QFLan: A tool for the Quantitative Analysis of Highly Reconfigurable Systems

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Class 21t 04/12/2023

References

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[TSE18] Maurice ter Beek, Axel Legay, Alberto Lluch Lafuente, Andrea Vandin, A framework for quantitative modeling and analysis of highly (re)configurable systems, IEEE Transactions on Software Engineering (TSE), 2018.

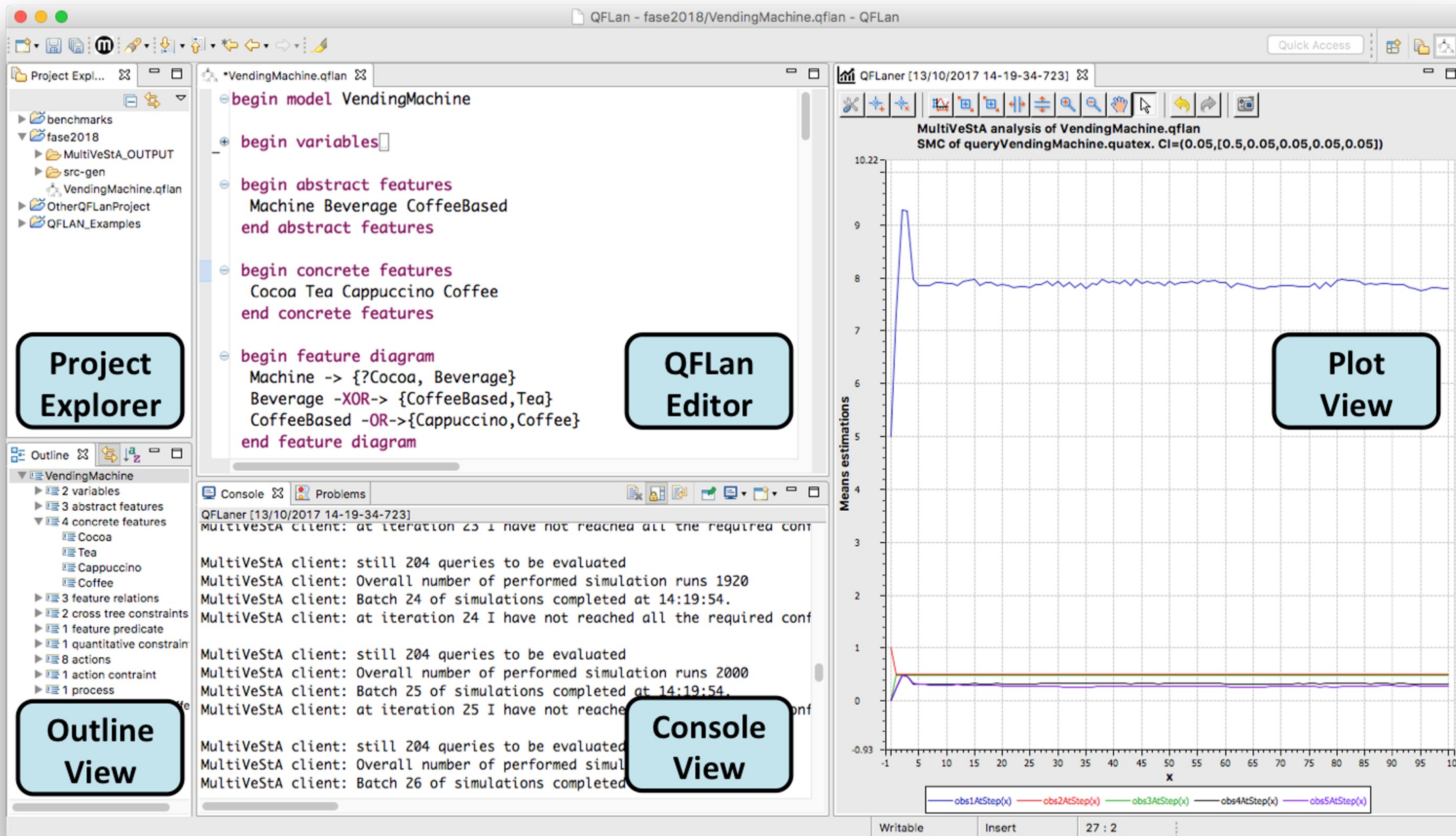
[FM18] Andrea Vandin, Maurice ter Beek, Axel Legay, Alberto Lluch Lafuente, QFLan: A Tool for the Quantitative Analysis of Highly Reconfigurable Systems.

[ISOLA16] Maurice ter Beek, Axel Legay, Alberto Lluch Lafuente, Andrea Vandin, Statistical Model Checking for Product Lines.

[SPLC15] Maurice ter Beek, Axel Legay, Alberto Lluch Lafuente, Andrea Vandin, Statistical Analysis of Probabilistic Models of Software Product Lines with Quantitative Constraints.

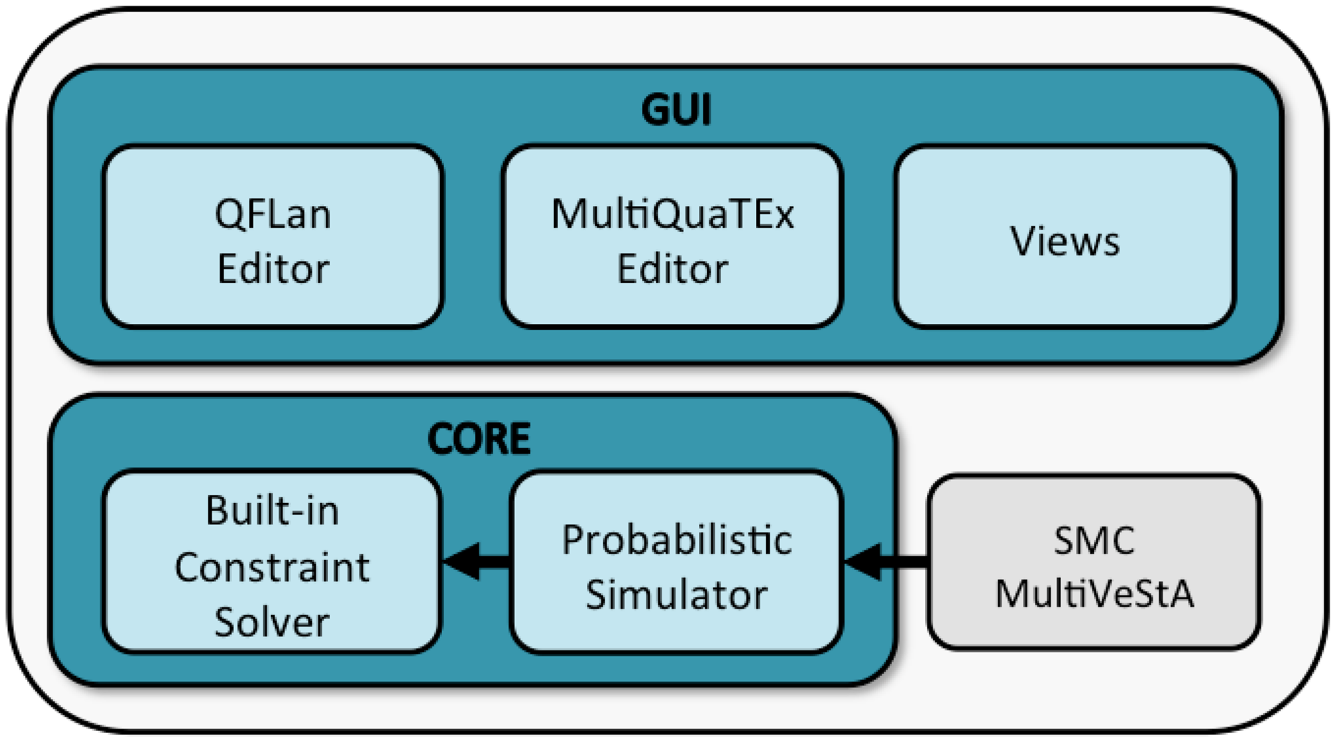
[FMSPLE15] Maurice ter Beek, Axel Legay, Alberto Lluch Lafuente, Andrea Vandin, Quantitative Analysis of Probabilistic Models of Software Product Lines with Statistical Model Checking.

Presented in [FM'18][TSE'18]
Prototypes in [FMSPLE'15][SPLC'15][ISOLA'16]



https://github.com/qflanTeam/QFLan/

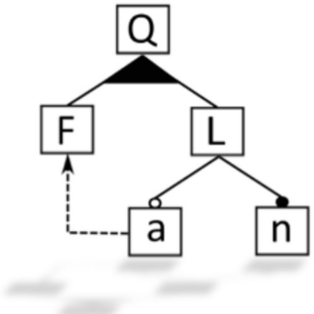
Presented in [FM’18][TSE’18]
Prototypes in [FMSPLE’15][SPLC’15][ISOLA’16]



https://github.com/qflanTeam/QFLan/

QFLan

A framework for quantitative modeling and analysis of highly (re)configurable systems



Summary

QFLan is a software tool for the modeling and analysis of highly reconfigurable systems, including software product lines.

The tool offers an easy-to-use, rule-based probabilistic language to specify models with probabilistic behaviour. Quantitative constraints can be used to restrict the class of admissible configurations (or products), like (using a family of reconfigurable vending machines from here):

- machines can have a certain maximum cost,
- machines serving coffee-based beverages cannot sell tea,
- in order to serve cappuccino it is necessary to have the feature of serving also coffee,

Also it is possible to express conditions like:

- machines serving cappuccino provided with a coca dispenser can serve chocaccino.

QFLan has been combined with the distributed statistical model checker MultiVeStA to perform

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- Source code

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https://github.com/qflanTeam/QFLan/

Outline

Feature Model

- Abstract and Concrete Features
- Cross-tree Constraints
- Quantitative Constraints

Behaviour

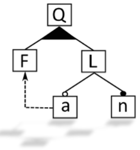
- Actions and Action Constraints
- Transitions
- Initial Configuration

MultiVeStA Analysis

- Analysis when a condition holds
- Analysis at varying of time

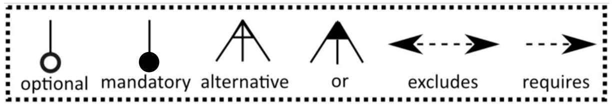
An Application to a Simple Security Scenario

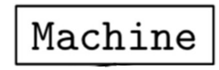
- Schneier’s SafeLock Attack Tree



A simple vending machine product line

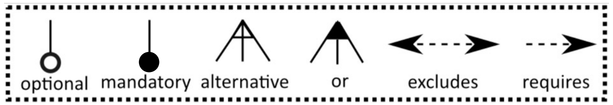
The feature model

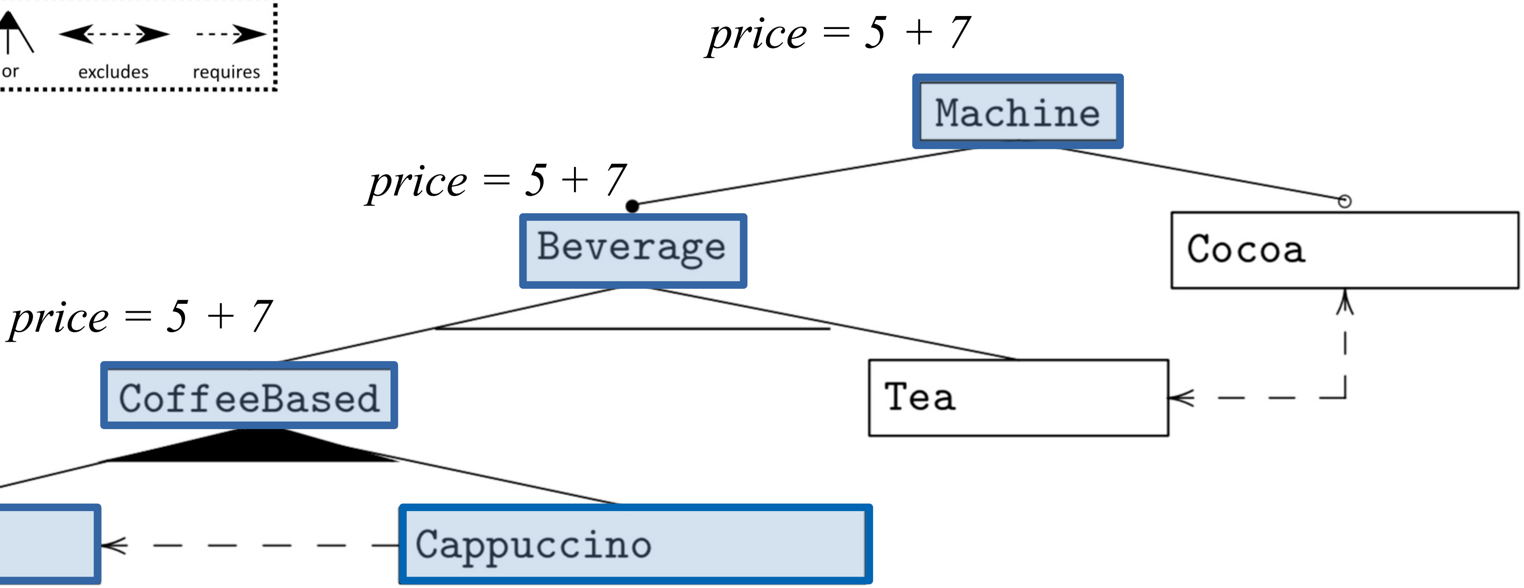




A simple vending machine product line

The feature model: Abstract & Concrete Features



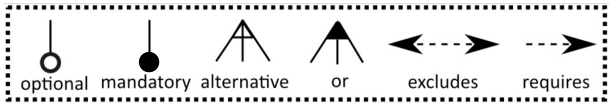


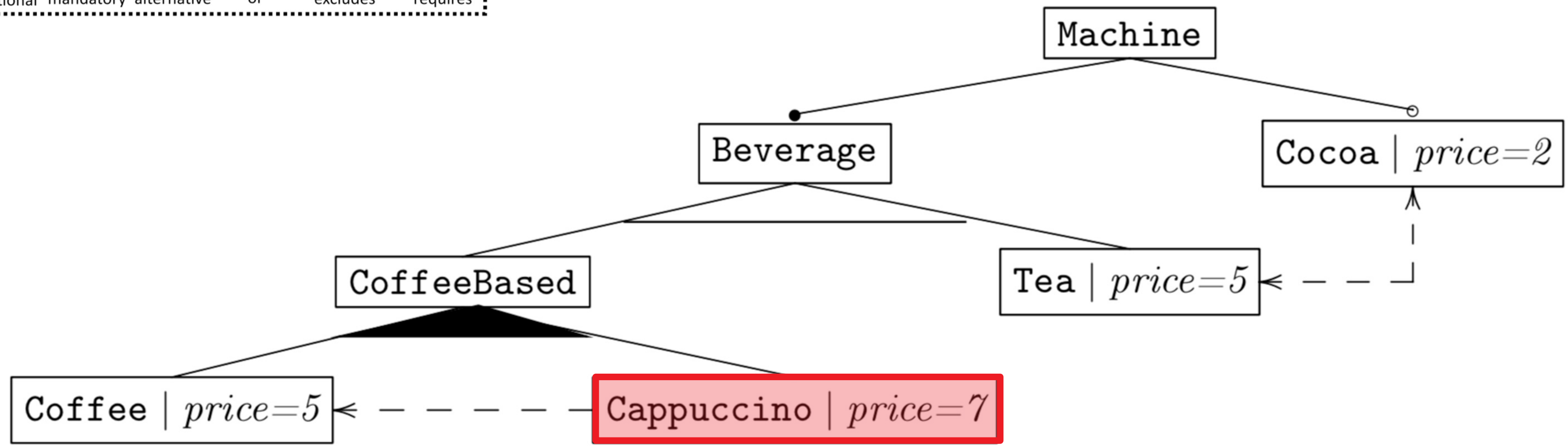

```
begin abstract features
 Machine Beverage CoffeeBased
end abstract features

begin concrete features
 Cocoa Tea Cappuccino Coffee
end concrete features

begin feature diagram
 Machine -> {?Cocoa, Beverage}
 Beverage -XOR-> {CoffeeBased,Tea}
 CoffeeBased -OR->{Cappuccino,Coffee}
end feature diagram
```

```
begin feature predicates
 price= { Cappuccino = 7, Coffee = 5,
          Cocoa = 2, Tea = 5 }
end feature predicates
```

A simple vending machine product line

The feature model: Cross-tree constraints






```
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begin feature diagram
 Machine -> {?Cocoa, Beverage}
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begin cross-tree constraints
 Cappuccino requires Coffee
 Tea excludes Cocoa
end cross-tree constraints
```

```
begin feature predicates
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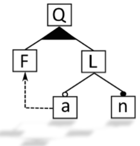

A simple vending machine product line

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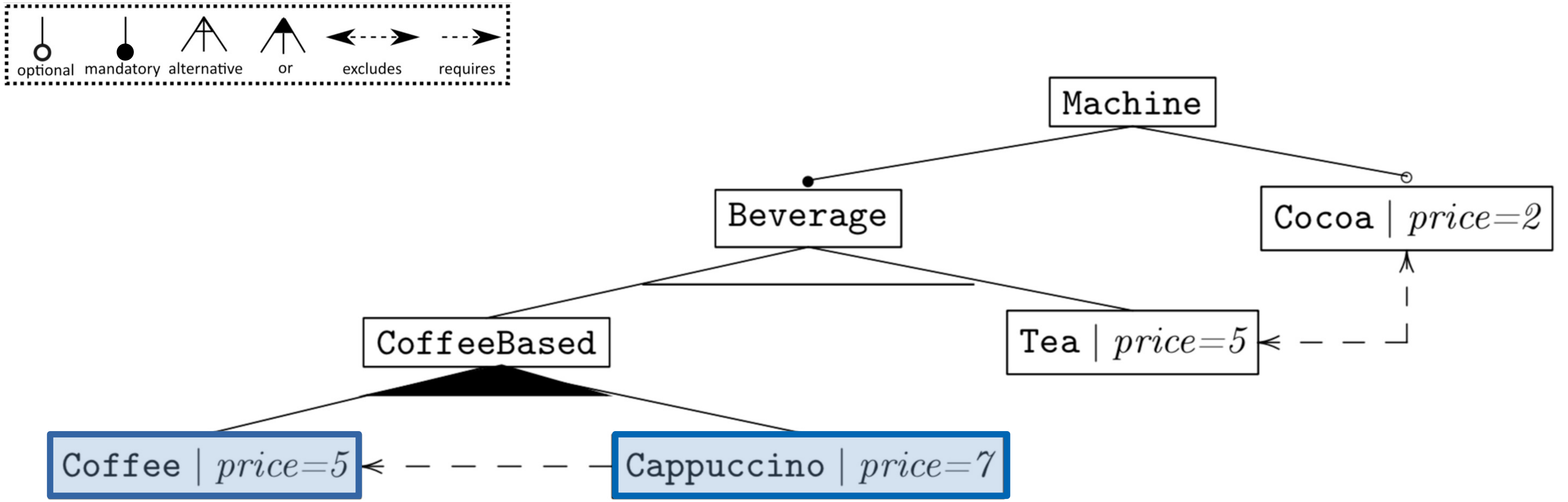


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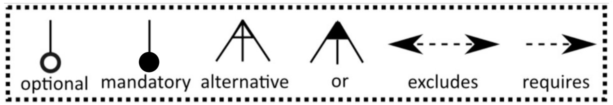

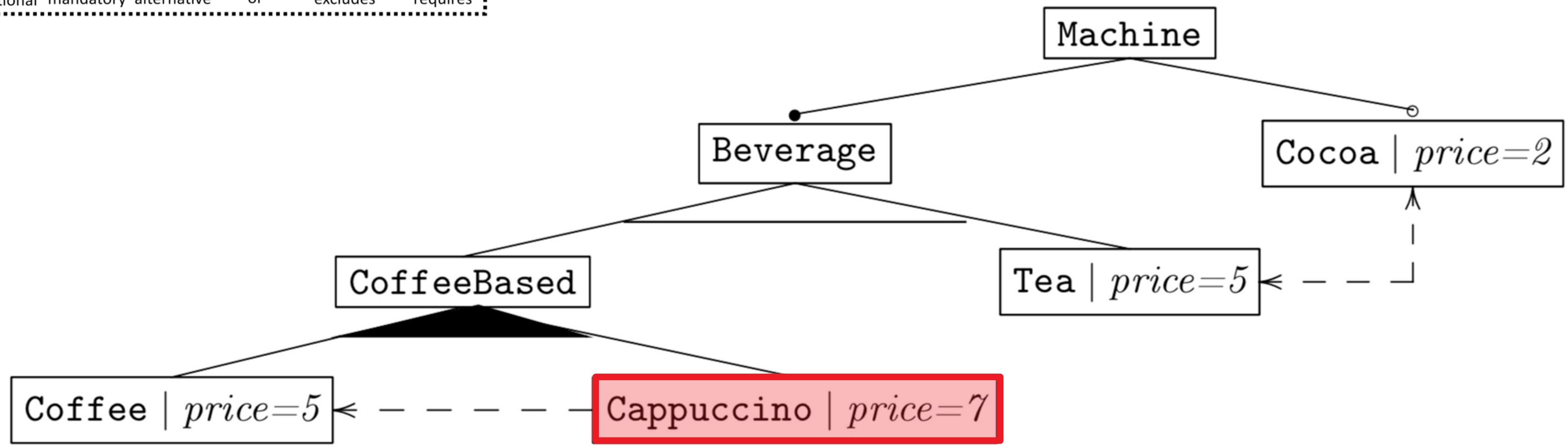


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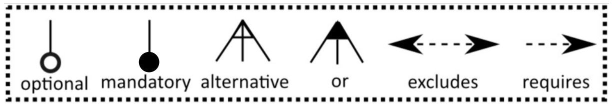
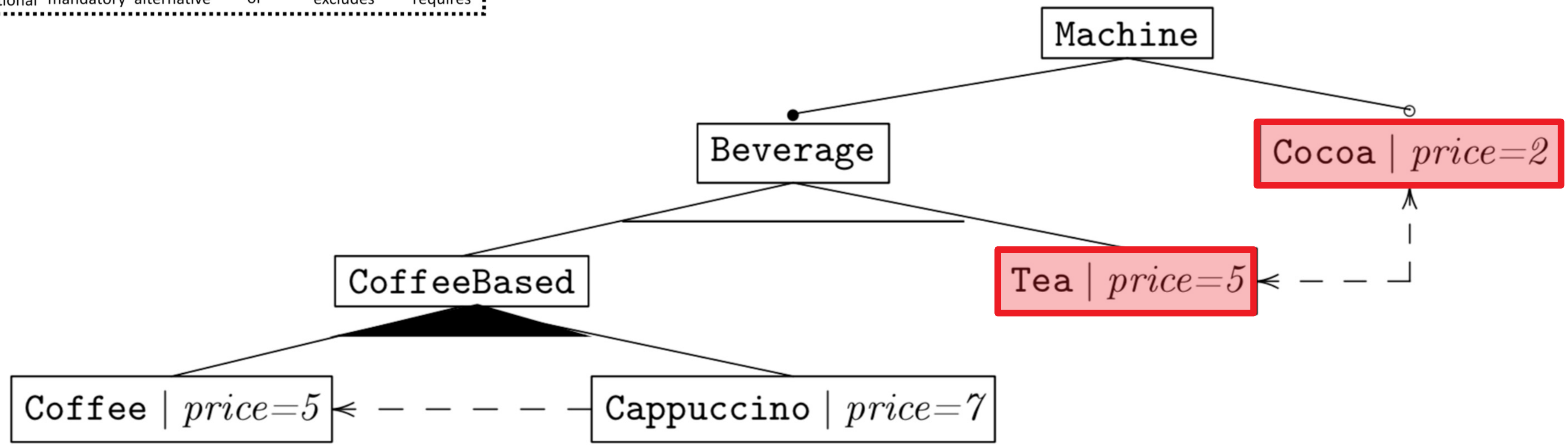
The feature model: Cross-tree constraints



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end feature predicates
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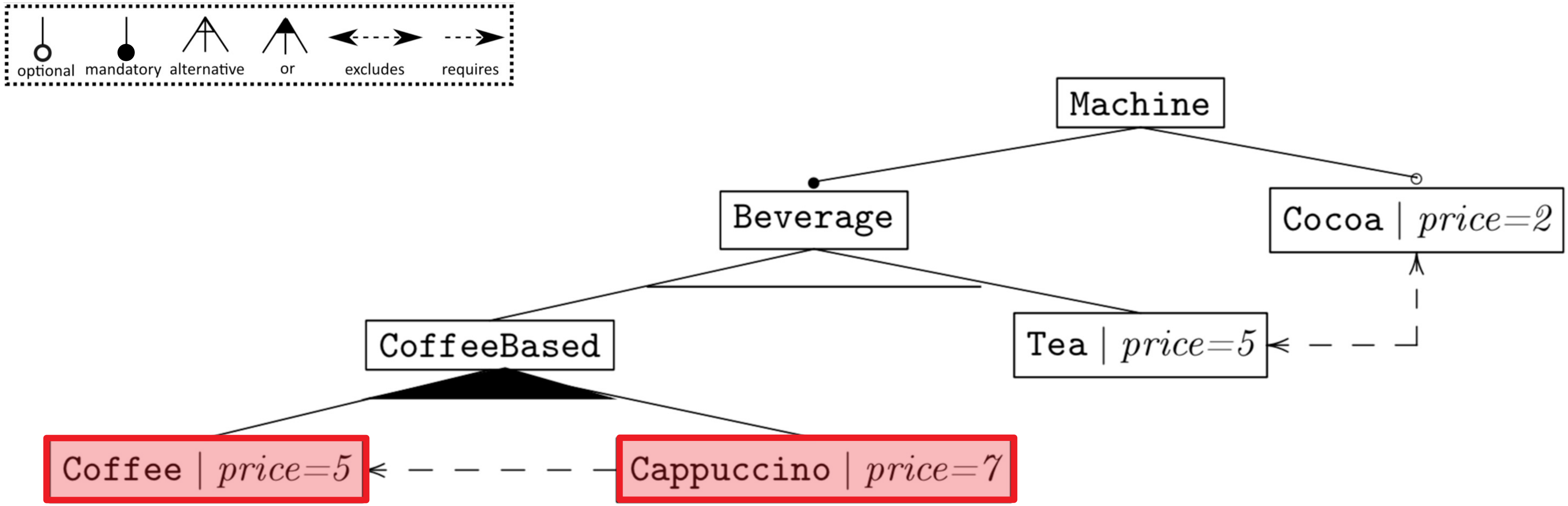
A simple vending machine product line

The feature model: Quantitative constraints

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begin abstract features
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end abstract features

begin concrete features
 Cocoa Tea Cappuccino Coffee
end concrete features

begin feature diagram
 Machine -> {?Cocoa, Beverage}
 Beverage -XOR-> {CoffeeBased,Tea}
 CoffeeBased -OR->{Cappuccino,Coffee}
end feature diagram

begin cross-tree constraints
 Cappuccino requires Coffee
 Tea excludes Cocoa
end cross-tree constraints
```

```
begin feature predicates
 price= { Cappuccino = 7, Coffee = 5,
          Cocoa = 2, Tea = 5 }
end feature predicates
begin quantitative constraints
 { price(Machine) <= 10 }
end quantitative constraints
```

