Quantitative Safety Analysis of Non-Deterministic System Architectures

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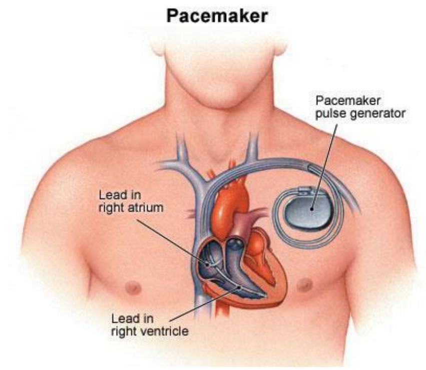
Motivation

- **Safety critical systems are everywhere**

- **These systems have to be verified against safety goals to ensure safe working**
  - Safety analysis should be easily supported during the development!
  - Best case: completely automatized



Outline

1. Motivation

2. **Preliminaries**

3. Safety Analysis of UML / SysML models

   - The QuantUM approach

4. Case Studies

5. Conclusion

Quantitative Safety Analysis of Non-Deterministic System Architectures

- **Industrial Practice (some demanded by safety standards)**

Qualitative Methods

„identify Failures“

- Qualitative FMEA
- Qualitative Fault Tree Analysis
- Event Tree Analysis

Quantitative Methods

„predict frequency of failures“

- Quantitative FMEA
- Quantitative Fault Tree Analysis
- Event Tree Analysis
- Markov models
- Reliability block diagrams

- **Academia**

Model Checking

Probabilistic Model Checking

- **How is non-determinism introduced in systems?**

  - Environmental behavior
    - No probability for environmental factors
    - Can happen non-deterministically at any point in time

  - Concurrency
    - Several processes / components run concurrently
    - Scheduler resolves non-determinism by deciding which process is allowed to take the next step

  - Abstraction
    - Some unknown aspects during design / modeling phase
    - "Incompleteness" of the design model
    - Simplification / abstraction of certain aspects in the system

- **Model-based Engineering**
  - Models help to structure, develop, analyze complex systems

- **Model-based Engineering promoted / demanded by modern standards**
  - ISO 26262
  - DO-178C
  - ARP 4754A
  - ESAAR4

- **Modeling languages**
  - *UML / SysML*
  - Matlab Simulink
  - AADL
  - ASCET
  - …

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3. **Safety Analysis of UML / SysML models**
   - The QuantUM approach
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The QuantUM Approach

QuantUM
Quantitative Analysis of UML Models

RECENTLY INTRODUCED

- **The Goal:**
  - Automatic verification of UML / SysML models easily applicable and consistent in industrial practice
  - Safety related information is directly encoded in the model using stereotypes
    - Normal + failure behavior
    - Quantitative information, i.e. failure rates
    - Safety requirements encoded in state configurations of the system
      - Automatic translation into reachability properties

The QuantUM Approach

QuantUM
Quantitative Analysis of UML Models

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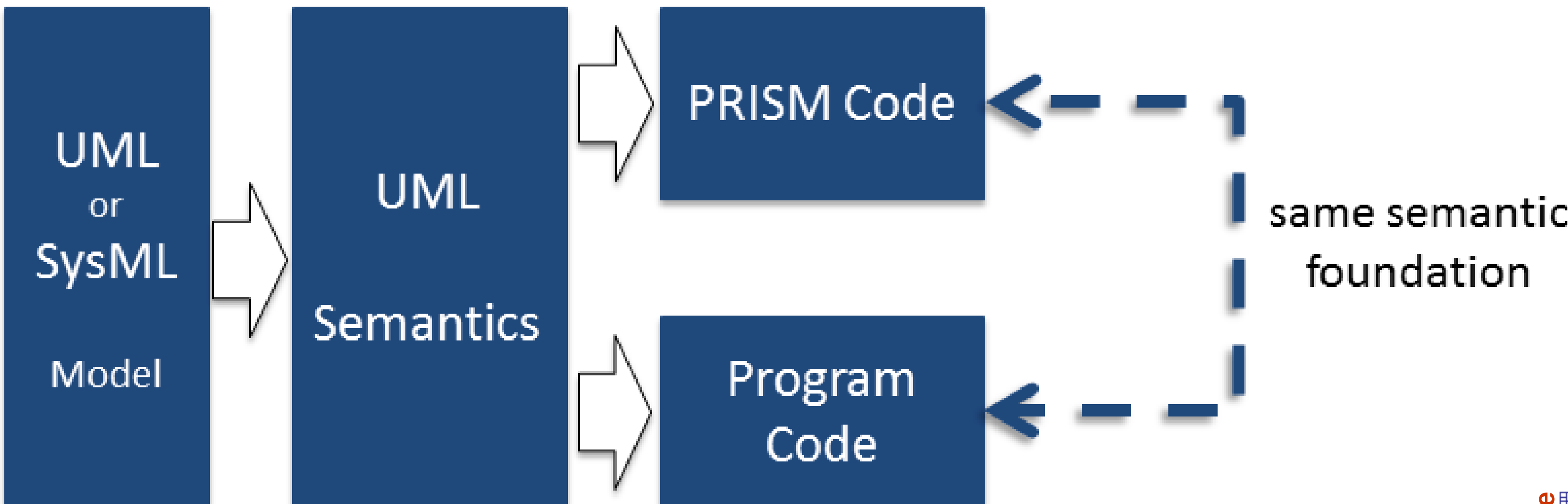


