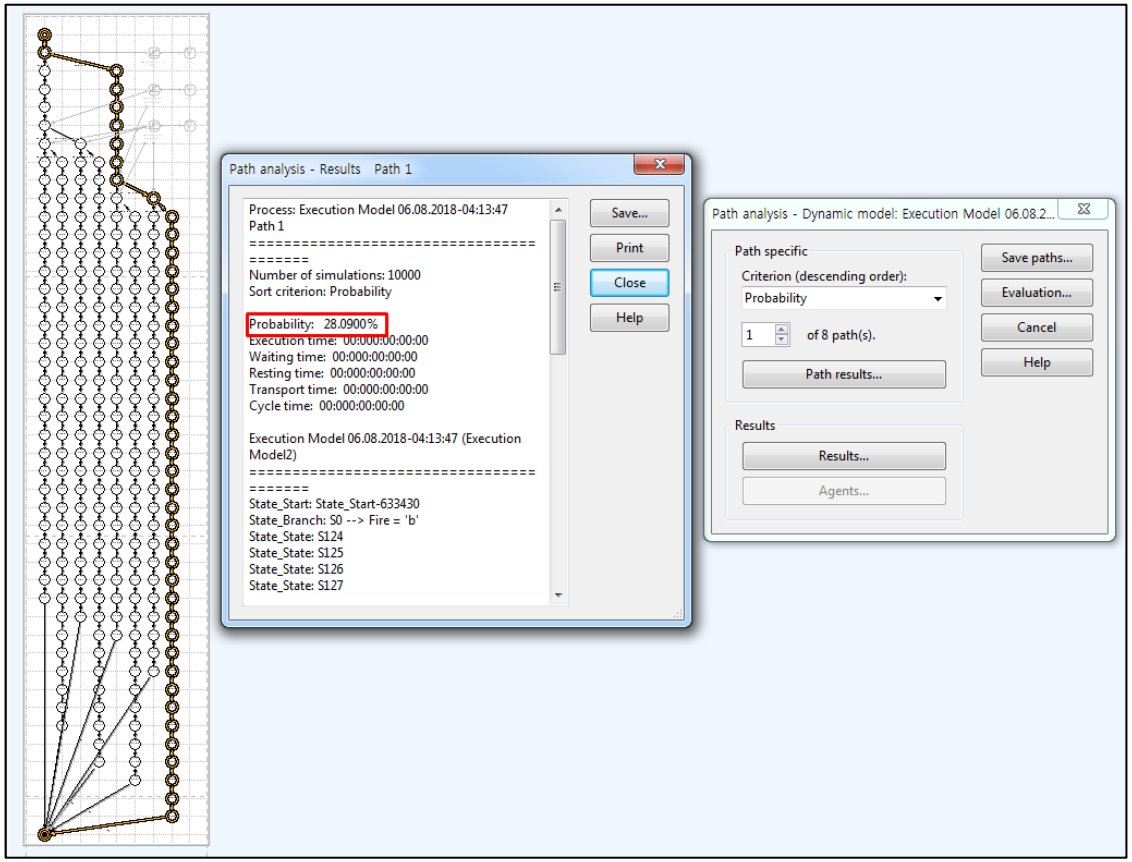


SAVE


SAVE-Menu
Modeling
Simulation
Kwlg-Base
Analysis
Model D: ITL
Model D: ITS
Model EM
Model GTS
MAP
Simulation/Log
Icons
Nodes
Edges
P
R1
R2
B
C
SAVE Components
Analyzer
Static Analyzer
Dynamic Analyzer
Simulator
EM Generator
Simulator
GTS
GTS Generator
GTS-S Generator
GTS Verifier
GTS Text Editor
SAVE Library
Consistency Checker
Query System
Path Analyzer
Simulator Engine
Requirement Analyzer
Code Analyzer
Behavior Ontology
Domain Engineering
SAVE Repository
Text spec
ITL
ITS
EM
GTS
GTS-S
GTS-V
ADOxx Meta-Modeling Platform

SAVE

- Simulation



Future Research

- Theory
  - Requirement analysis methods for probability
  - Requirement verification methods for probability
- System
  - Apply to real IoT examples

Q & A