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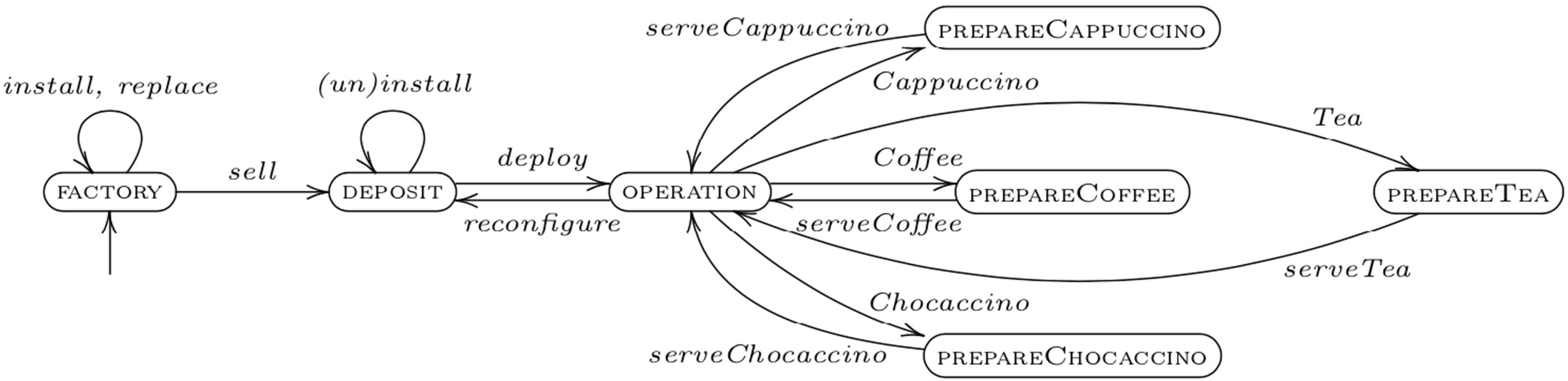
A simple vending machine product line

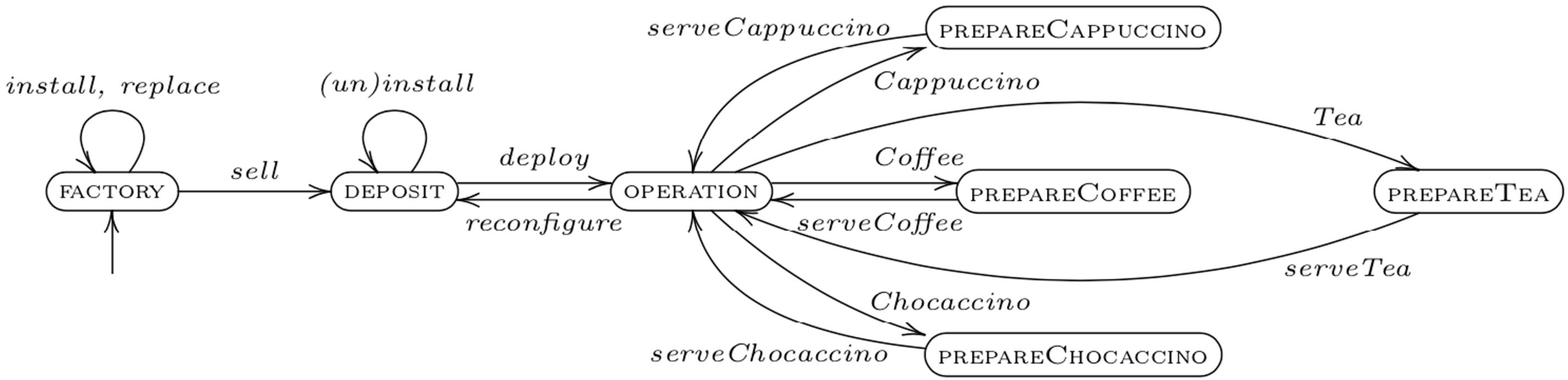
Behaviour: actions and action constraints




```
begin actions
 sell deploy reconfigure
 chocaccino
 serveCoffee serveCappuccino
 serveChocaccino serveTea
end actions

begin action constraints
 do(chocaccino) -> (has(Cappuccino)
                    and has(Cocoa) )
end action constraints
```

A simple vending machine product line

Behaviour: transitions



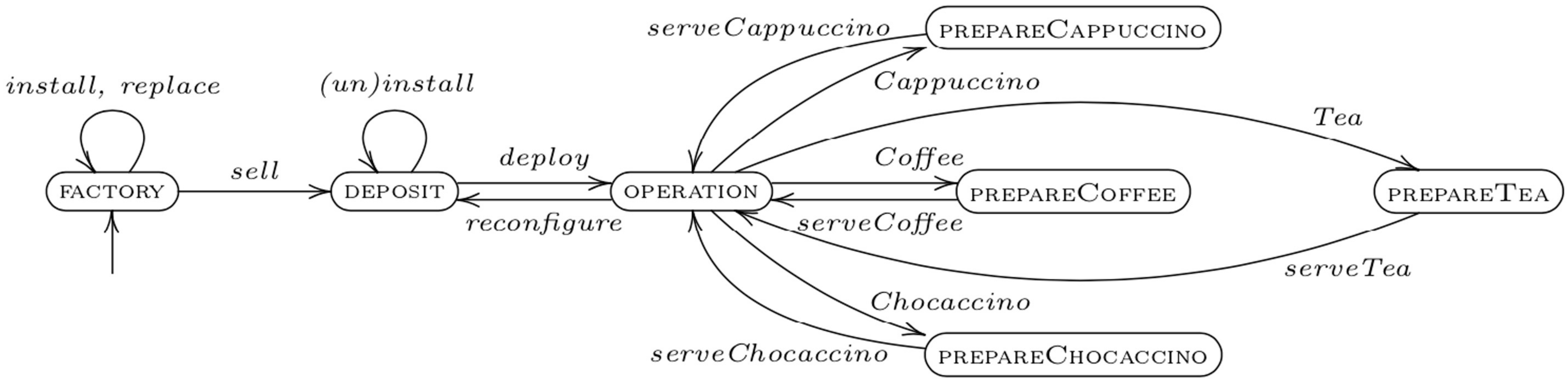

```
begin variables
 sold = 0
 deploys = 0
end variables

begin actions
 sell deploy reconfigure
 chocaccino
 serveCoffee serveCappuccino
 serveChocaccino serveTea
end actions

begin action constraints
 do(chocaccino) -> (has(Cappuccino)
                   and has(Cocoa) )
end action constraints
```

```
begin processes diagram
 begin process dynamics

 states = factory , deposit , operating , prepareCoffee ,
          prepareCappuccino, prepareTea , prepareChocaccino
```

```
//Operating
    //Coffee
operating -(Coffee,3)-> prepareCoffee,
prepareCoffee -(serveCoffee,1) -> operating,
    //Cappuccino
operating -(Cappuccino,3)-> prepareCappuccino,
prepareCappuccino -(serveCappuccino,1) -> operating,
    //Chocaccino
operating -(chocaccino,2)-> prepareChocaccino,
prepareChocaccino -(serveChocaccino,1) -> operating,
    //Tea
operating -(Tea,3)-> prepareTea,
prepareCappuccino -(serveTea,1) -> operating,

operating -(reconfigure,1) -> deposit
 end process
end processes diagram
```

A simple vending machine product line

Behaviour: inital configuration




```
begin variables
 sold = 0
 deploys = 0
end variables

begin actions
 sell deploy reconfigure
 chocaccino
 serveCoffee serveCappuccino
 serveChocaccino serveTea
end actions

begin action constraints
 do(chocaccino) -> (has(Cappuccino)
                    and has(Cocoa) )
end action constraints

begin init
 installedFeatures = { Coffee }
 initialProcesses = dynamics
end init
```

```
begin processes diagram
 begin process dynamics

 states = factory , deposit , operating , prepareCoffee ,
          prepareCappuccino, prepareTea , prepareChocaccino

 transitions =
   //Factory
   factory -(replace(Coffee,Tea),20)->factory,
   factory -(install(Cocoa),10)->factory,
   factory -(install(Cappuccino),10)->factory,
   factory -(sell,1,{sold=1})-> deposit,

   //Deposit
   deposit -(install(Cappuccino),2.0)->deposit,
   deposit -(uninstall(Cappuccino),2.0)->deposit,
   deposit -(install(Cocoa),2.0)->deposit,
   deposit -(uninstall(Cocoa),2.0)->deposit,
   deposit -(deploy,2,{deploys=deploys+1})-> operating
```

```
   //Operating
       //Coffee
   operating -(Coffee,3)-> prepareCoffee,
   prepareCoffee -(serveCoffee,1) -> operating,
       //Cappuccino
   operating -(Cappuccino,3)-> prepareCappuccino,
   prepareCappuccino -(serveCappuccino,1) -> operating,
       //Chocaccino
   operating -(chocaccino,2)-> prepareChocaccino,
   prepareChocaccino -(serveChocaccino,1) -> operating,
       //Tea
   operating -(Tea,3)-> prepareTea,
   prepareCappuccino -(serveTea,1) -> operating,

   operating -(reconfigure,1) -> deposit
 end process
end processes diagram
```

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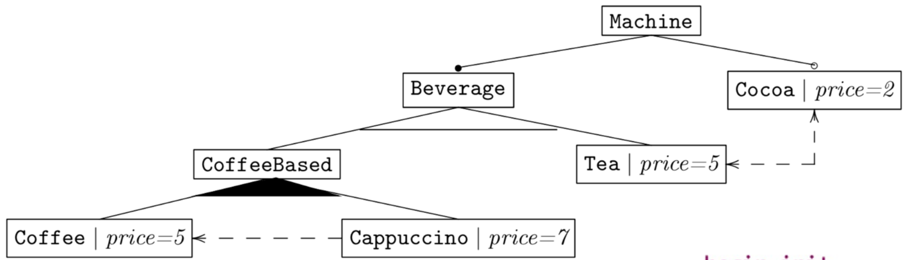
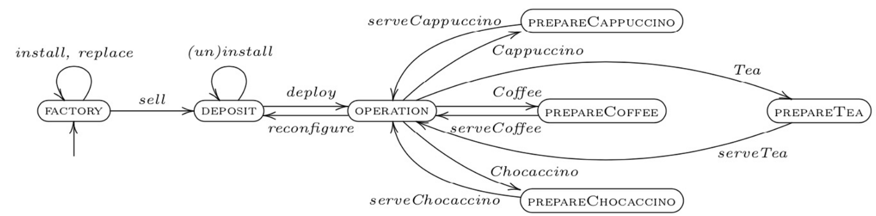
MultiVeStA Analysis: analysis of sold machines




```
begin quantitative constraints
 { price(Machine) <= 10 }
end quantitative constraints
```




```
begin init
 installedFeatures = { Coffee }
 initialProcesses = dynamics
end init
```

```
begin variables
 sold = 0
 deploys = 0
end variables
```

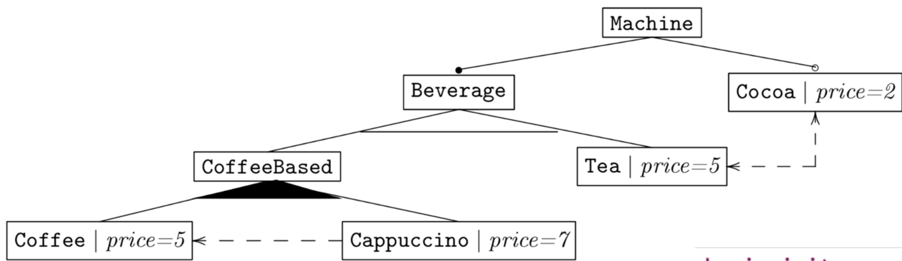
```
begin action constraints
 do(chocaccino) -> (has(Cappuccino)
                    and has(Cocoa) )
end action constraints
```

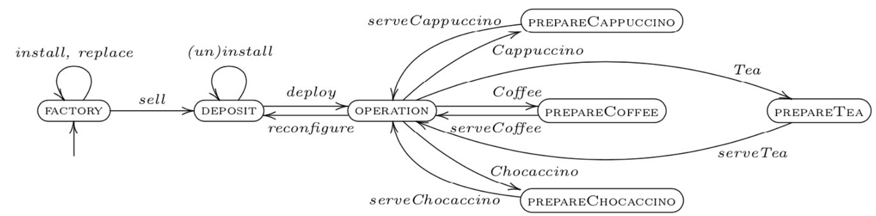
```
begin analysis

query = eval when {sold == 1.0 } :
{  price(Machine) [delta=0.5],
   Coffee , Tea , Cappuccino , Cocoa
}

default delta=0.05
alpha = 0.05
parallelism = 1

end analysis
```

```
begin processes diagram
 begin process dynamics

 states = factory , deposit , operating , prepareCoffee ,
          prepareCappuccino, prepareTea , prepareChocaccino

 transitions =
   //Factory
   factory -(replace(Coffee,Tea),20)->factory,
   factory -(install(Cocoa),10)->factory,
   factory -(install(Cappuccino),10)->factory,
   factory -(sell,1,{sold=1})-> deposit,

   //Deposit
   deposit -(install(Cappuccino),2.0)->deposit,
   deposit -(uninstall(Cappuccino),2.0)->deposit,
   deposit -(install(Cocoa),2.0)->deposit,
   deposit -(uninstall(Cocoa),2.0)->deposit,
   deposit -(deploy,2,{deploys=deploys+1})-> operating ,
```

A simple vending machine product line

MultiVeStA Analysis: analysis of sold machines






```
begin quantitative constraints
 { price(Machine) <= 15 }
end quantitative constraints
```

```
begin init
 installedFeatures = { Coffee }
 initialProcesses = dynamics
end init
```

```
begin variables
 sold = 0
 deploys = 0
end variables
```

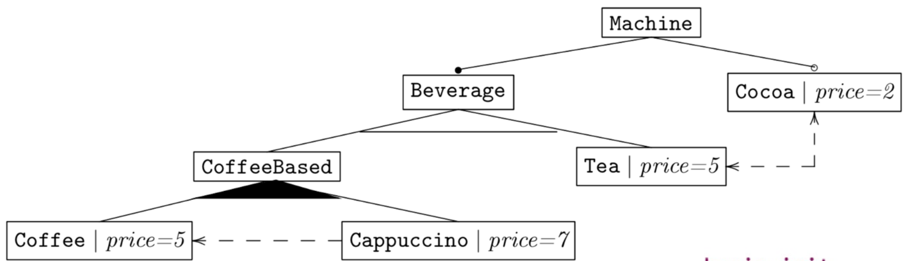
```
begin action constraints
 do(chocaccino) -> (has(Cappuccino)
                    and has(Cocoa) )
end action constraints
```

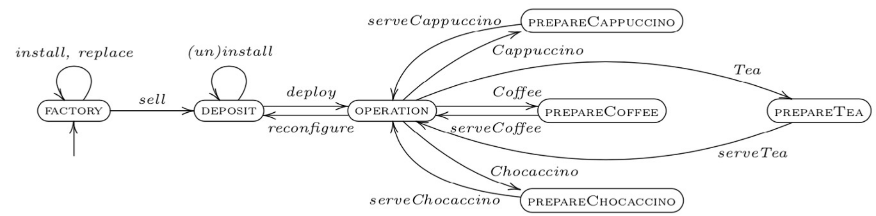
```
begin analysis

query = eval when {sold == 1.0 } :
{  price(Machine) [delta=0.5],
   Coffee , Tea , Cappuccino , Cocoa
}

default delta=0.05
alpha = 0.05
parallelism = 1

end analysis
```

	Price	Coffee	Tea	Cappuccino	Cocoa
	5.68	0.36	0.64	0.00	0.34

A simple vending machine product line

MultiVeStA Analysis: analysis at varying of time






```
begin quantitative constraints
 { price(Machine) <= 15 }
end quantitative constraints
```

```
begin init
 installedFeatures = { Coffee }
 initialProcesses = dynamics
end init
```

```
begin variables
 sold = 0
 deploys = 0
end variables
```

```
begin action constraints
 do(chocaccino) -> (has(Cappuccino)
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end action constraints
```
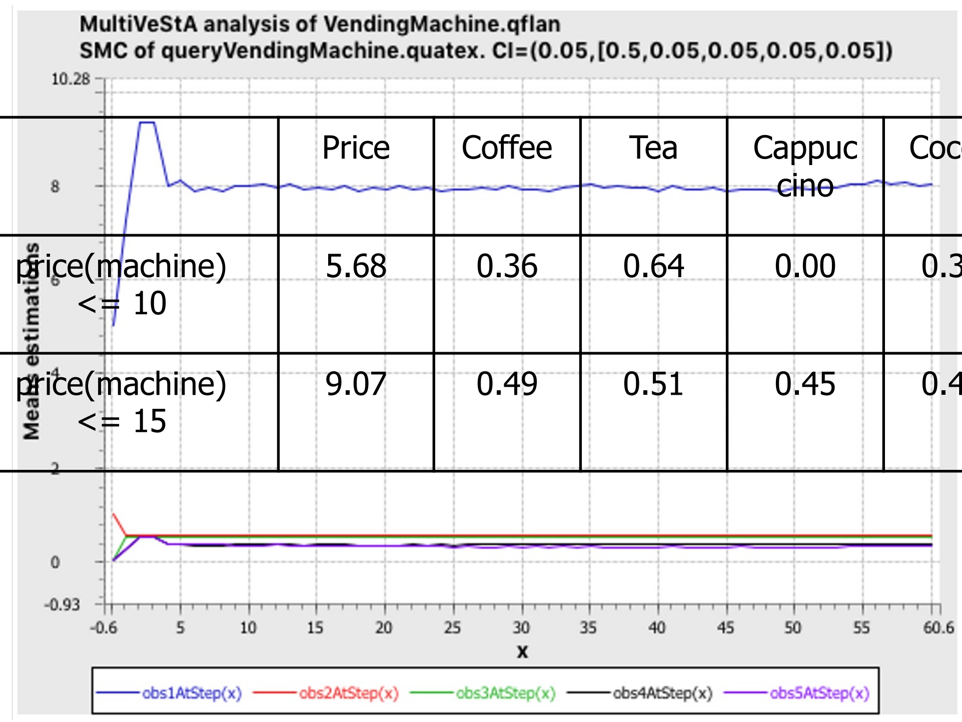

```
begin analysis

query = eval when {sold == 1.0 } :
{  price(Machine) [delta=0.5],
   Coffee , Tea , Cappuccino , Cocoa
}

default delta=0.05
alpha = 0.05
parallelism = 1

end analysis
```



	Price	Coffee	Tea	Cappuccino	Cocoa
price(machine) <= 10	5.68	0.36	0.64	0.00	0.34
price(machine) <= 15	9.07	0.49	0.51	0.45	0.44