The QuantUM Approach

QuantUM
Quantitative Analysis of UML Models

- **QuantUM relies on the concept of model checking**
  - Automatic exploration of the state space of the model of a system
    - **PRISM model checker**
      - Probabilistic analysis
    - SPIN model checker
      - Functional analysis
  - Systematic search for modeling flaws in the system

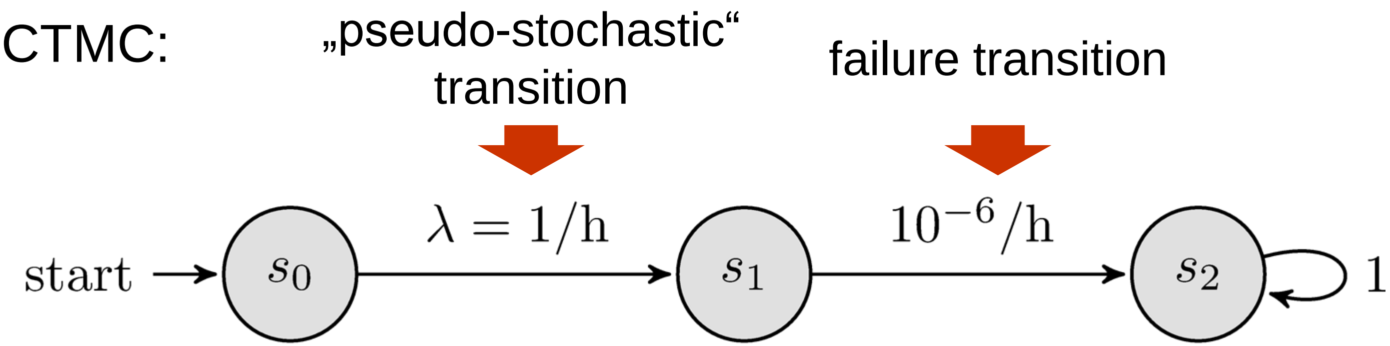
The QuantUM Approach

QuantUM
Quantitative Analysis of UML Models

- **The Problem:**
  - Model of computation until now:
    Continuous Time Markov Chains
    - Only stochastic transitions
    - Modeling trick:
      - Non-determinism is approximated using pseudo-stochastic transitions
      - Introduced error often very large

The QuantUM Approach

- **Example:**
  - CTMC:



  - Probability of reaching state s_1 within 1h is ≈ 0.63
    - Expectation: reaching state s_1 within 1h should always give a probability of 1
  - Even when setting λ to a higher value this phenomenon has an impact along long paths