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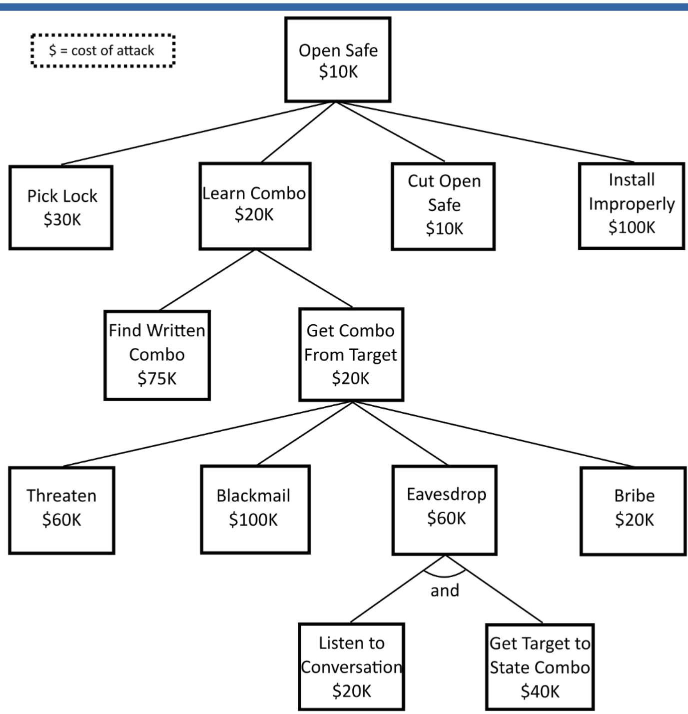
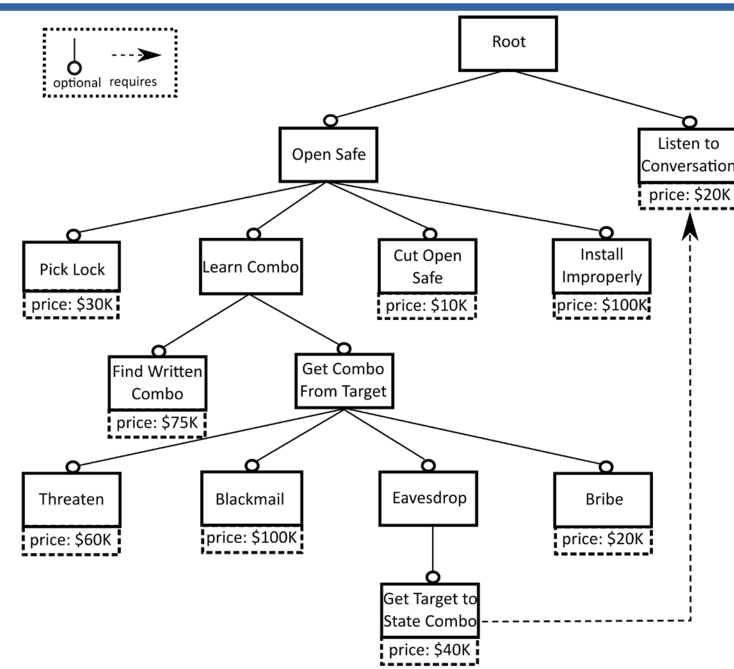
Schneier's SafeLock Attack Tree

An application of QFLan to security

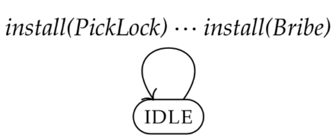


Schneier's simple attack tree

www.schneier.com/academic/archives/1999/12/attack_trees.html



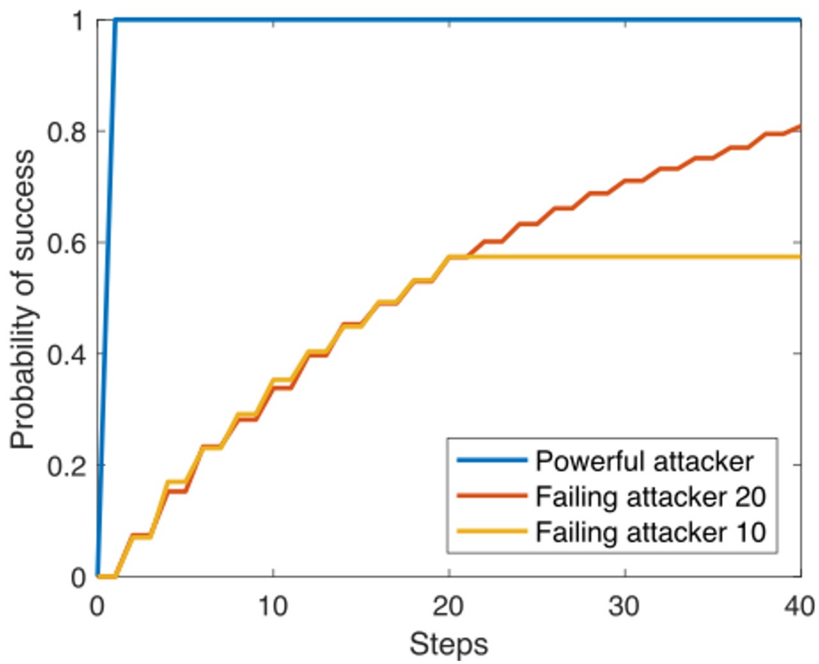
A feature model version of the attack tree **[TSE'18]**



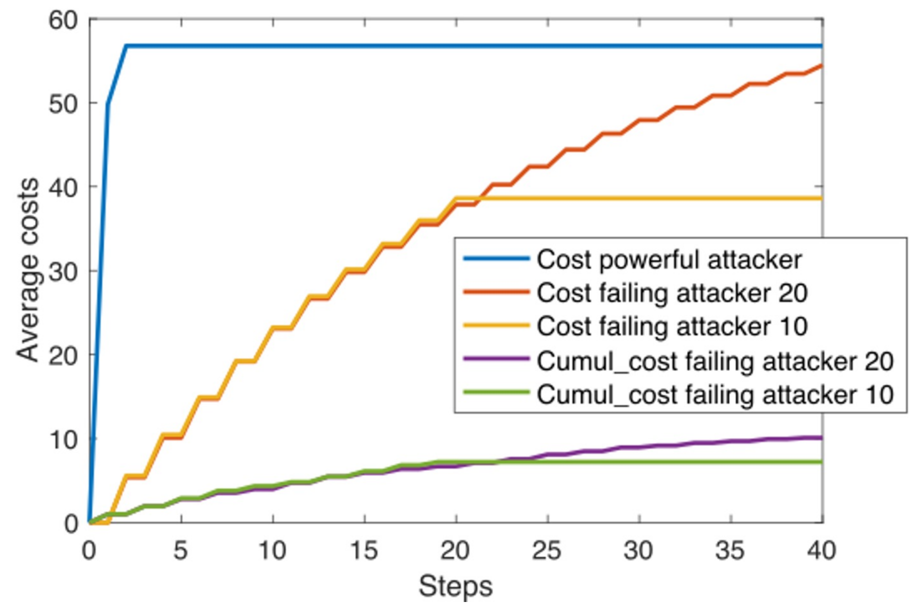

```
begin quantitative constraints
 //Restrict to attacks that cost less than 100
 { cost(Root) <= 100 }

end quantitative constraints
```

Schneier’s SafeLock Attack Tree

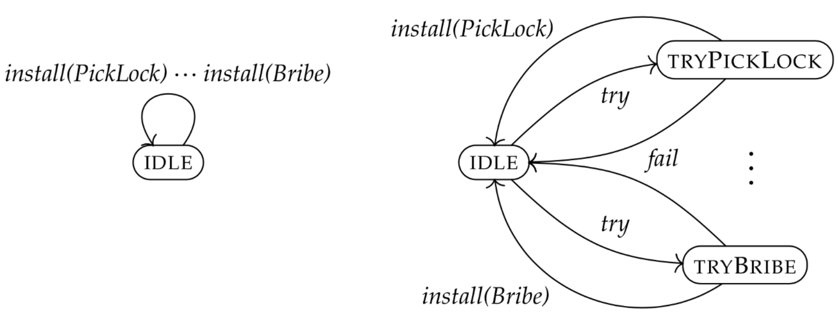
An application of QFLan to security



Probabilities of successful attacks



Costs of successful attacks




```
begin quantitative constraints
 //Restrict to attacks that cost less than 100
 { cost(Root) <= 100 }
 //Attacks can fail. Attacks attempts cost.
 //Restrict to attackers with a maximum bugdet.
 { accumulated_cost <= 10}
 //{ accumulated_cost <= 20}
end quantitative constraints
```

Future work

Extend semantics with notion of time

For the analysis of time-related properties

Continue investigating applicability to security domain

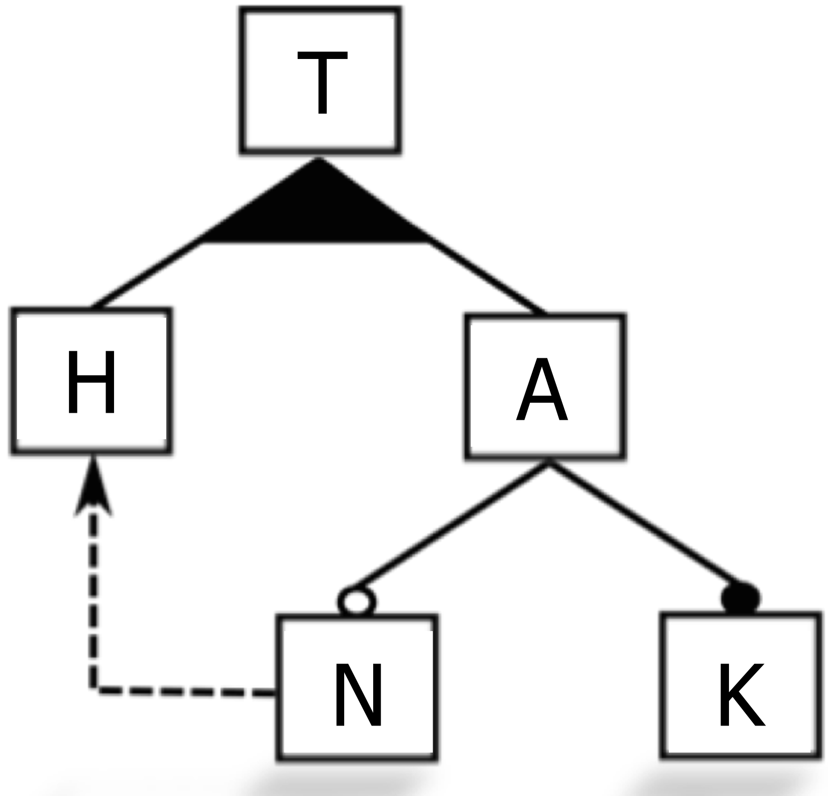
Adapt QFLan to attack trees domain

Synthesis of constraints

We had to relax the constraint “price(Machine) <= 10”

Can we synthesize the ‘right’ constraints automatically?

QUESTIONS?



YOU!

https://github.com/qflanTeam/QFLan/

QFLan: A tool for the Quantitative Analysis of Highly Reconfigurable Systems

A Software Engineering Approach to Quantitative Security Risk Modeling and Analysis using QFLan

Andrea Vandin
Sant'Anna School of Advanced Studies Pisa, Italy
DTU Technical University of Denmark

Maurice H. ter Beek
ISTI CNR Pisa, Italy

Axel Legay
UCLouvain, Belgium

Alberto Lluch Lafuente
DTU, Denmark

Classes 21t-22t, Software Validation and Verification, Unipi, 04-05/12/2023
Class 21t 04/12/2023

Outline

From QFLan to RisQFLan

- QFLan's Limitations for Risk Modeling and Analysis
- A Bank robbery scenario in RisQFLan
- How did we go from QFLan to RisQFLan?

Conclusions

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Conclusions

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QFLan limitations for Risk Modeling/Analysis

Not entirely direct encoding of the scenario
- The extra root node, the extra states to model failures, etc

We need different types of nodes
- Attack, defense, countermeasu

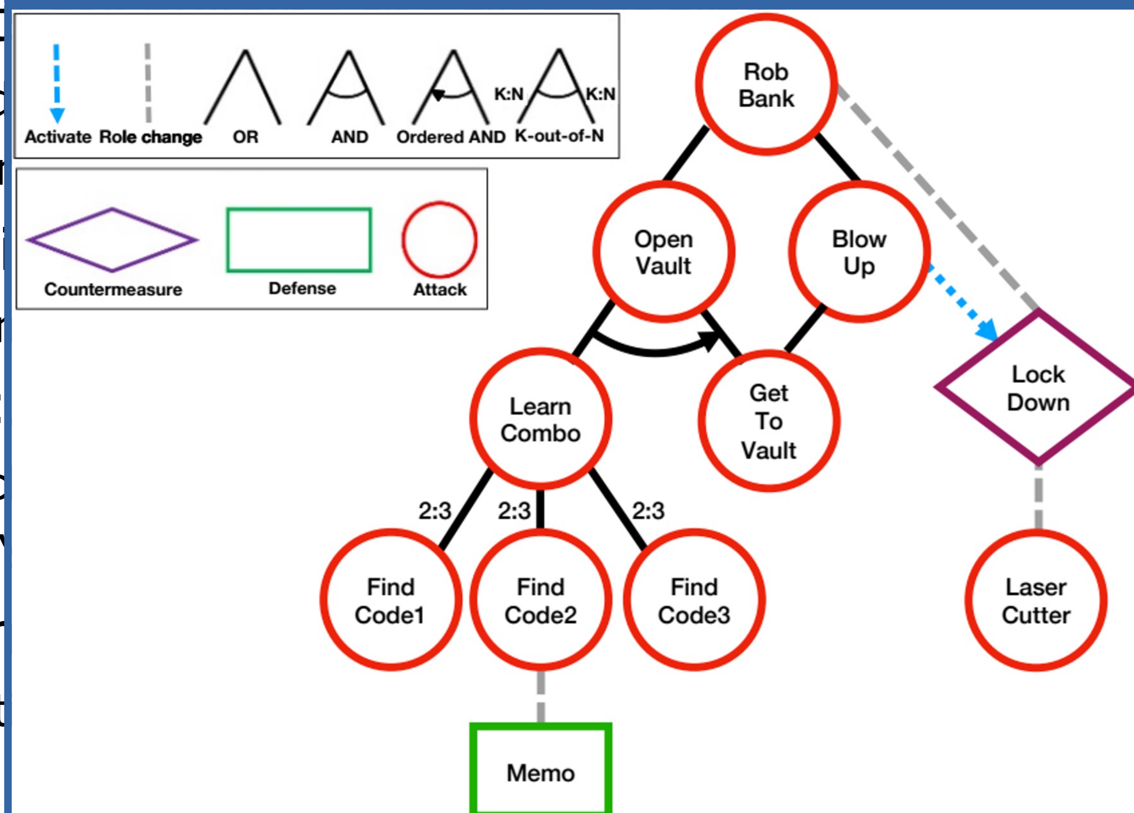
We need richer construct
- QFLan has: or, requires, excluc
- Missing *common* constructs: ar

Attack attempts might fai
- The 'install' of an attack node r

There is no 'absolute sec
- *Qualitative* constraints like 'exc
- Often, failure probabilities are '

Exact analysis might be r
- Complement MultiVeStA Statist

We want to model scenarios like this



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- **A Bank robbery scenario in RisQFLan**
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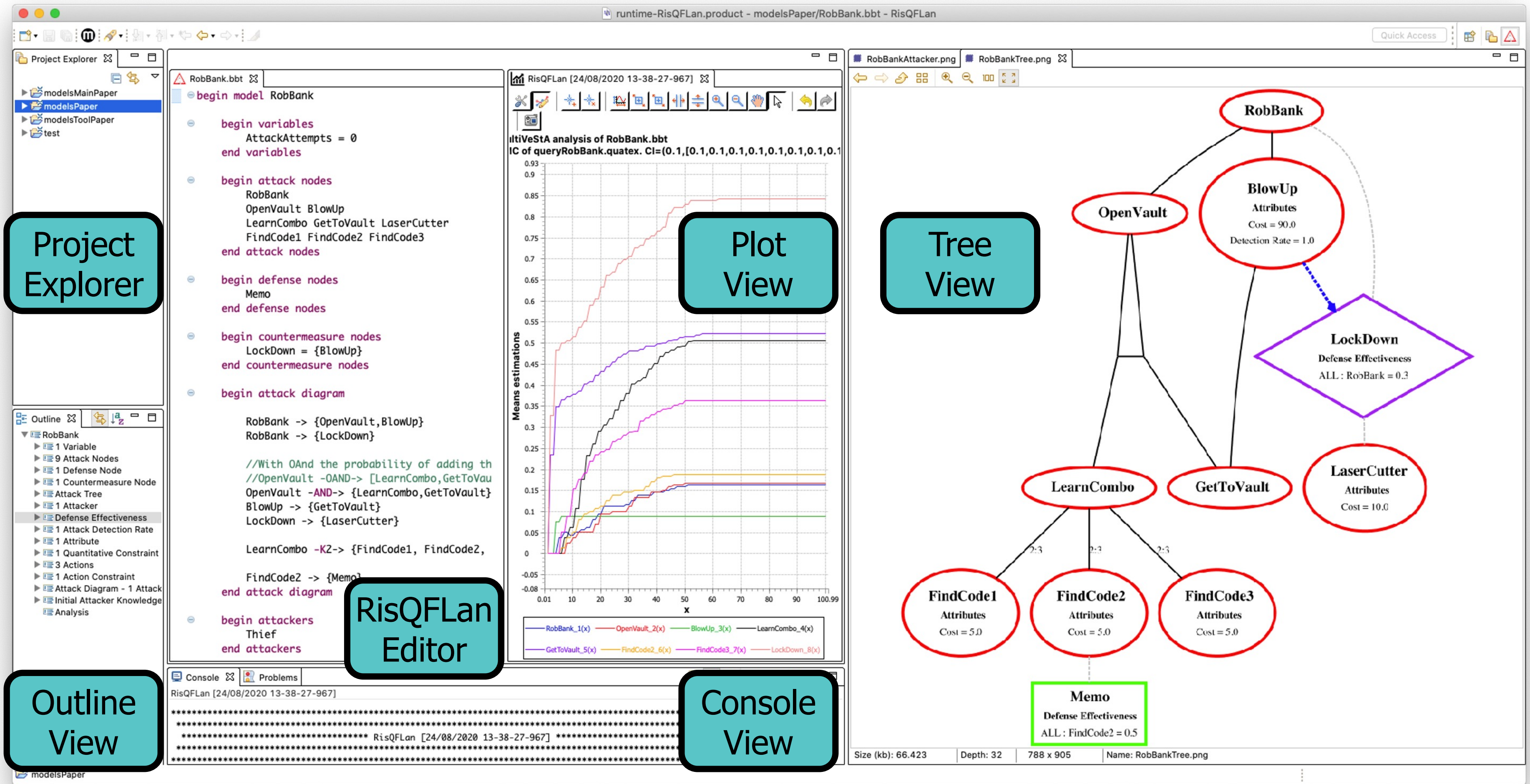
Conclusions

A Bank Robbery Scenario in RisQFLan

A screenshot of RisQFLan



bit.ly/RisQFLan

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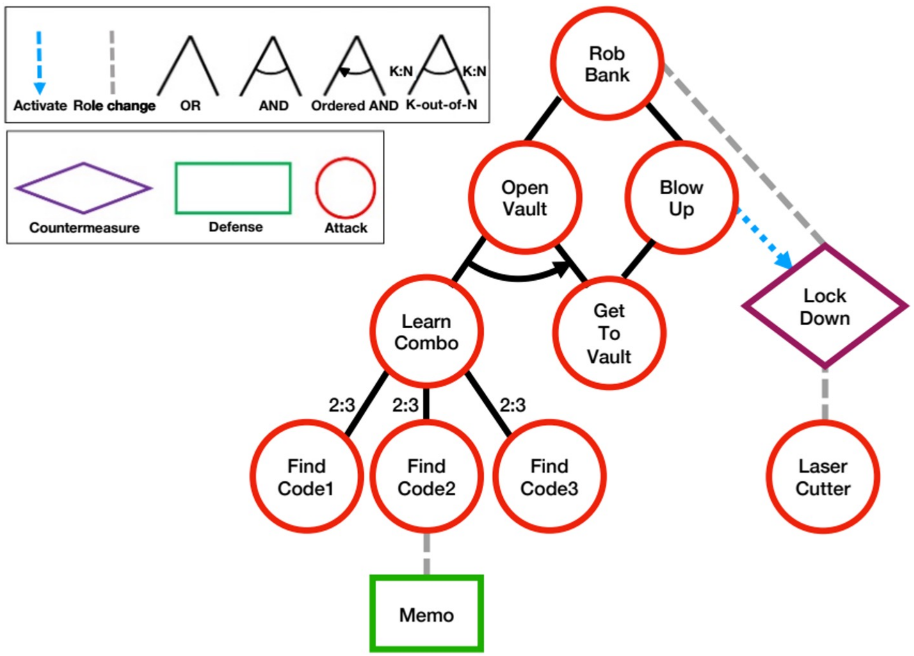
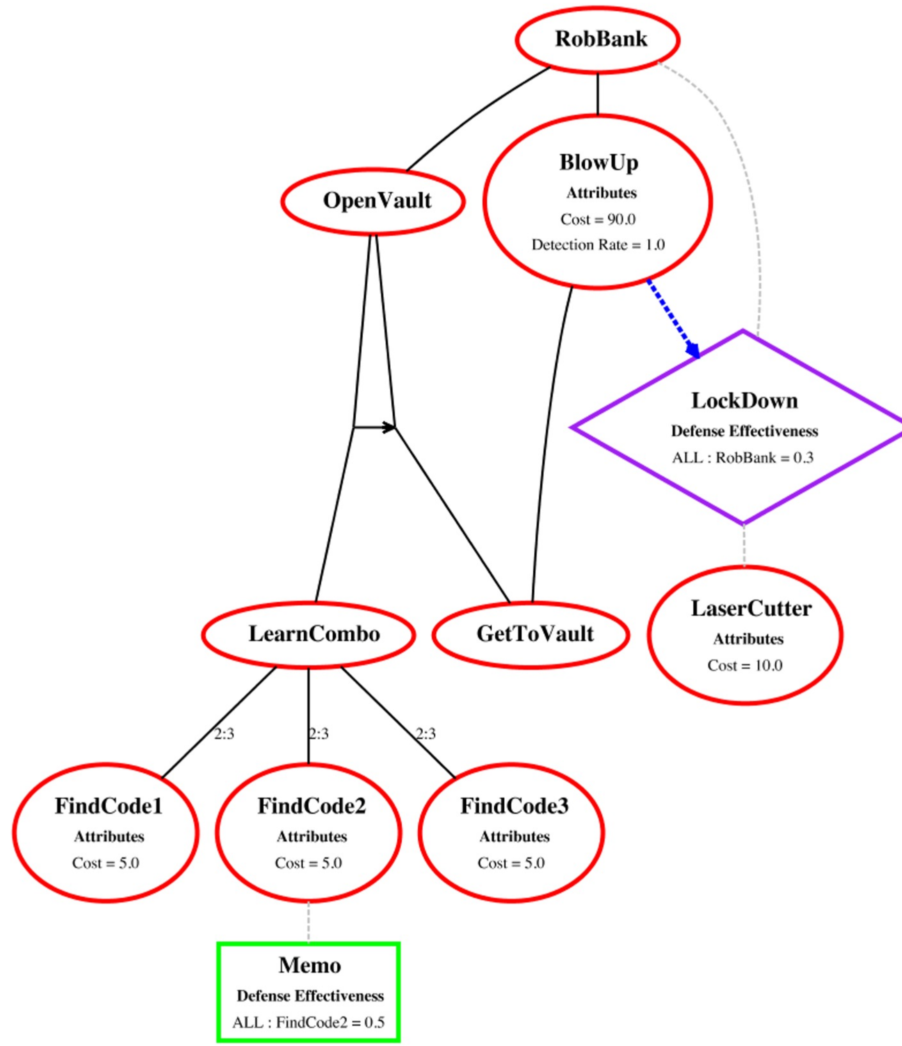
A Bank Robbery Scenario in RisQFLan

Attack-defense tree



Desired scenario



Modeled Scenario

bit.ly/RisQFLan

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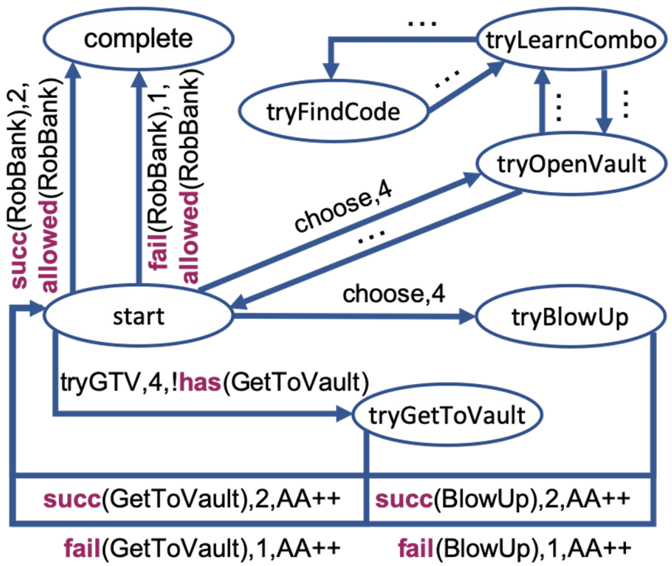
A Bank Robbery Scenario in RisQFLan
Behaviour



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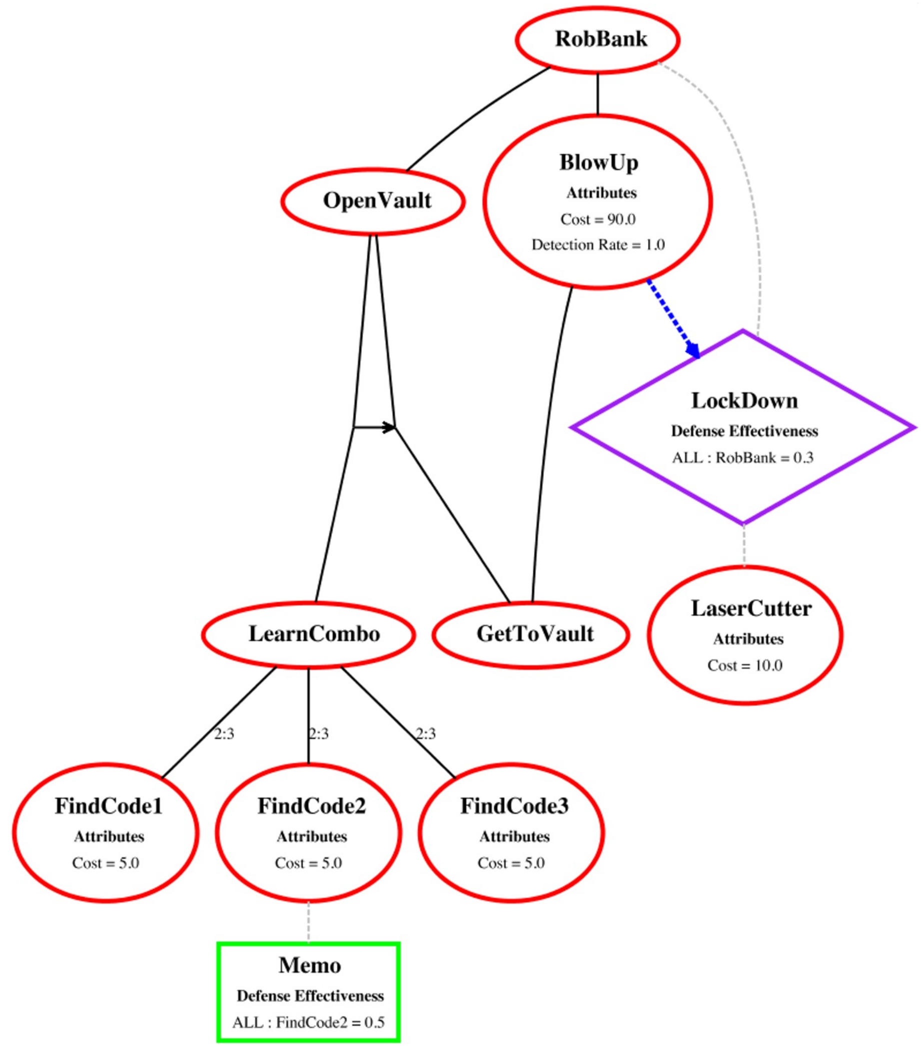

Attack-defense tree

bit.ly/RisQFLan

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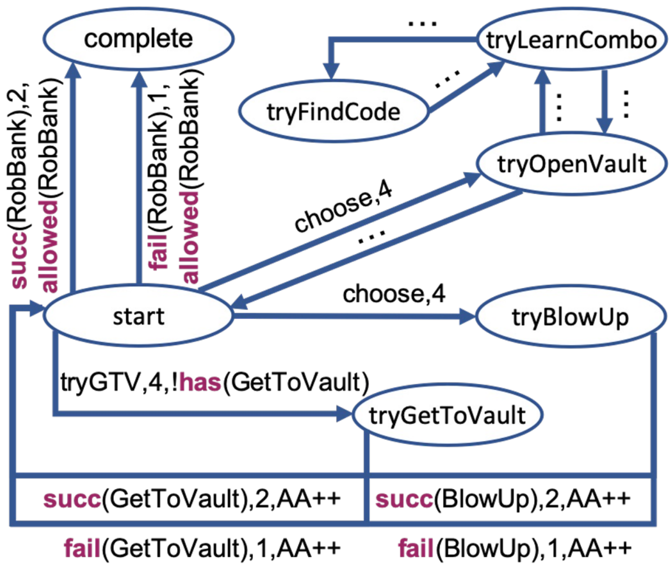
A Bank Robbery Scenario in RisQFLan

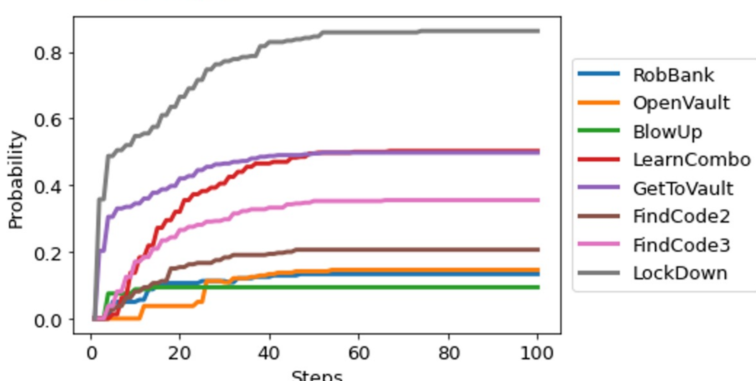
Analysis: SMC with MultiVeStA

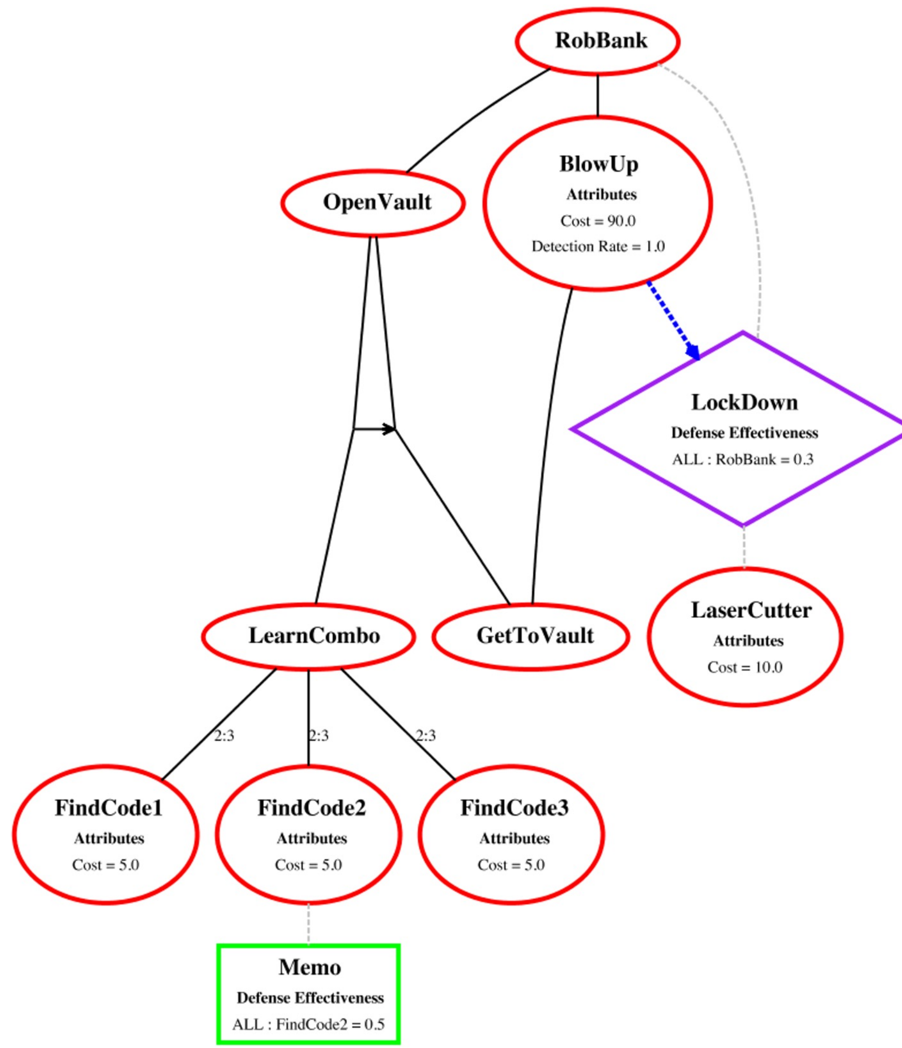


Behaviour

Statistical SMC Analysis

```
begin analysis
    query = eval from 1 to 100 by 1 :
    { RobBank, OpenVault, BlowUp,
      LearnCombo, GetToVault,
      FindCode2, FindCode3, LockDown }
    default delta = 0.1 alpha = 0.1
    parallelism = 1
end analysis
```





Attack-defense tree

bit.ly/RisQFLan

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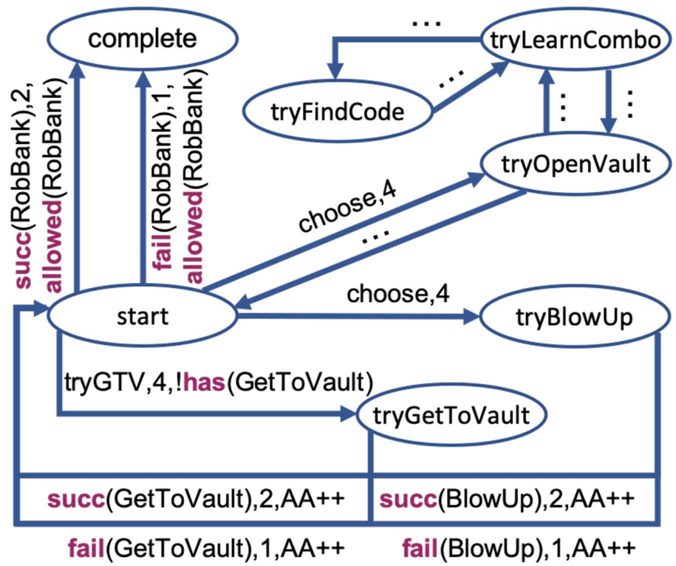
A Bank Robbery Scenario in RisQFLan

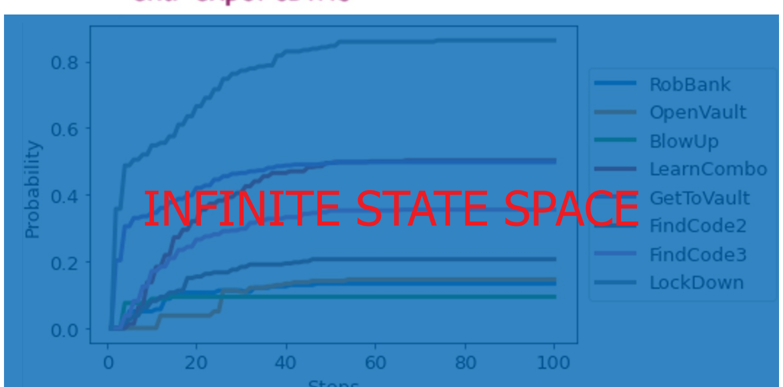
Analysis: PMC with PRISM/STORM

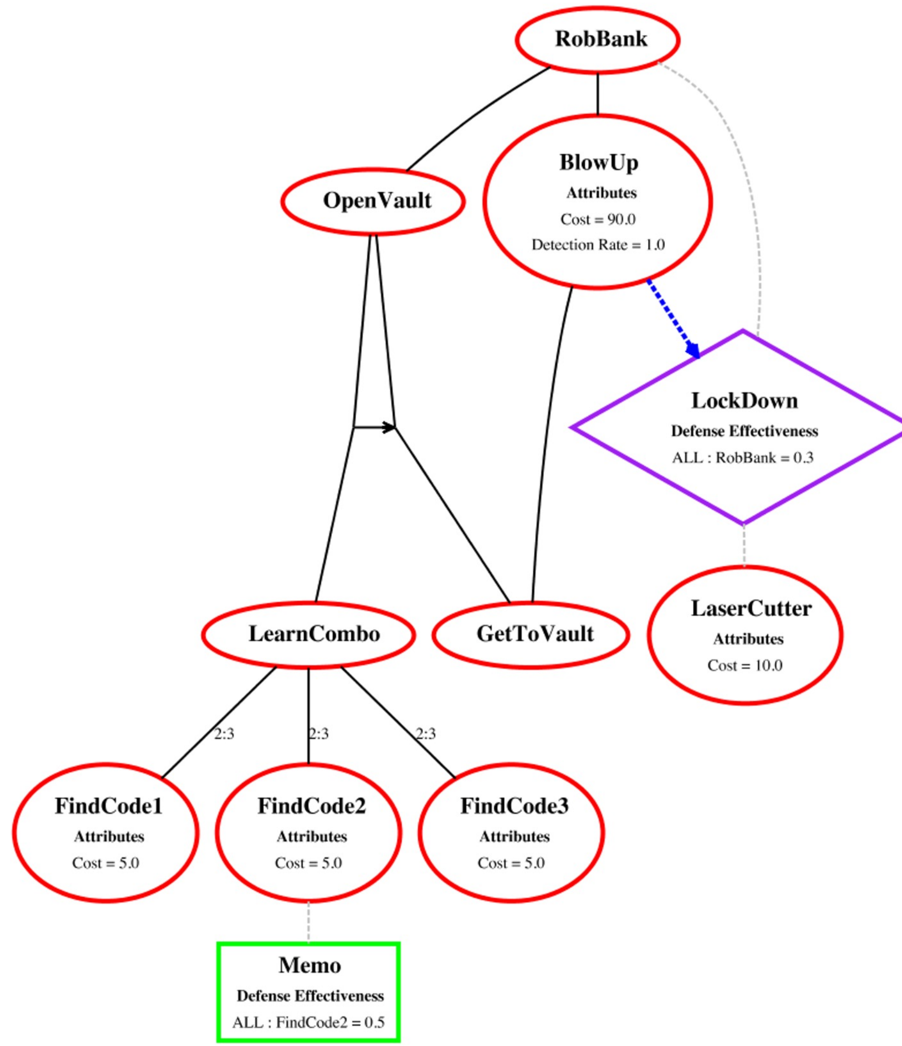


Behaviour

```
begin exportDTMC
  file ="RobBank.prism"
  label with "Succeeded"
        when has(RobBank)
end exportDTMC
```

Exact PMC Analysis





Attack-defense tree

bit.ly/RisQFLan

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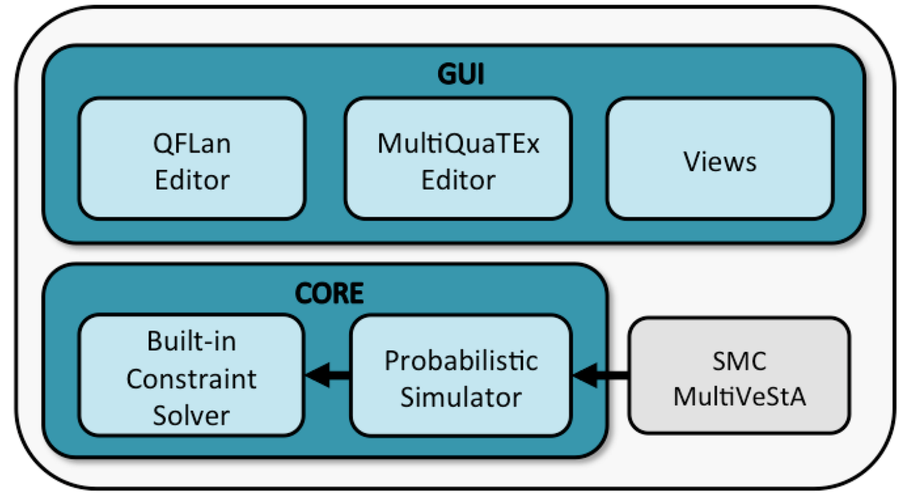
Conclusions

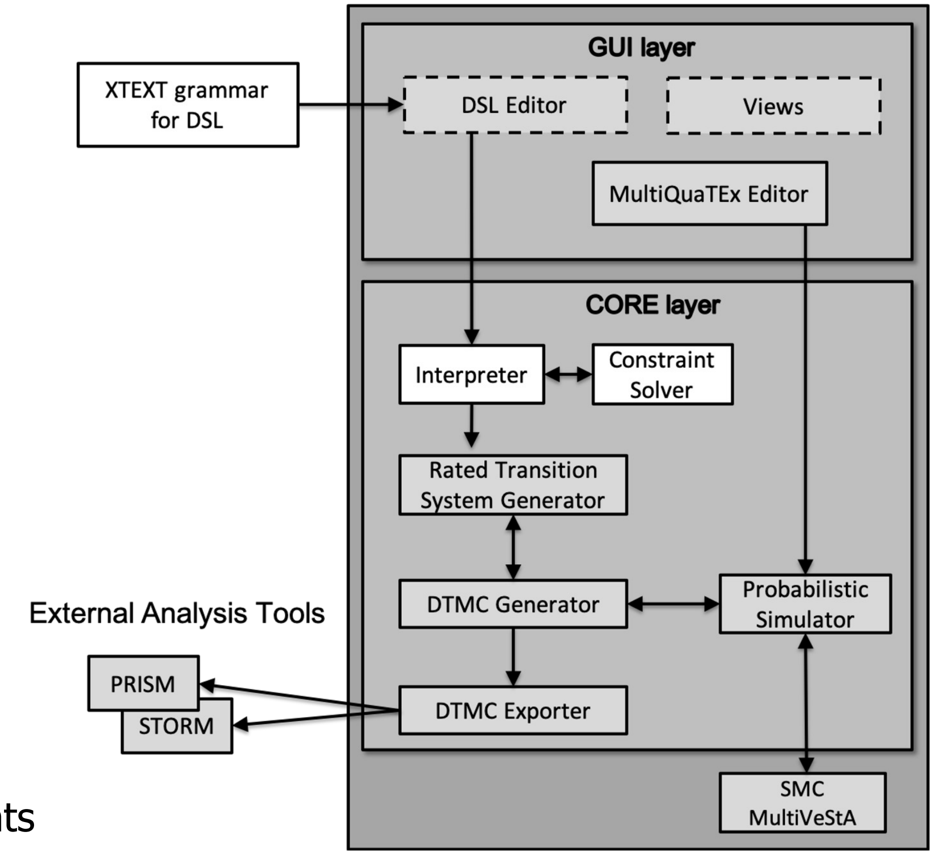
From QFLan to RisQFLan

Generalizing the QFLan approach

QFLan Architecture [FM’18][TSE’18]



Generalized QFLan Architecture [Draft’20]



…	Existing domain-independent components
…	Automatically generated domain-independent components
…	Domain-specific components necessary to instantiate the architecture in a new domain

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Conclusions

RisQFLan: A Software Engineering Approach to Quantitative Security Risk Modeling and Analysis

- Obtained via a DSL-independent generalization of QFLan + its instantiation to security domain
- Both QFLan and RisQFLan are open-source projects

Main improvements

- Modeling: Richer constructs specific to the security domain
- Analysis: New support for exact PMC engines (**PRISM**, STORM) complementing existing SMC engine (MultiVeStA)

Related work

- Due to the generality and versatility of our framework, we succeeded in incorporating many features from proposals in the literature
- E.g.: o-and, noticeability, countermeasures (see validation in [Draft20])
- The explicit probabilistic attacker behaviour is somehow new, as
- Specific dynamic threat profiles is a related feature. But it is often unsupported
  - Supported only recently by a few approaches in a limited way
- RisQFLan allows for nodes with multiple parents
  - This is convenient: allows to keep models small. But it is often unsupported

Future work

Attributes of leaf nodes are propagated up the tree via sum.

- Other approaches, e.g. SecurITree, allow for attribute-specific propagation functions (e.g., min, max, product)

Allow for non-deterministic (unspecified) aspects in RisQFLan

- Use external tools (Uppaal Stratego?) to synthetize the attacker with highest success probability/the defense with best impact

Even though the design of RisQFLan is inspired by the most common features from the literature, we want to:

- Better understand relation of RisQFLan with the huge related work

Validate RisQFLan scalability and expressiveness considering realistic scenarios

- E.g. the Attack Tree Benchmarks www7.in.tum.de/~kraemerj/upload/index.php

Current work

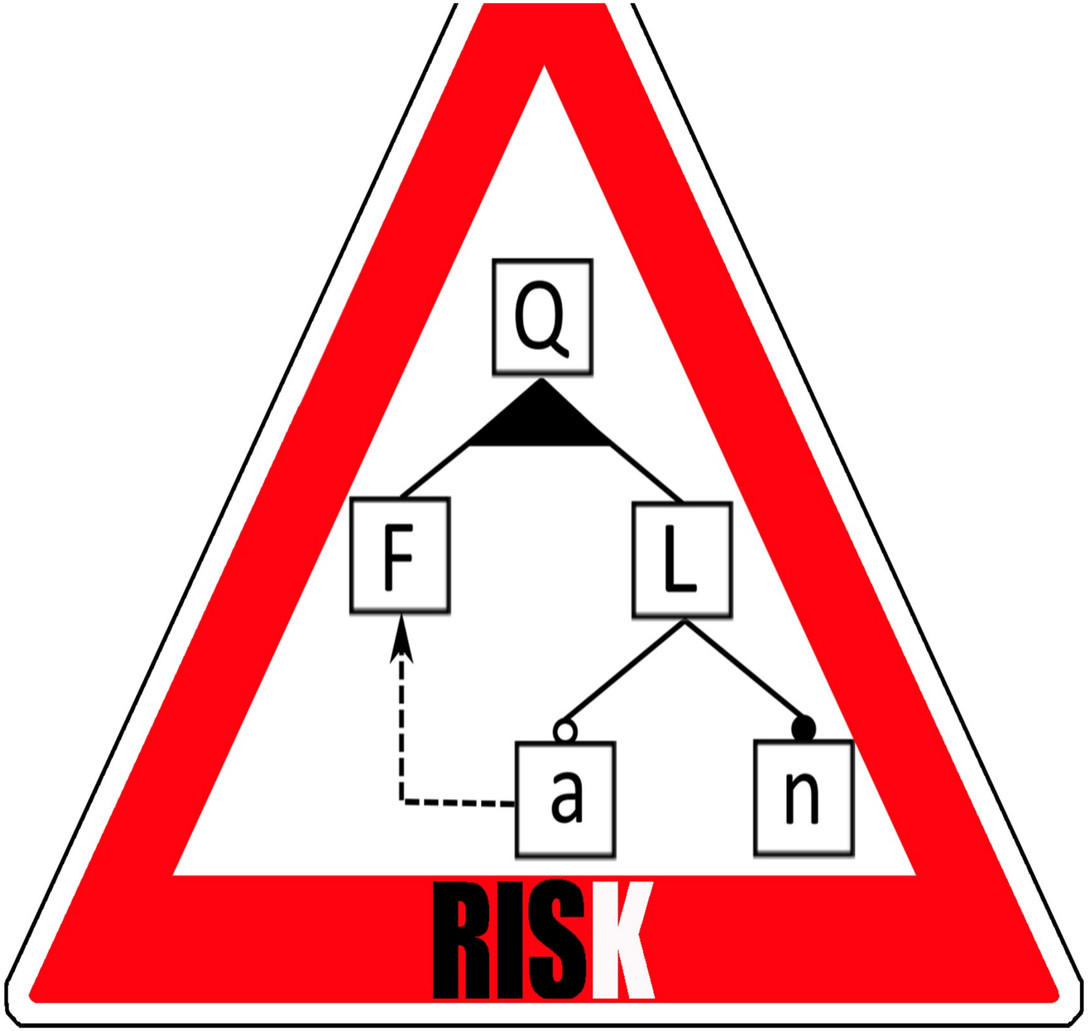
The great expressive power coming from the quantitative constraints, etc, might make it difficult to understand what a model does

SMC and PMC give only limited information on what the model does

- We get black-box numbers
- Are these numbers due to the nature of the studied system?
- Are these numbers due to bugs?

Can we exploit novel techniques to **explain SMC?**

QUESTIONS?



bit.ly/RisQFLan

STATISTICAL MODEL CHECKING MEETS PROCESS MINING

WHITE-BOX VALIDATION OF SIMULATION MODELS

Andrea Vandin

Sant'Anna School of Advanced Studies – Pisa

Institute of Economics

Department of Excellence 2018 - 2022 2023-2027!

EMbeDS Economics and Management in the era of Data Science

DTU Danmarks Tekniske Universitet

Classes 21t-22t, Software Validation and Verification, Unipi, 04-05/12/2023

Class 21t 04/12/2023

WHITE-BOX VALIDATION OF PRODUCT LINES AND THREAT MODELS BY STATISTICAL MODEL CHECKING AND PROCESS MINING

Roberto Casaluce, Andrea Burattin, Francesca Chiaromonte,
Alberto Lluch Lafuente, Andrea Vandin

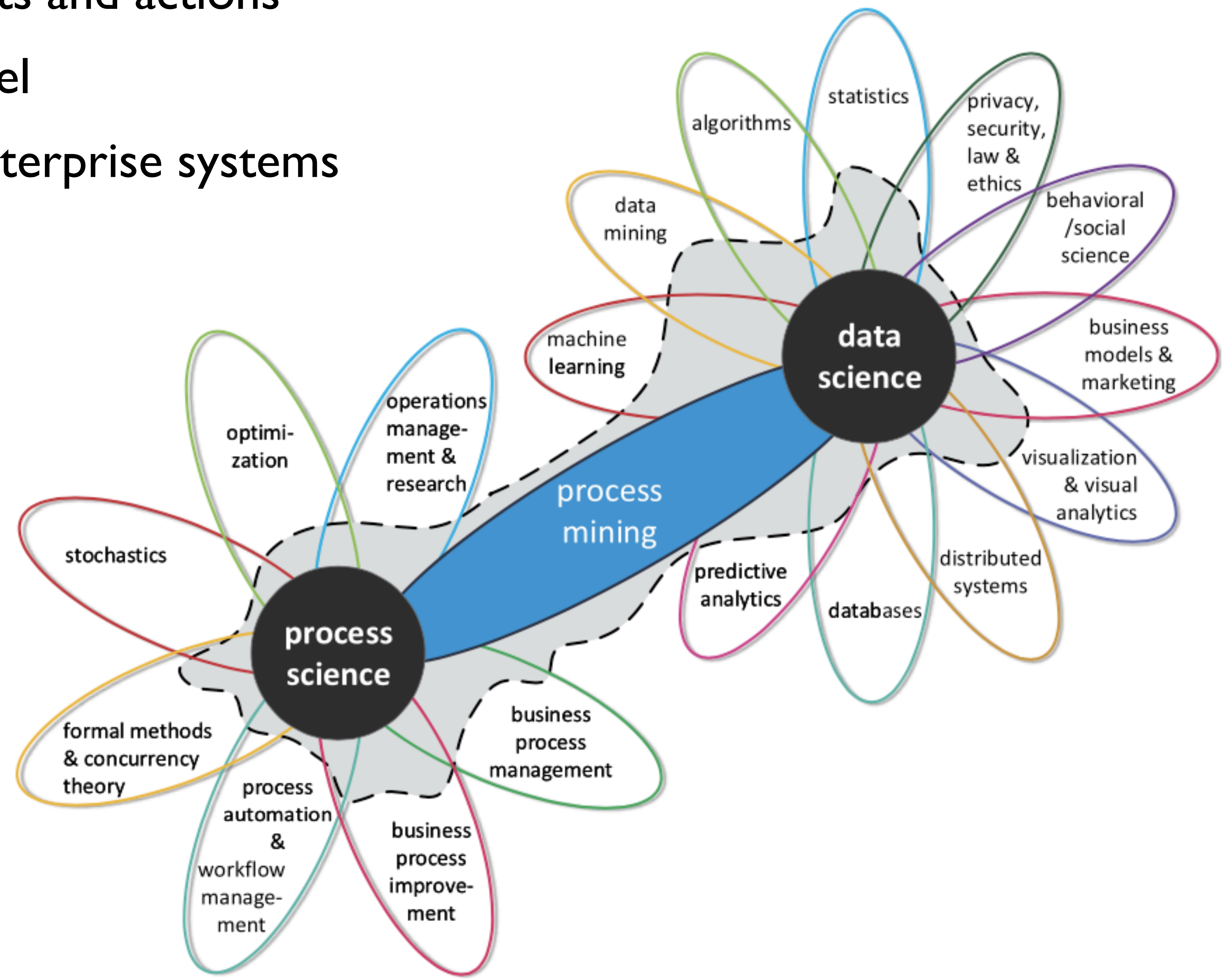
Recently published at DEC2H
zenodo.org/record/6623377

Journal extension at JSS: 2nd round of review
zenodo.org/record/6623377

‘A SIMPLIFIED OVERVIEW’

WHAT IS PROCESS MINING?

- A family of techniques linking data science and process management to support the analysis of processes
- Aims at turning event logs into insights and actions
- Uses data to discover a process model
  - It observes events recorded by enterprise systems



Van Der Aalst, W., et al. (2011, August). Process mining manifesto. In *Conference on Business Process Management*

WHAT IS PROCESS MINING?

The reference process…

The traces, or process logs

- The *actual* process…

WHAT IS PROCESS MINING?


Picture by Koen Olsthoorn

With Process Mining we can discover that
- The actual process is different from the expected one

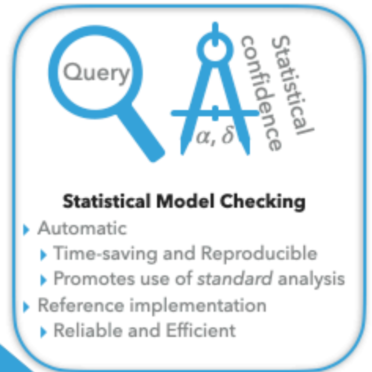
Idea
Can PM explain the SMC results?

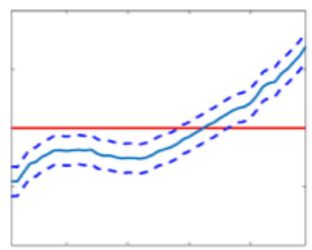
The reference process…

The traces, or process logs
- The *actual* process…

OUR METHODOLOGY 4 WHITE-BOX VALIDATION

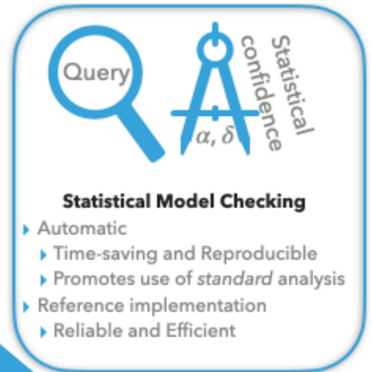
newstalkzb.co.nz/news/education/modern-lego-sets-more-complex-less-inspiring/

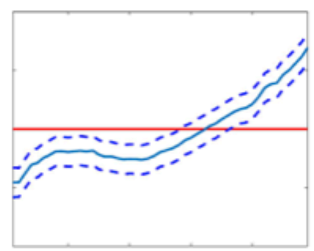




OUR METHODOLOGY 4 WHITE-BOX VALIDATION

newstalkzb.co.nz/news/education/modern-lego-sets-more-complex-less-inspiring/





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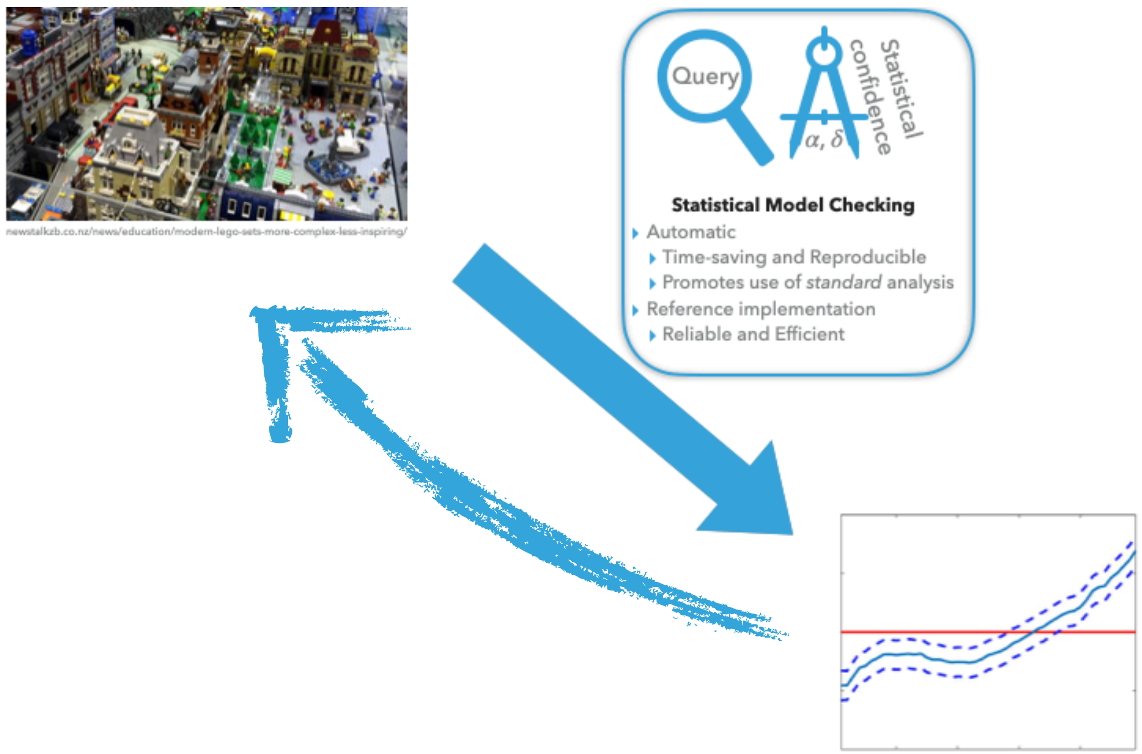
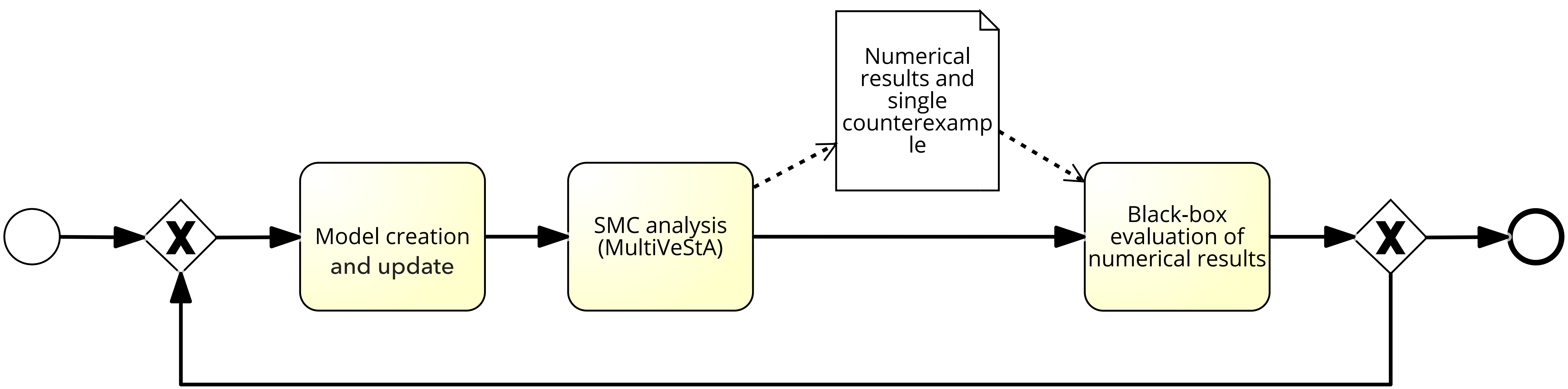
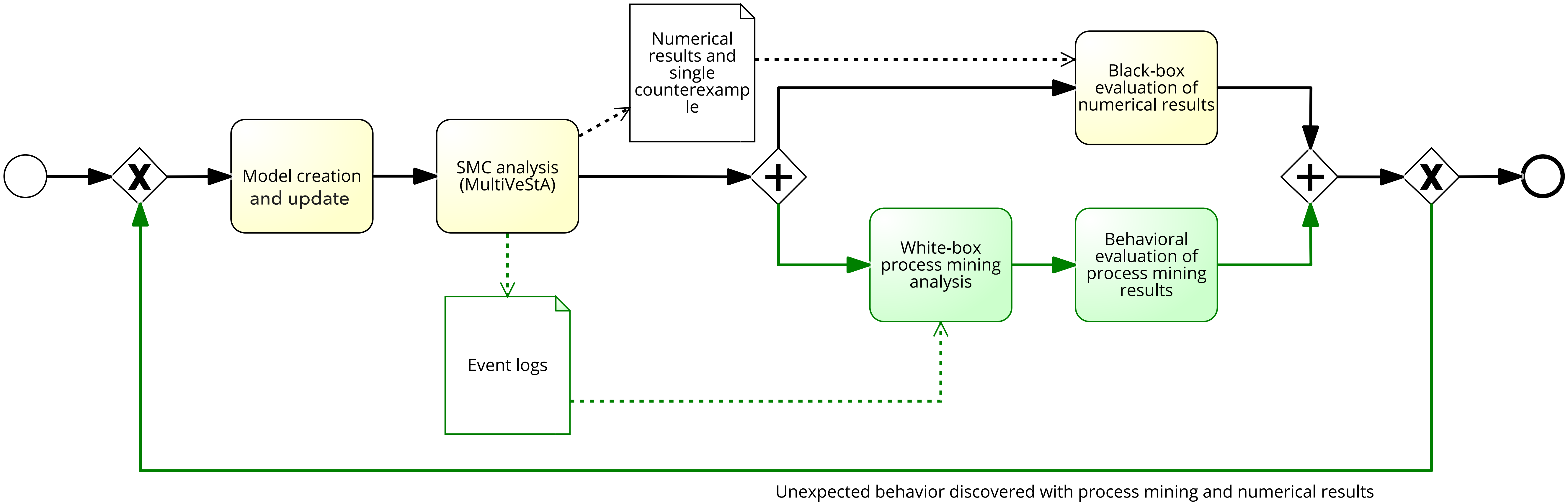


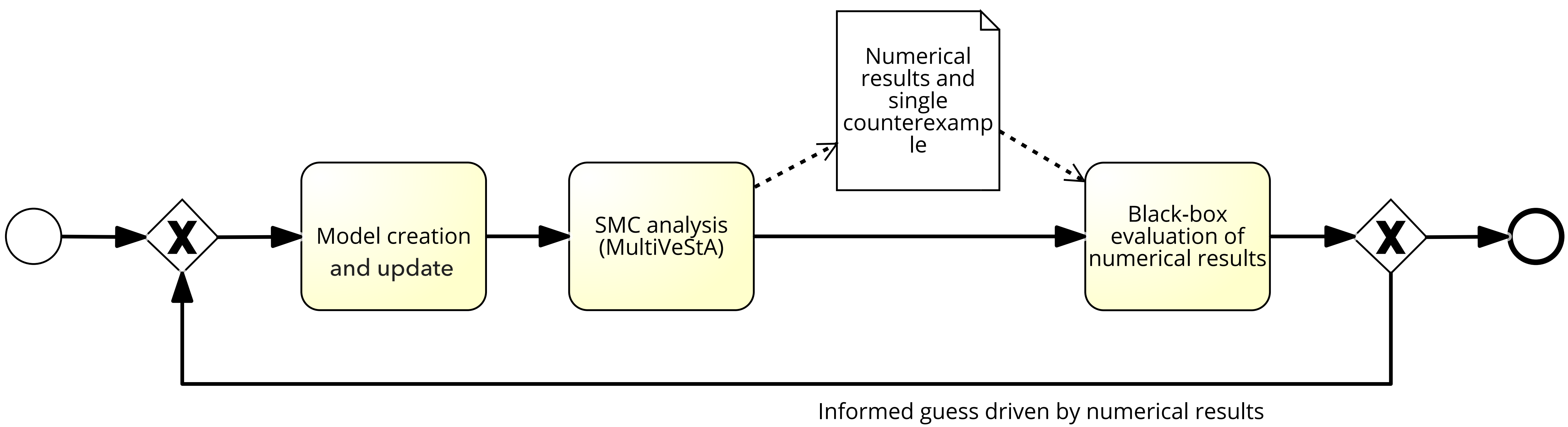


State-of-the-art life-cycle of SMC-analysed simulation

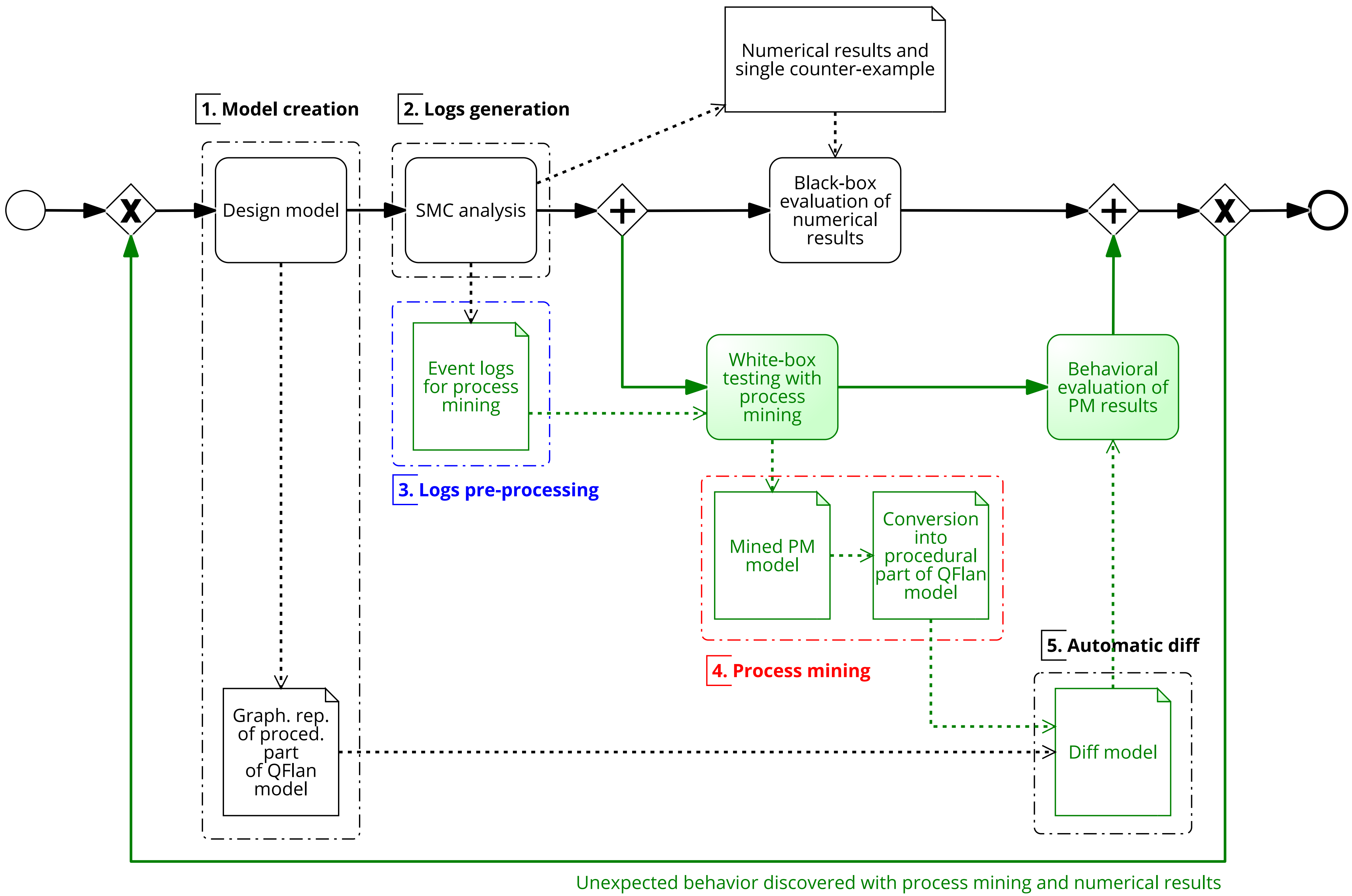
OUR METHODOLOGY 4 WHITE-BOX VALIDATION



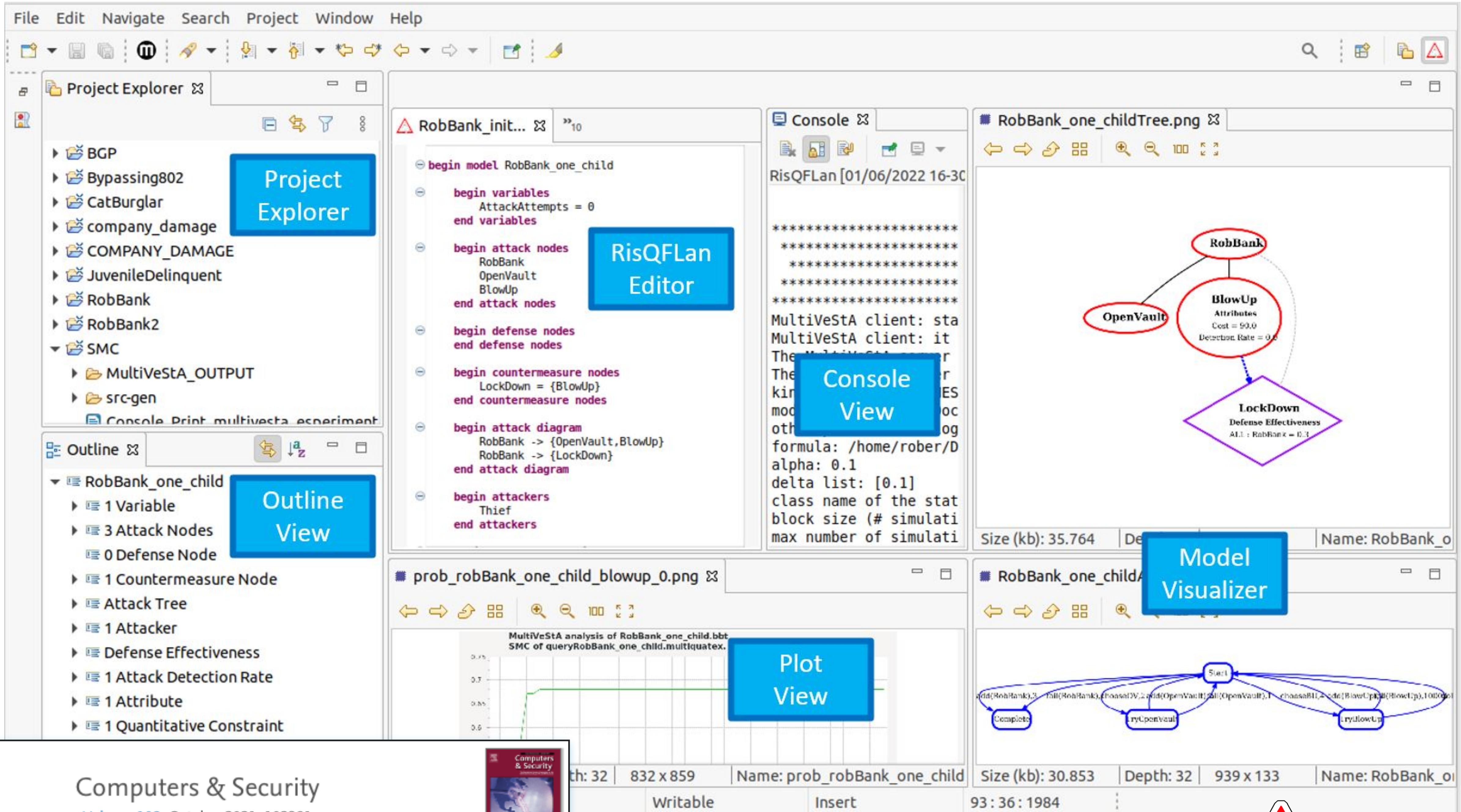
Our novel SMC- and PM-guided methodology for white-box model validation



Usual life-cycle of SMC-analysed simulation models


Numerical results and single counter-example
1. Model creation
2. Logs generation
Design model
SMC analysis
Black-box evaluation of numerical results
Event logs for process mining
White-box testing with process mining
Behavioral evaluation of PM results
3. Logs pre-processing
Mined PM model
Conversion into procedural part of QFlan model
4. Process mining
5. Automatic diff
Graph. rep. of proced. part of QFlan model
Diff model
Unexpected behavior discovered with process mining and numerical results

APPLICATION ON SIMPLE THREAT ANALYSIS EXAMPLE



Computers & Security

Volume 109, October 2021, 102381

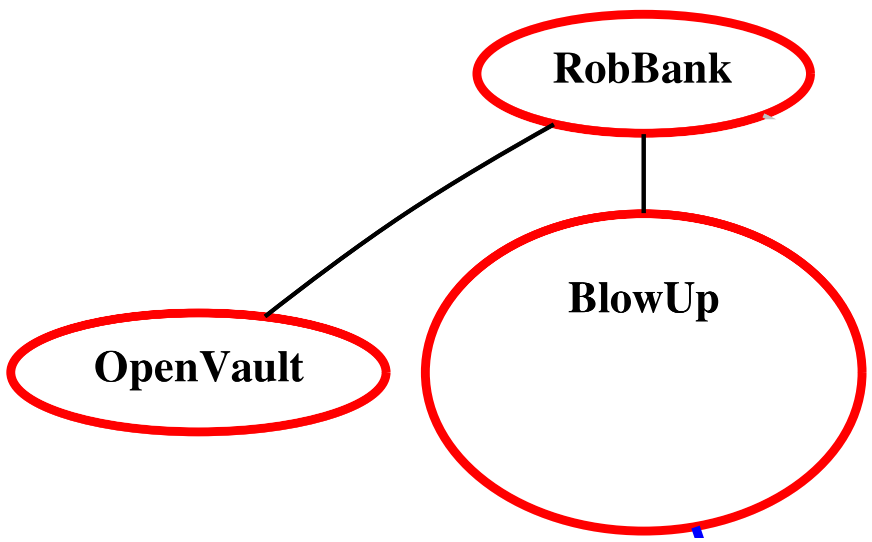
ELSEVIER

TC 11 Briefing Papers

Quantitative Security Risk Modeling and Analysis with RisQFLan

Maurice H. ter Beek [a], Axel Legay [b], Alberto Lluch Lafuente [c], Andrea Vandin [c, d]

APPLICATION ON SIMPLE THREAT ANALYSIS EXAMPLE



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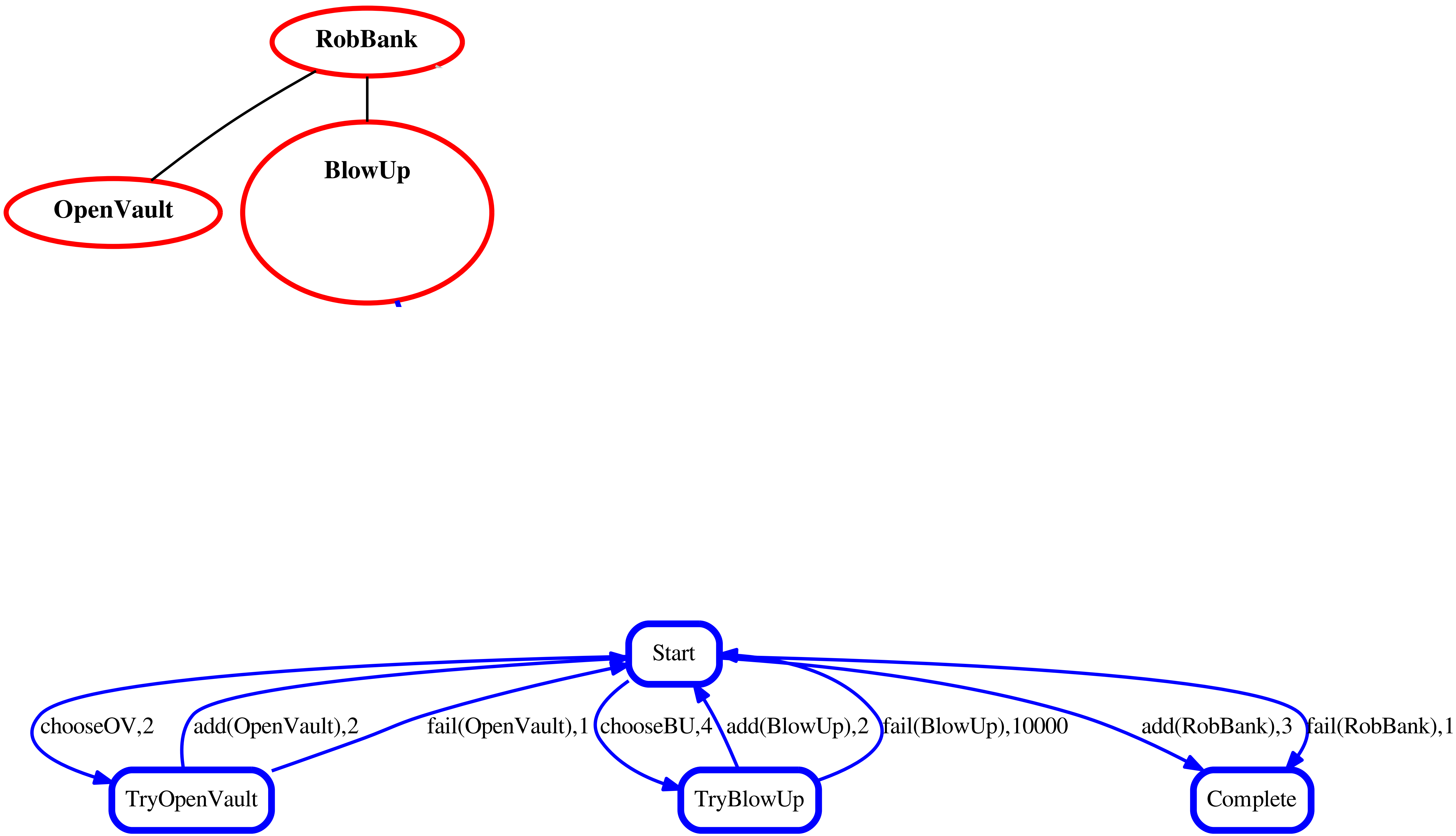

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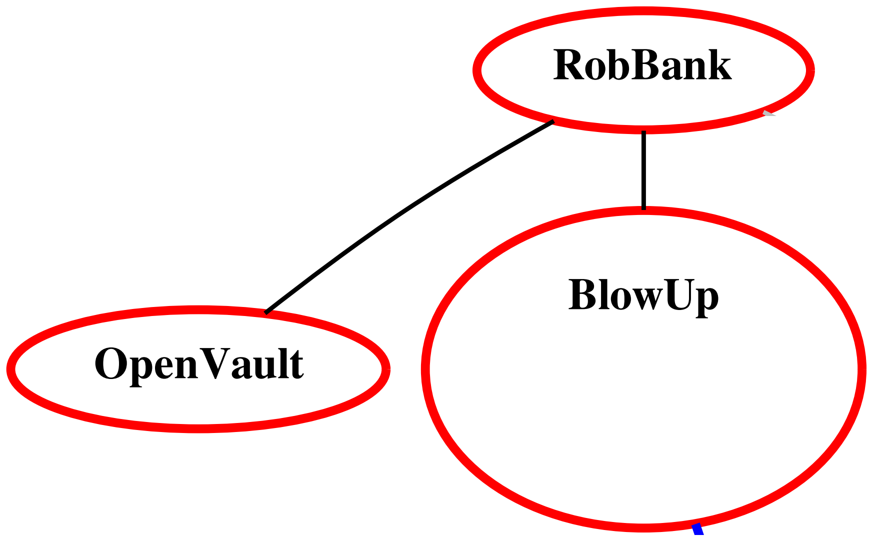

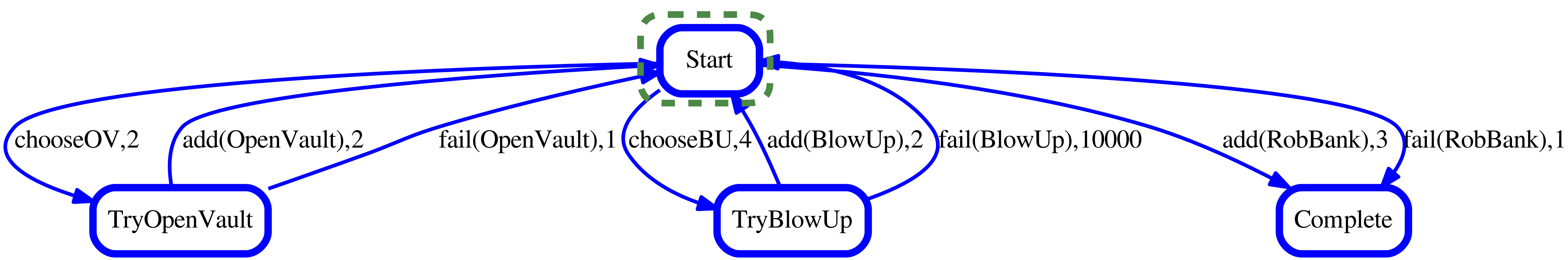

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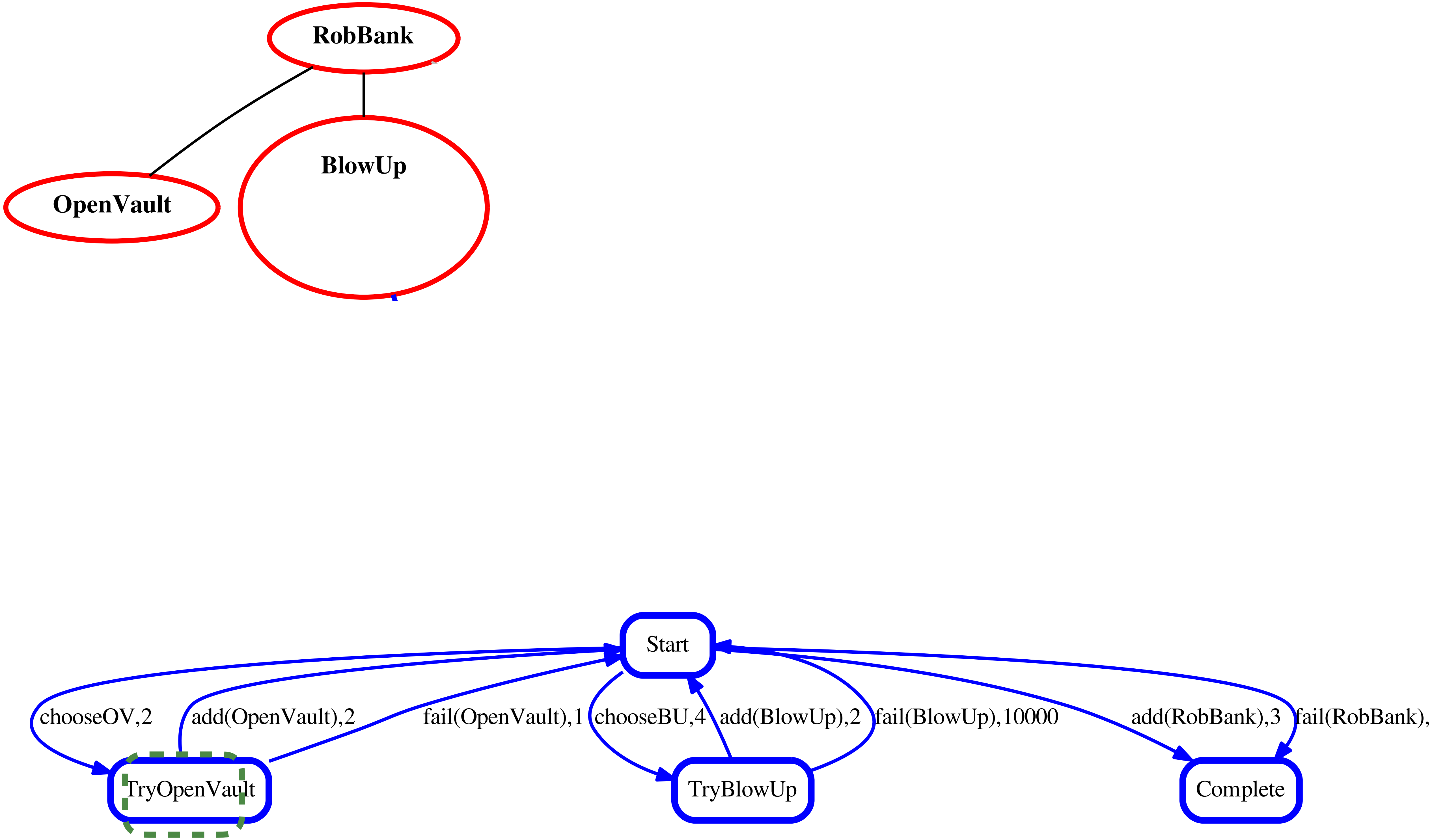

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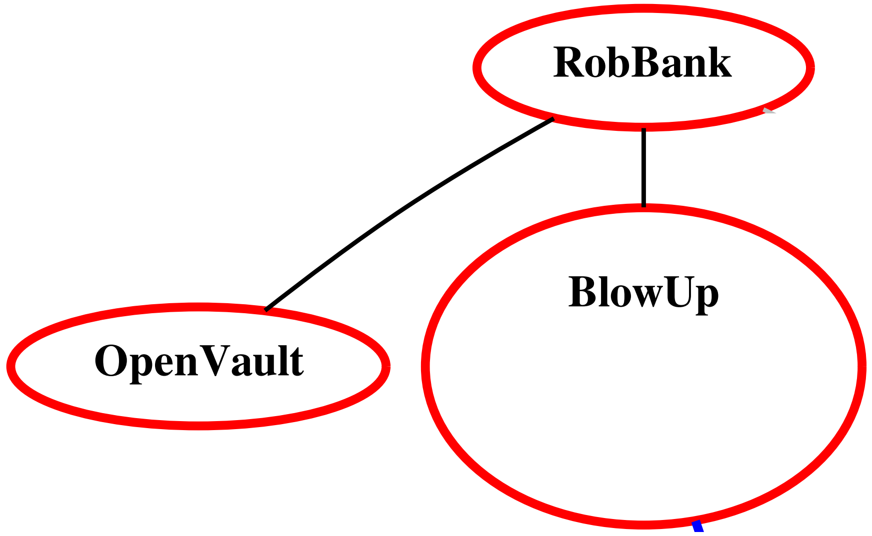
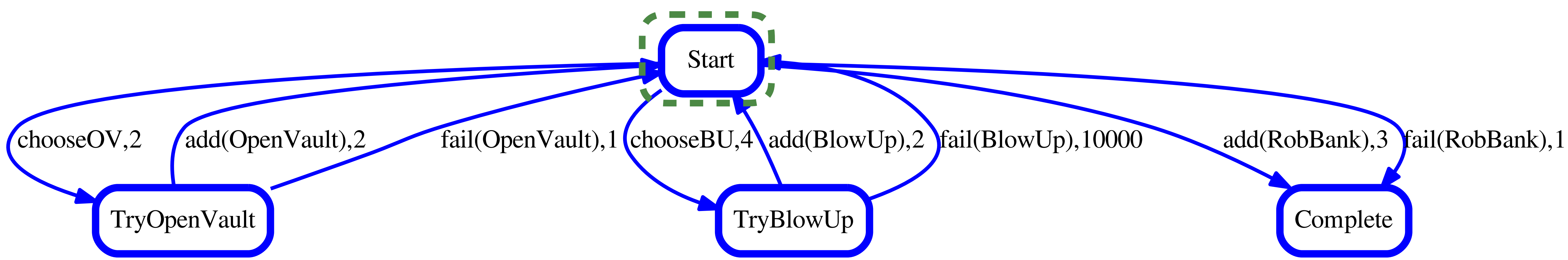
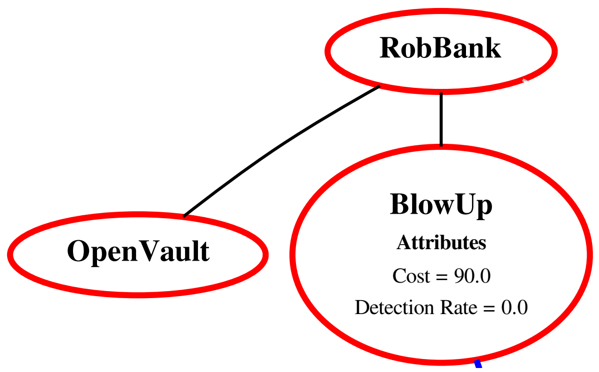
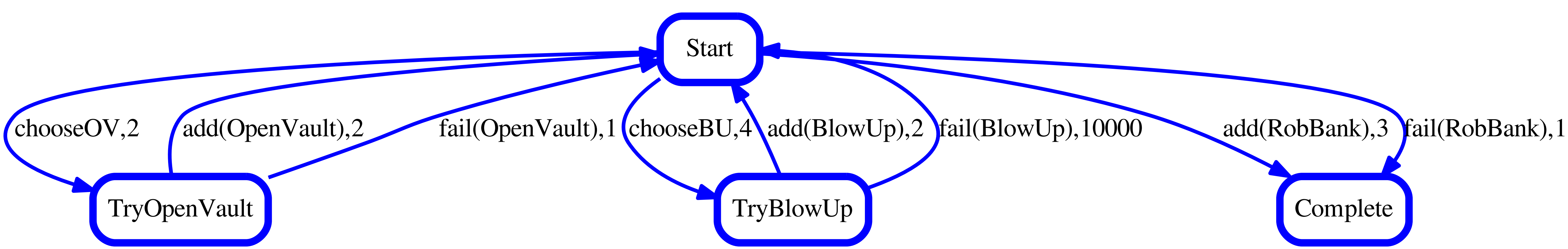




ANALYSIS OF ORIGINAL MODEL



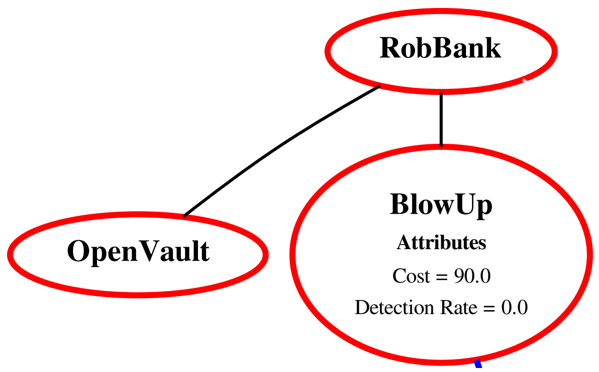


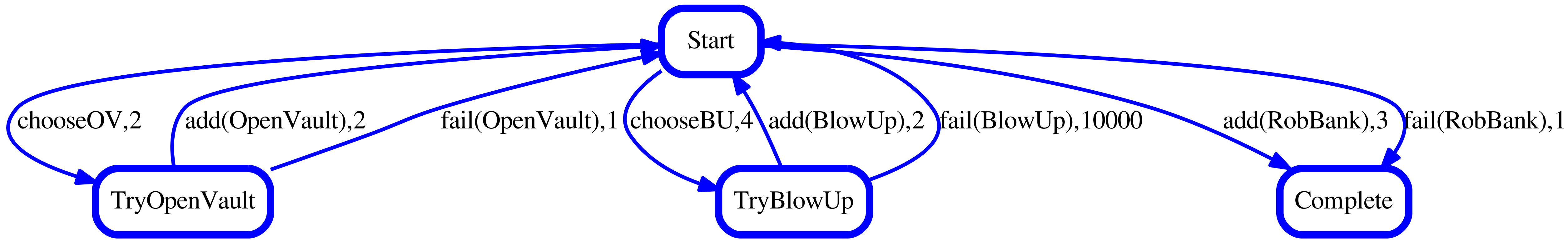
ANALYSIS OF ORIGINAL MODEL

Probability of successful bank robbery!? **0.17**

Why?

1) My defences are *good*
2) The attacker is *bad*
3) **Or my model is bad**!?





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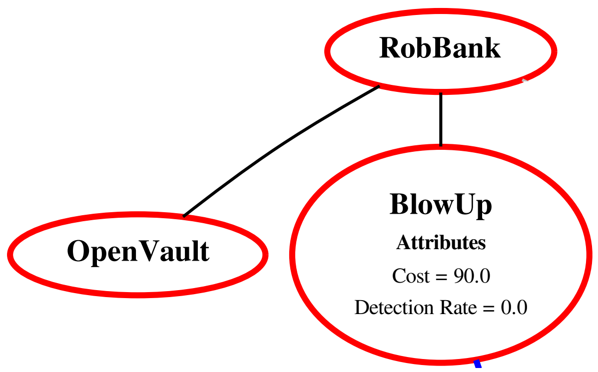
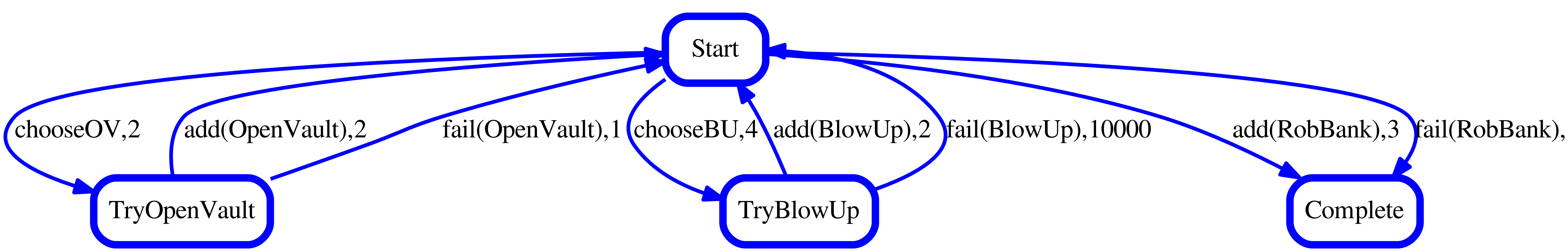
We set alpha=0.1, delta=0.1

MultiVeStA performs **240 simulations**

- We generate **logs for each simulation**
- We ask **Fluxicon Disco mine these logs**
- Can we spot **any issue in the model?**





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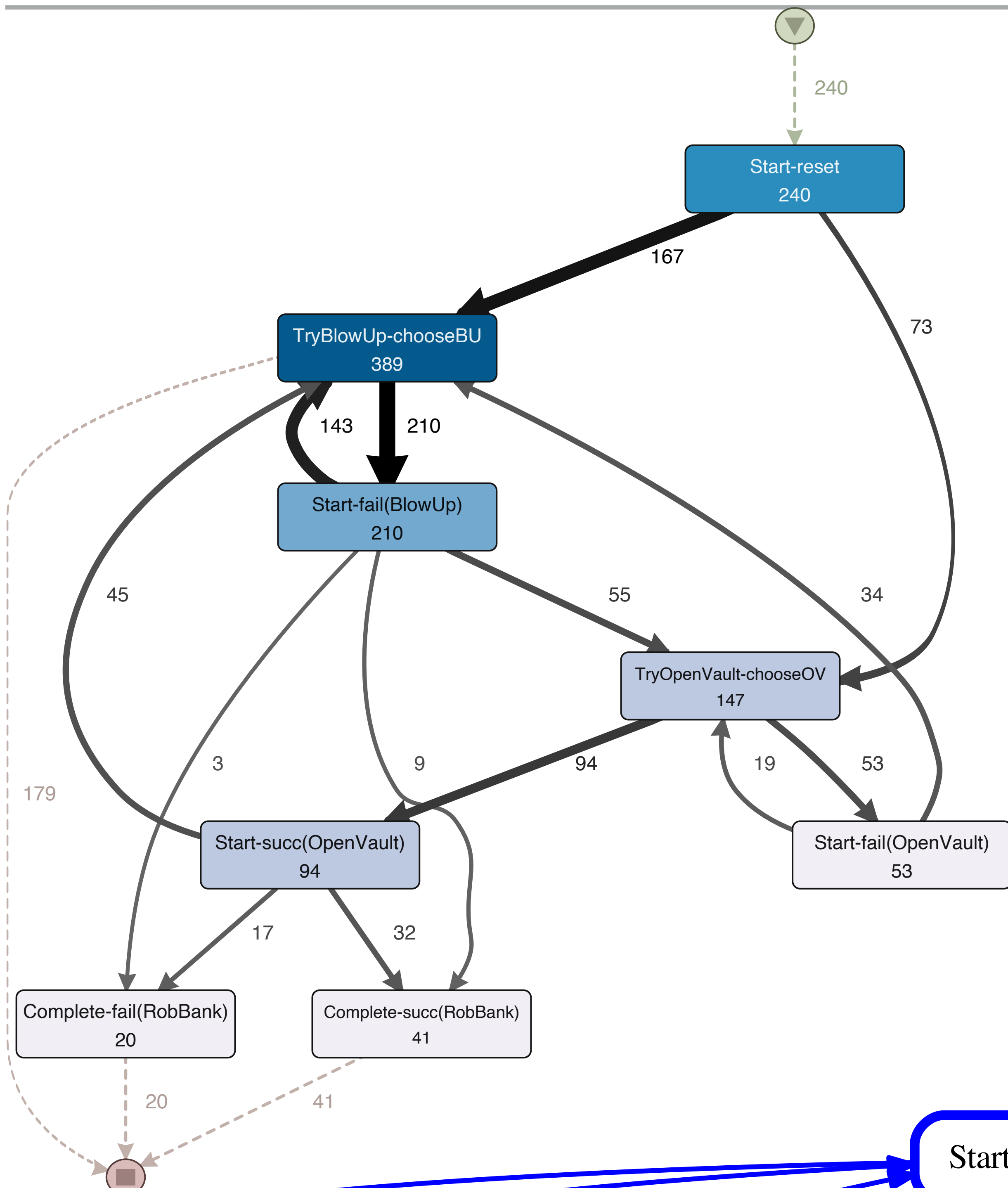

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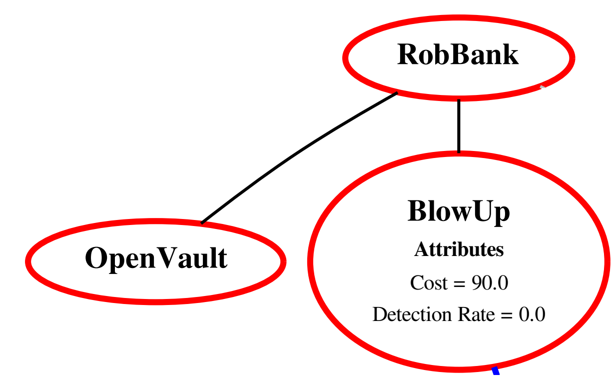

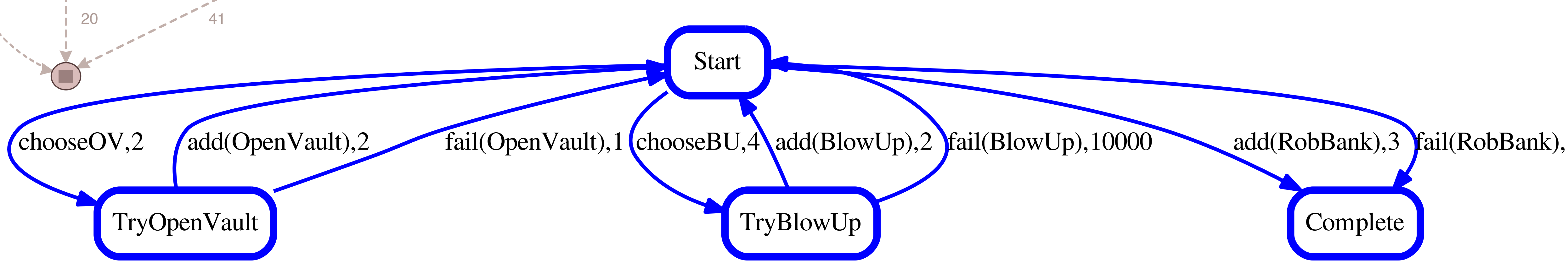

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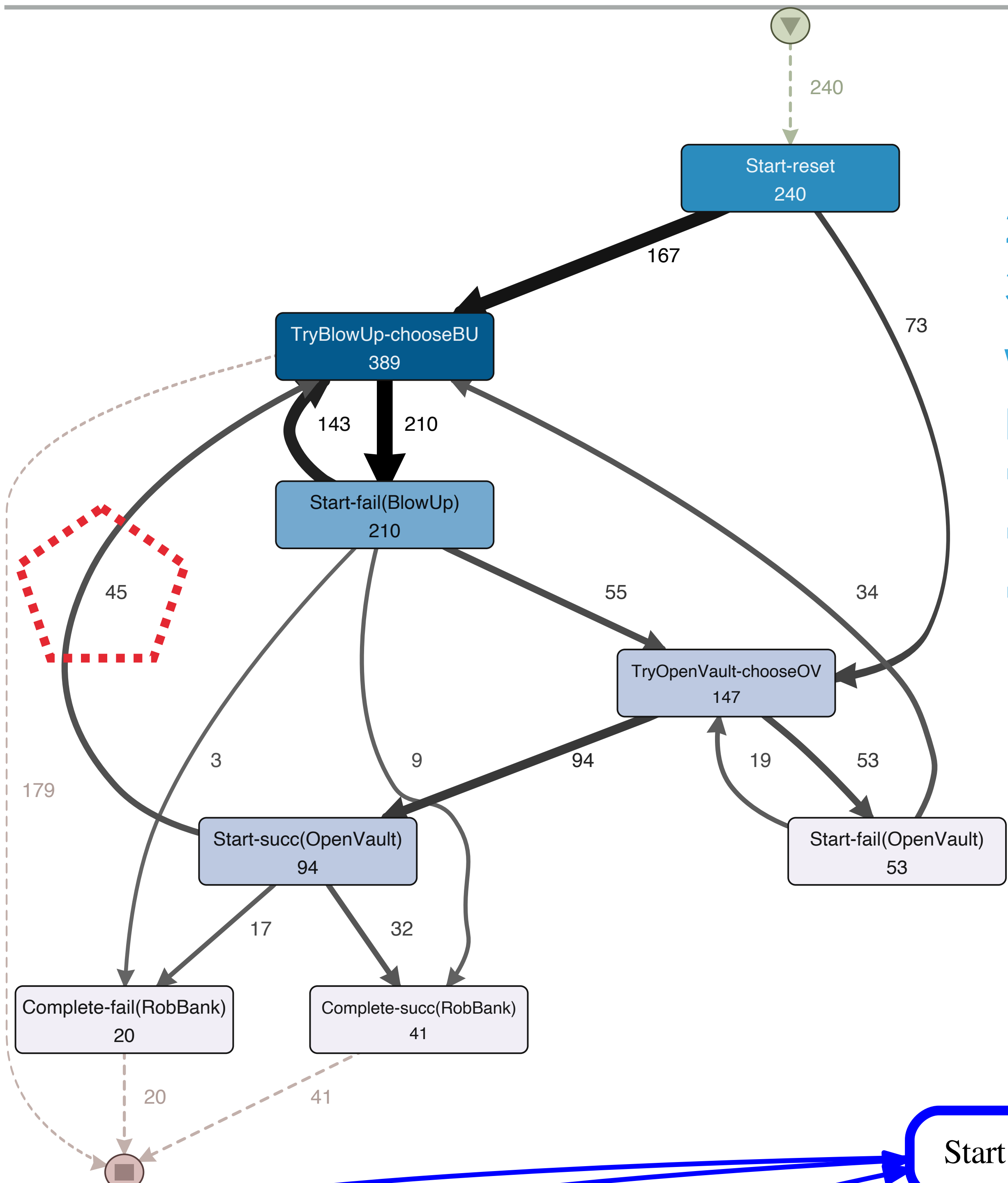

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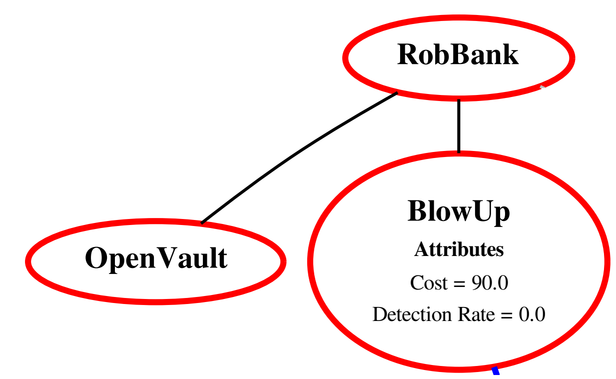
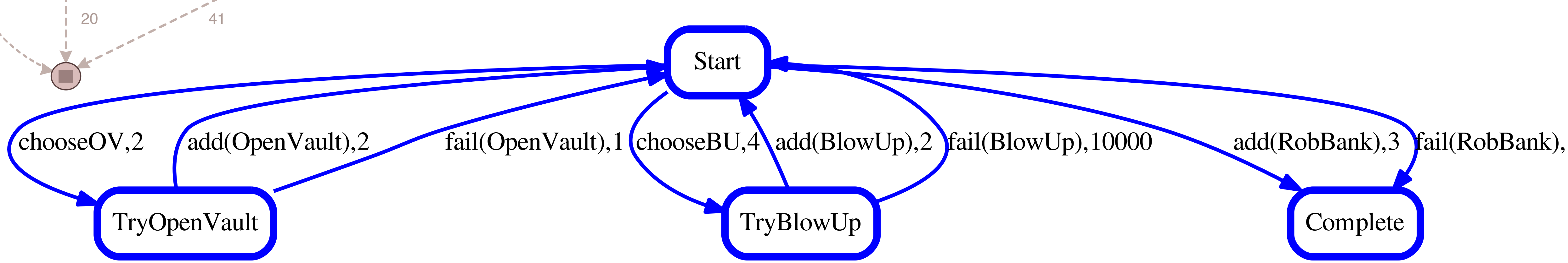
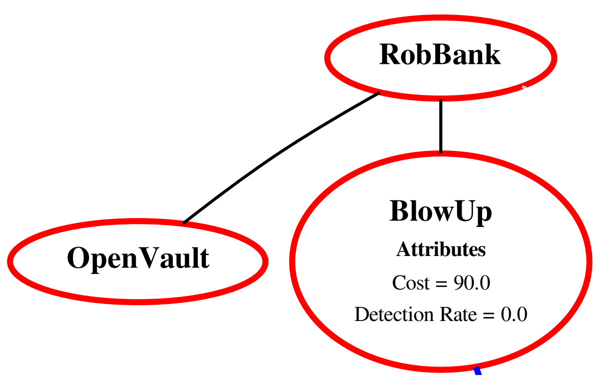
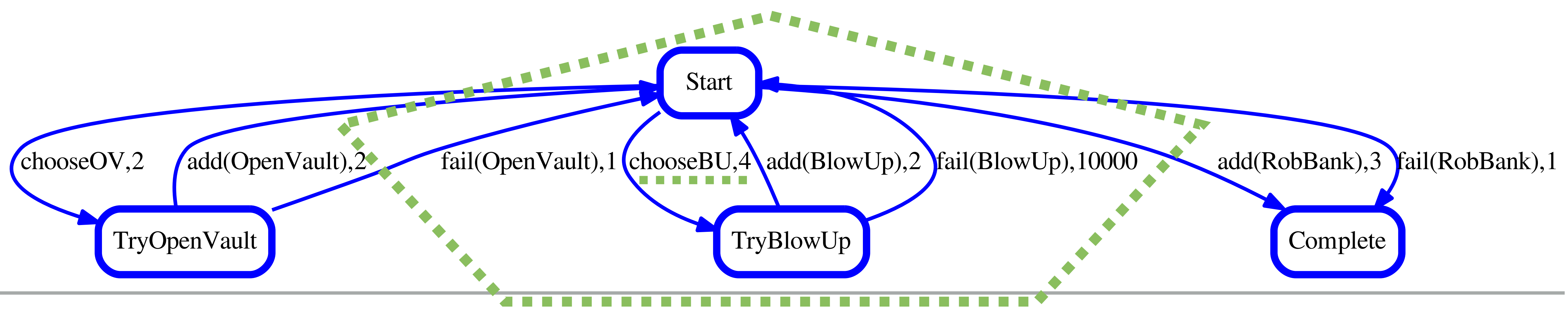




FIRST REFINEMENT: PARSIMONIOUS ATTACKER




```
// We add the !allowed(RobBank)
Start -(chooseBU, 4, !allowed(RobBank)) -> TryBlowUp,
TryBlowUp -(succ(BlowUp),     2) -> Start,
TryBlowUp -(fail(BlowUp), 10000) -> Start
```



FIRST REFINEMENT: PARSIMONIOUS ATTACKER – ANALYSIS

Probability of successful bank robbery!? ~~**0.17**~~ **0.31**

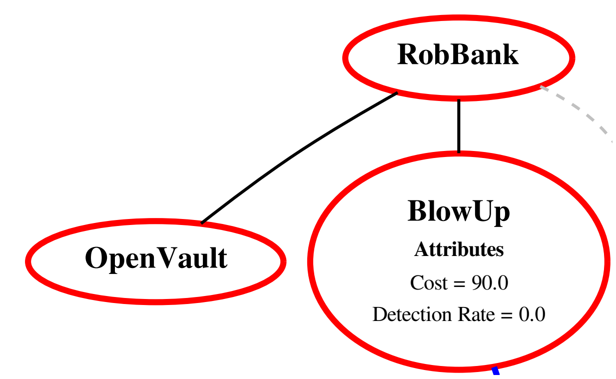
Why?

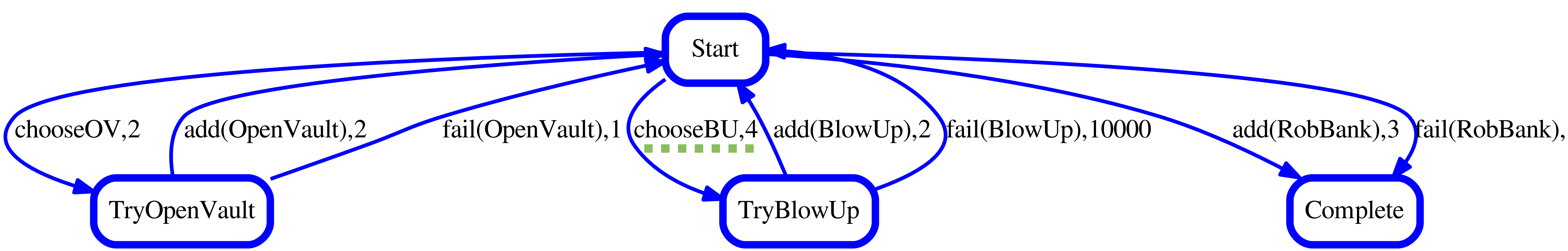
1) My defences are *good*
2) The attacker is *bad*
3) **Or my model is bad**!?

We set alpha=0.1, delta=0.1

MultiVeStA performs **240 simulations**

- We generate **logs for each simulation**
- We ask **Fluxicon Disco mine these logs**
- Can we spot **any issue in the model?**





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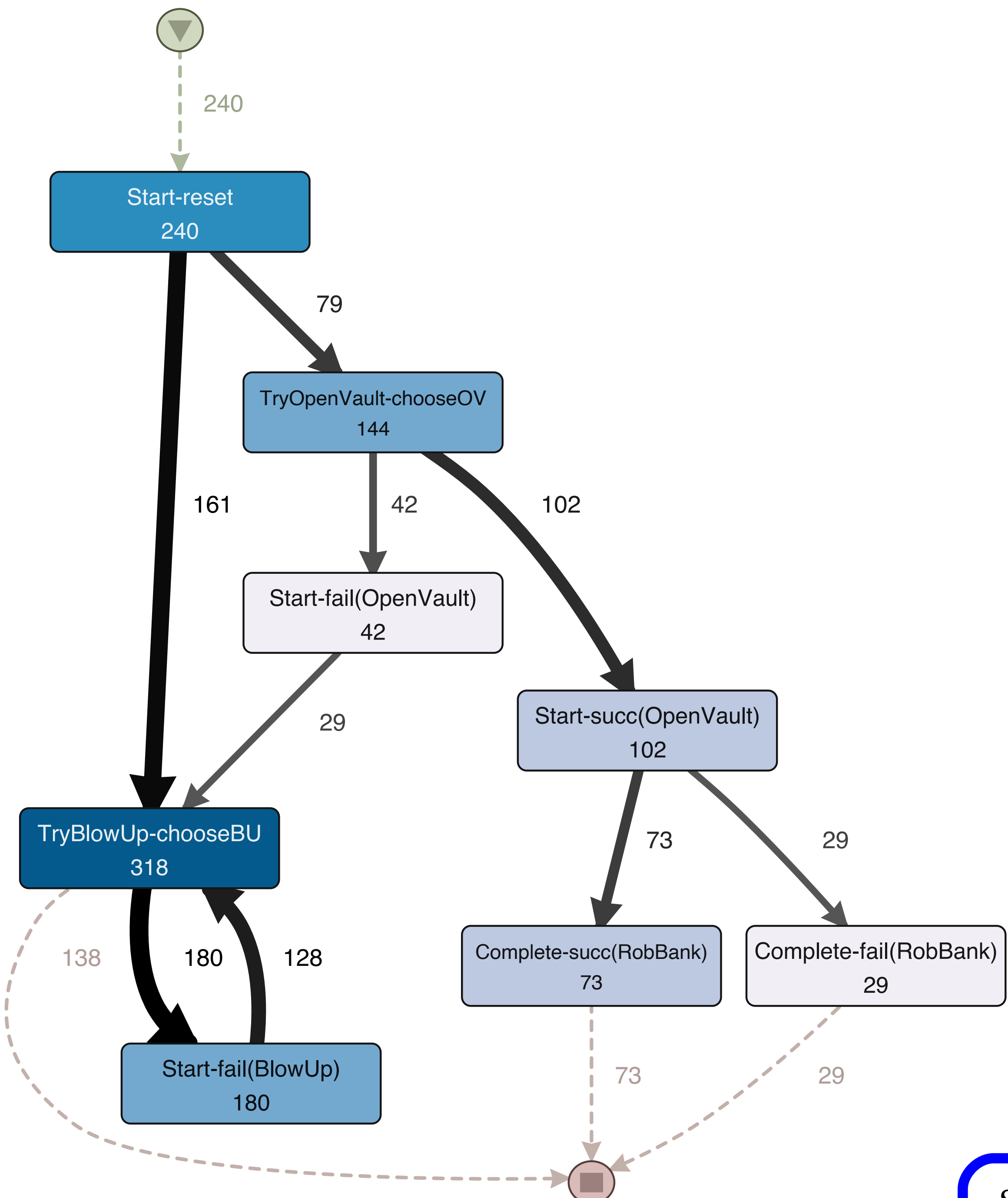

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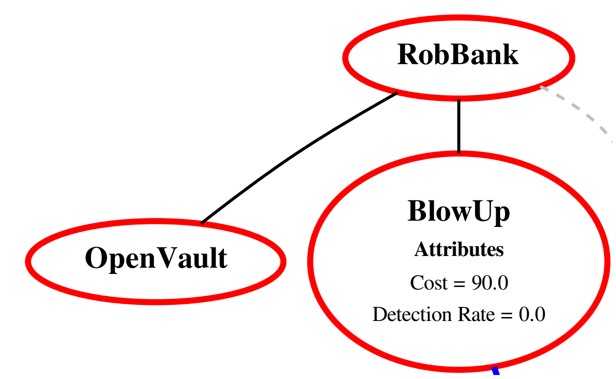
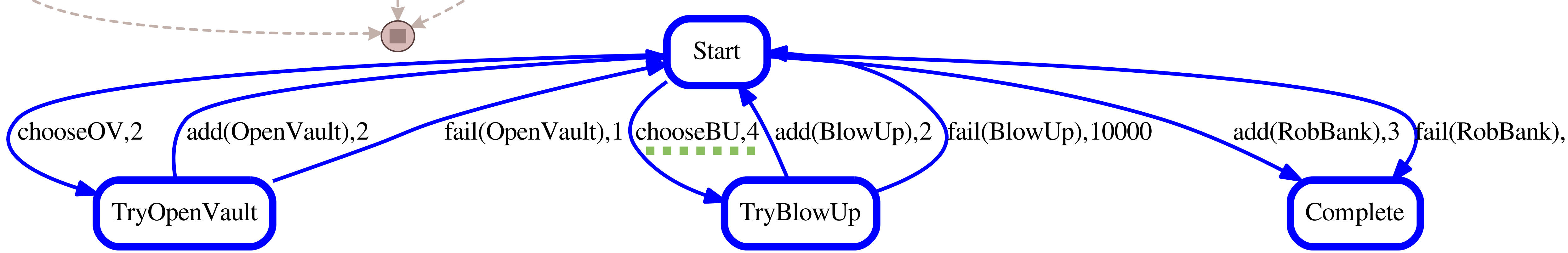
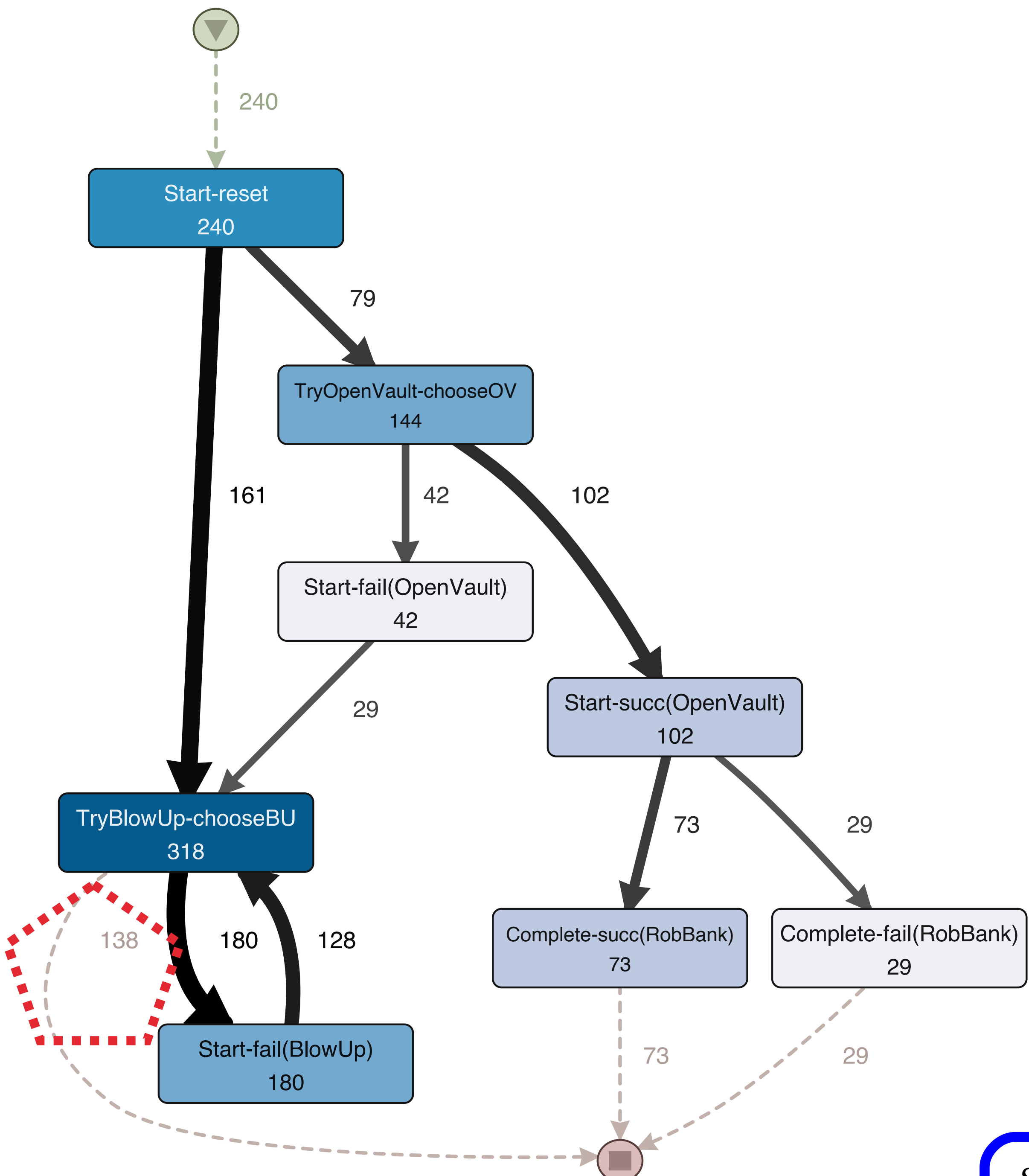




FIRST REFINEMENT: PARSIMONIOUS ATTACKER – ANALYSIS



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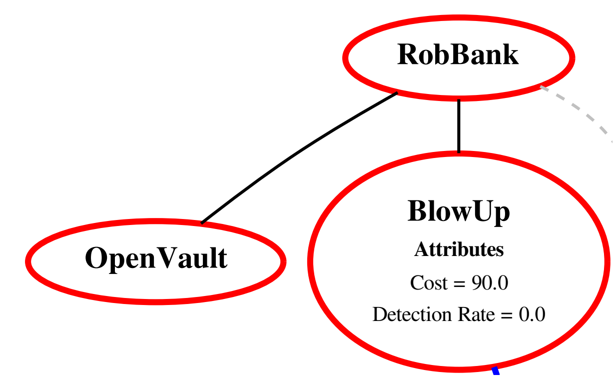
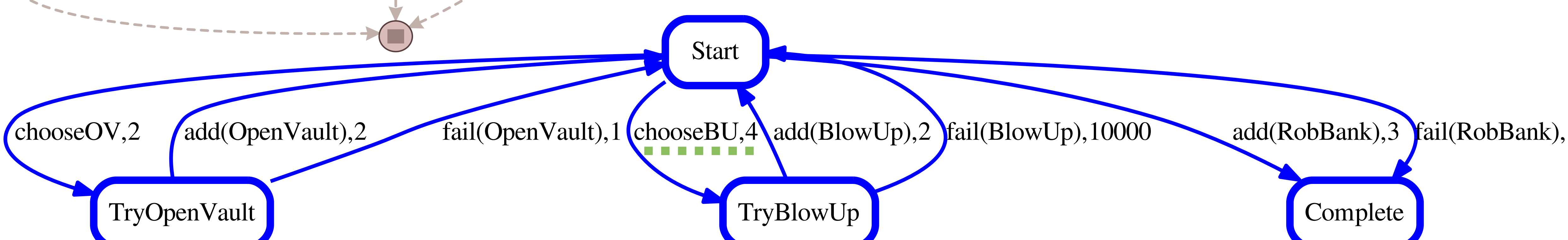
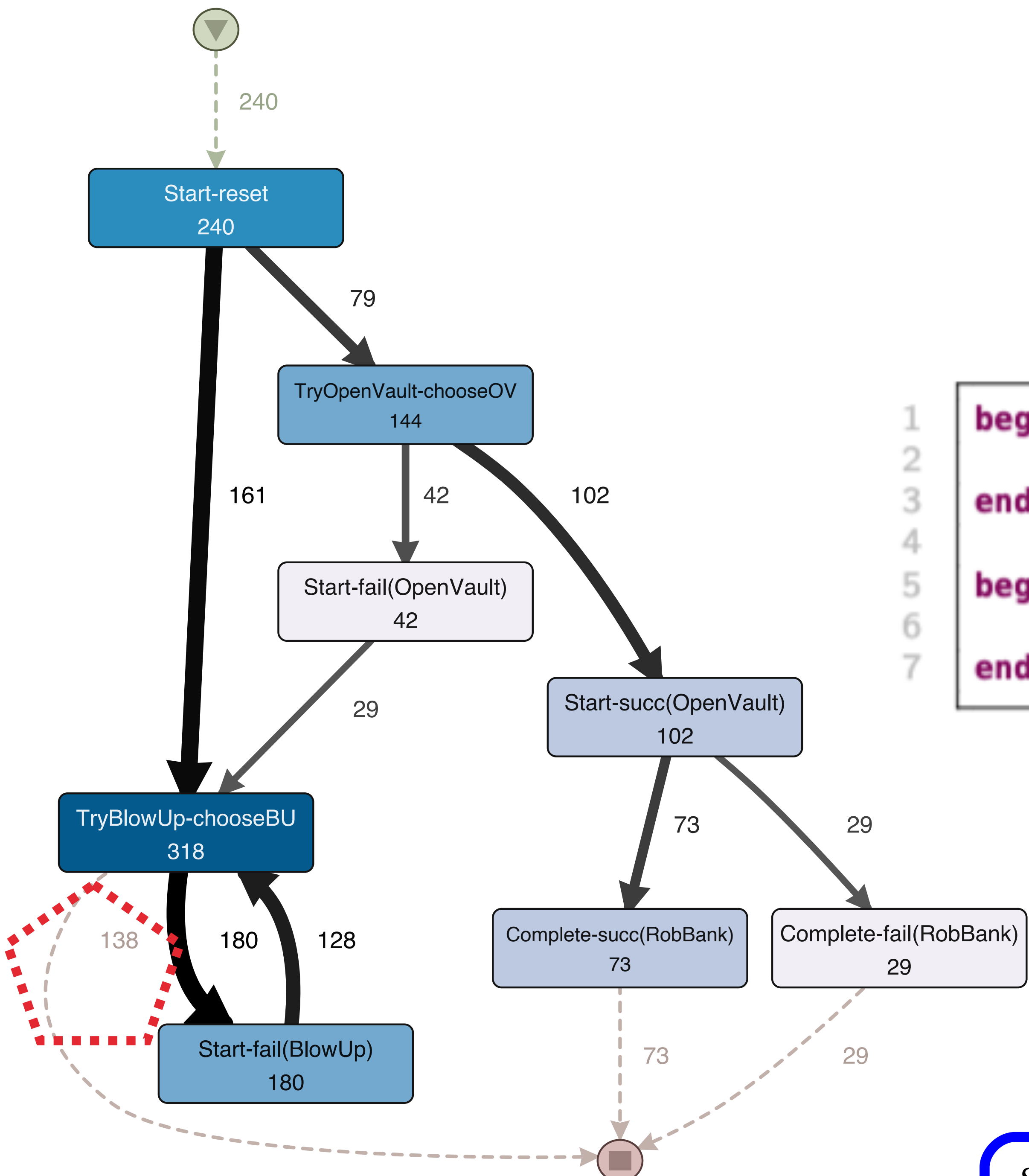




FIRST REFINEMENT: PARSIMONIOUS ATTACKER – ANALYSIS



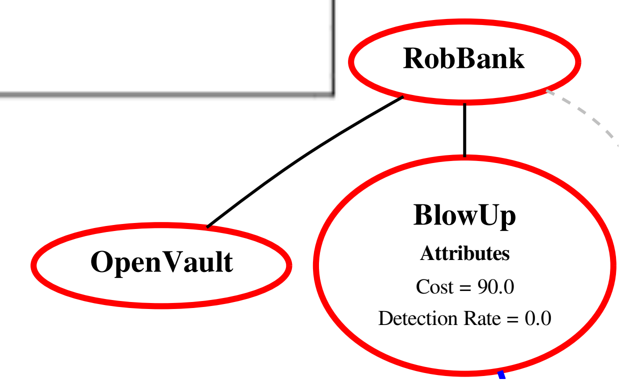
Probability of successful bank robbery!? ~~0.17~~ **0.31**

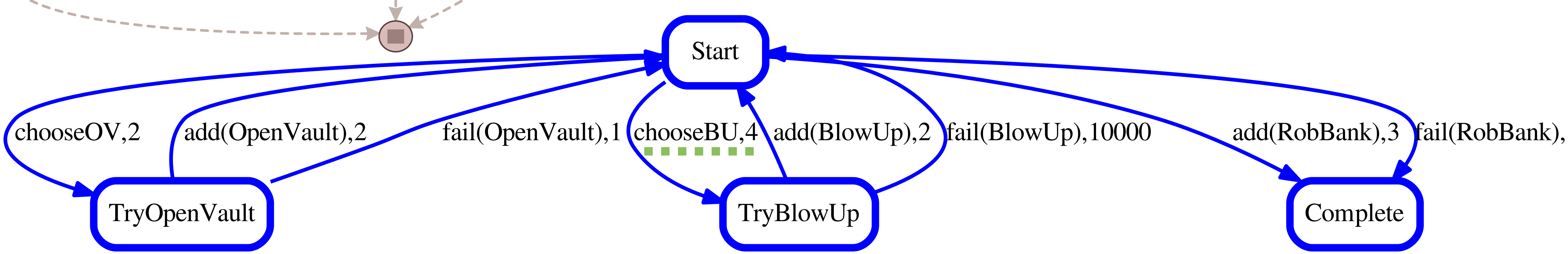
Why?

1) My defences are *good*
2) The attacker is *bad*
3) **Or my model is bad**!?

```
begin attributes
    Cost = {BlowUp = 90, OpenVault = 0}
end attributes

begin quantitative constraints
    { value(Cost) <= 100 }
end quantitative constraints
```





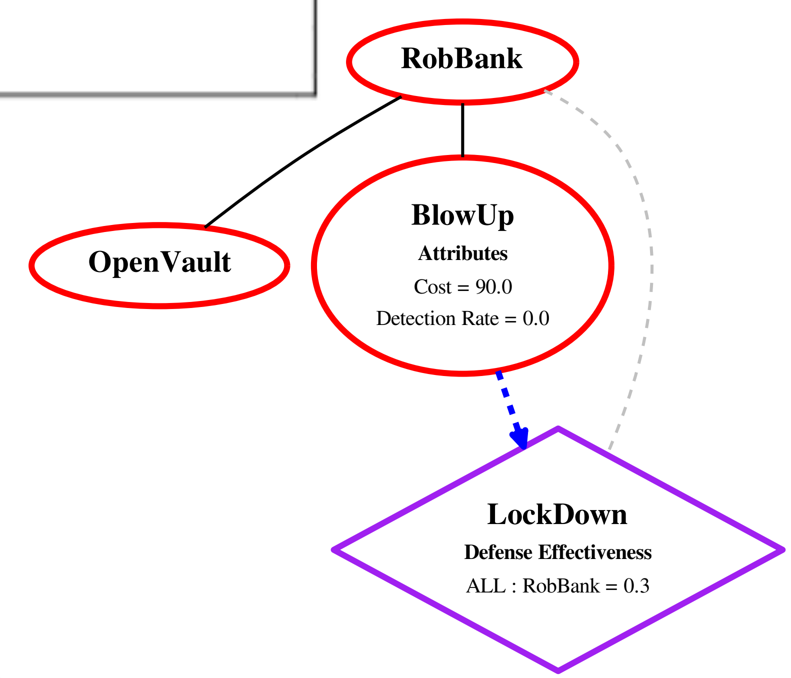
SECOND REFINEMENT

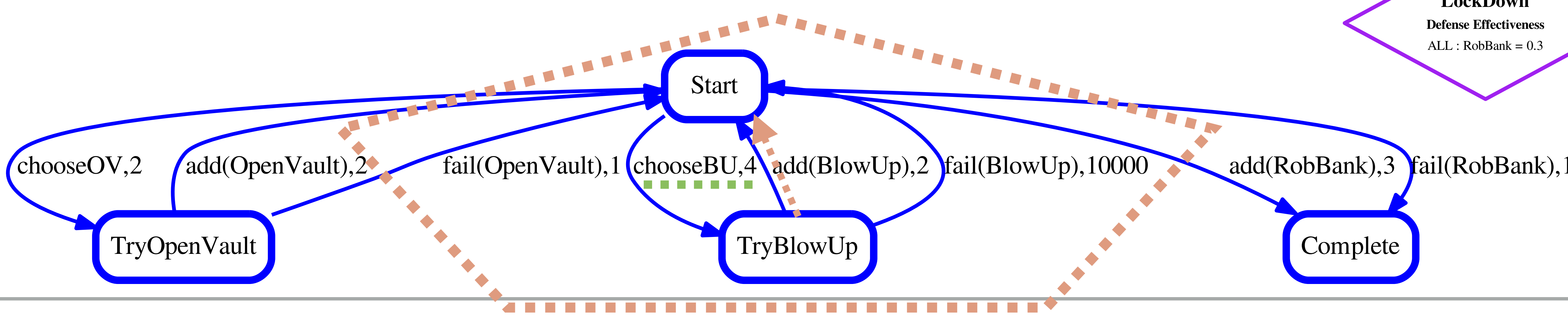
```
begin attributes
    Cost = {BlowUp = 90, OpenVault = 0}
end attributes

begin quantitative constraints
    { value(Cost) <= 100 }
end quantitative constraints
```

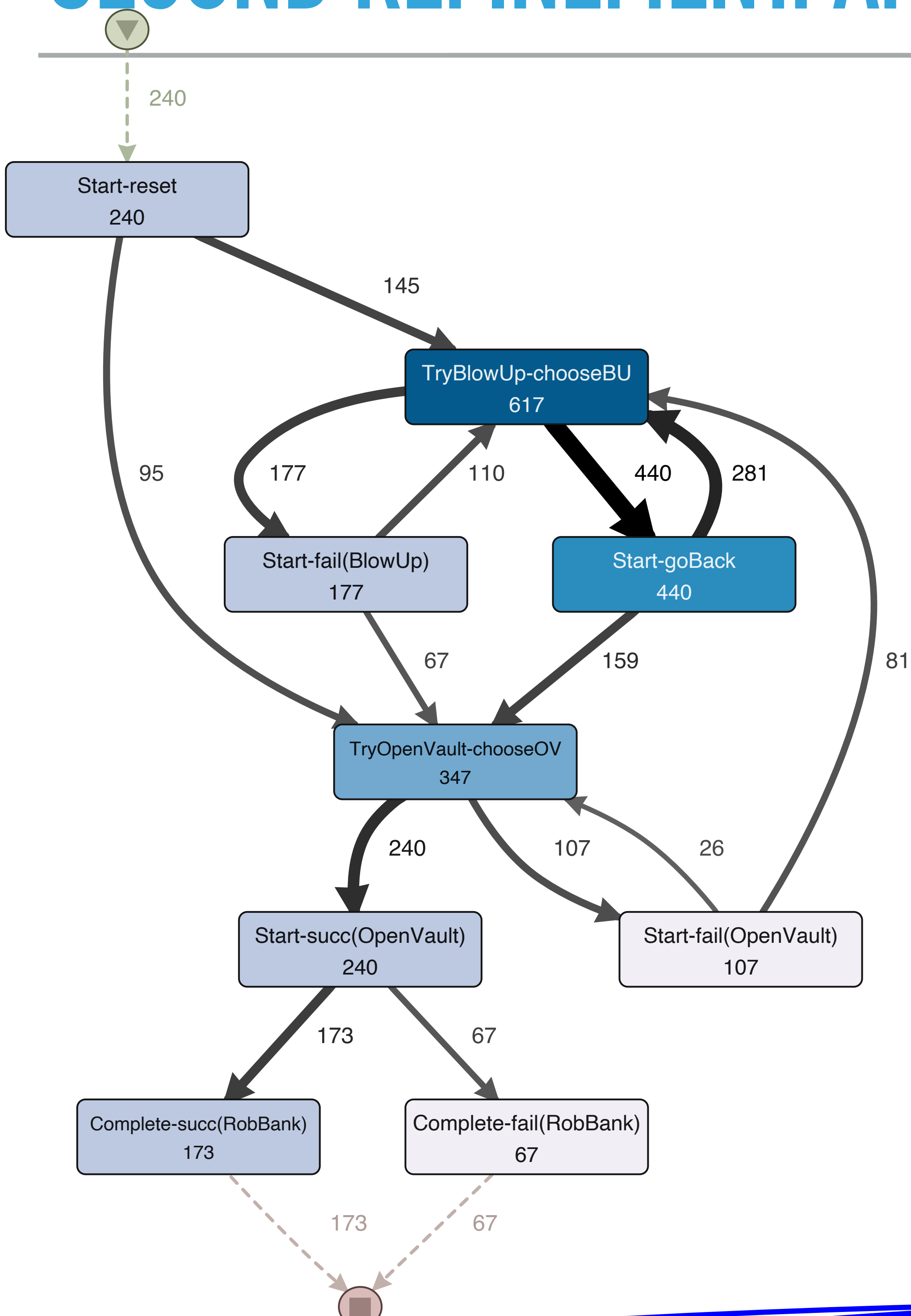
```
begin actions
    chooseOV
    chooseBU
    goBack
end actions
```

```
// Strategy where the attacker tries to blow up the vault
Start -(chooseBU, 4, !allowed(RobBank)) -> TryBlowUp,
TryBlowUp -(succ(BlowUp),     2) -> Start,
TryBlowUp -(fail(BlowUp), 10000) -> Start,
TryBlowUp -(goBack, 0.00001) -> Start
```





SECOND REFINEMENT: ANALYSIS



Probability of successful bank robbery!? ~~0.17~~ ~~0.31~~ **0.72**

We set alpha=0.1, delta=0.1

MultiVeStA performs **240 simulations**

- We generate **logs for each simulation**
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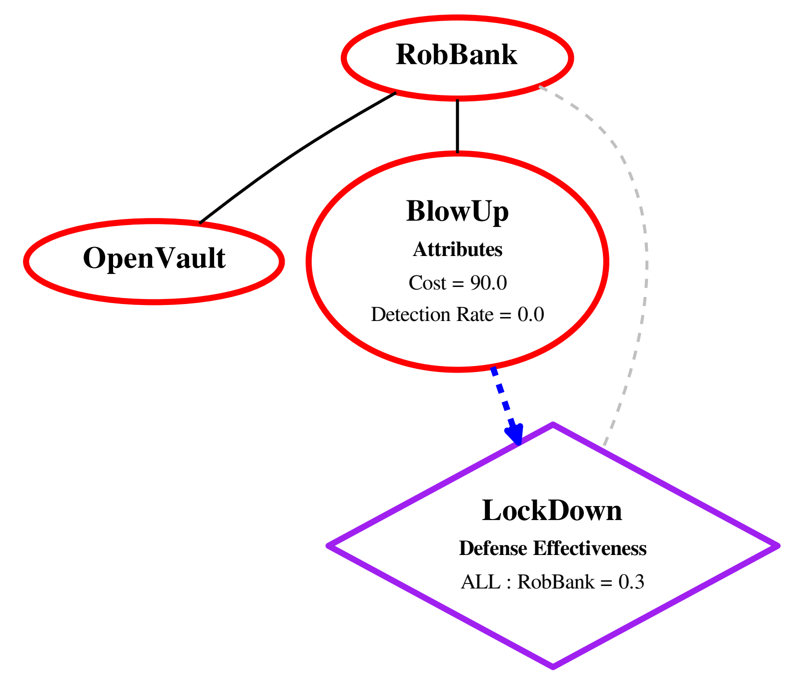
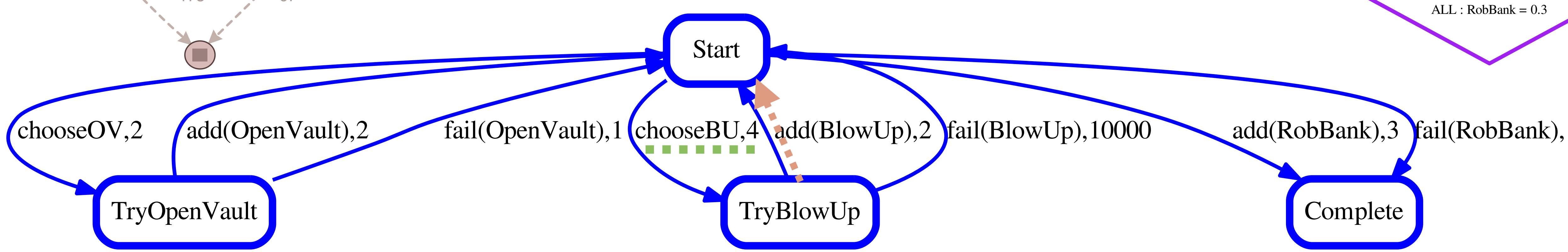
- Can we spot **any issue in the model?**





PM MEETS SMC: CONCLUSIONS & FUTURE WORKS

- We proposed a novel methodology for validating and enhancing simulation models to make them more reliable
  - We obtained: **SMC- and PM-guided white-box behavioral** model **validation** and enhancement
- **Future works**
  - More realistic models, from more domains (e.g., ABM from social sciences)
  - Conformance checking might help our white-box analysis
  - Currently, we use **PM *after* SMC**:
    - **Using PM *during* SMC**: streaming PM might help improving SMC analysis
    - **Using PM *before* SMC**: discovery algorithms might be applied to real data to
      - synthesize attack-defense trees and/or attacker behaviors
      - or parts of simulation models in general

THANK YOU FOR YOUR ATTENTION!

QUESTIONS?

FEEDBACK?

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