The QuantUM Approach

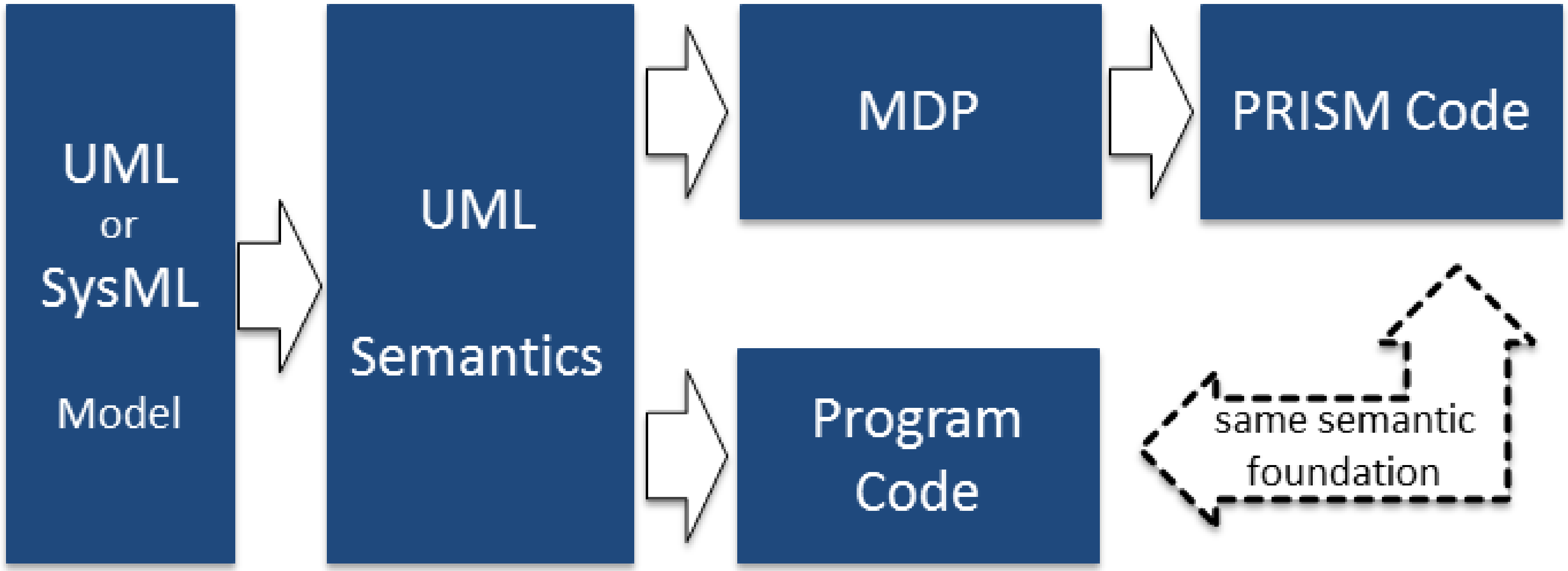
- **Solution:** Use Markov Decision Processes

  - MDPs support non-determinism by definition
  - MDPs have a discrete time-basis
    - No continuous failure rates are supported by MDPs
    - Discretization is possible:
      Approximation of continuous negative exponential distribution with a discrete geometric distribution

      - Introduced error is computable and orders of magnitude smaller than the actual value

      - Discretization step size has a significant effect on computation time

How is the translation done?



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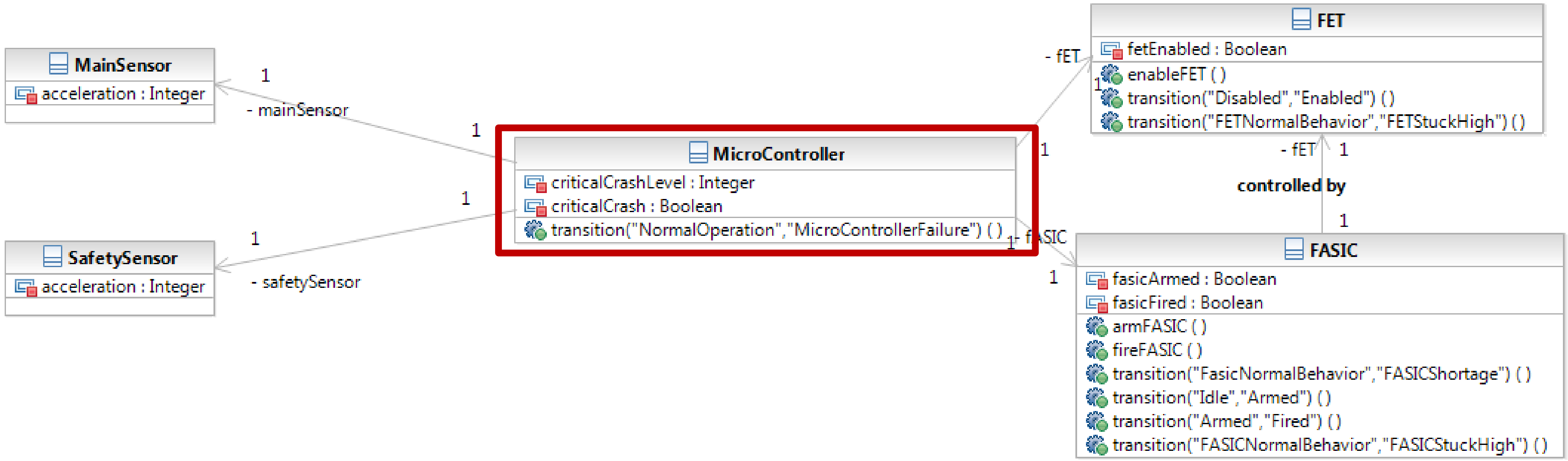
Case Studies

- Airbag System

- Airport Surveillance Radar

Example: Airbag System

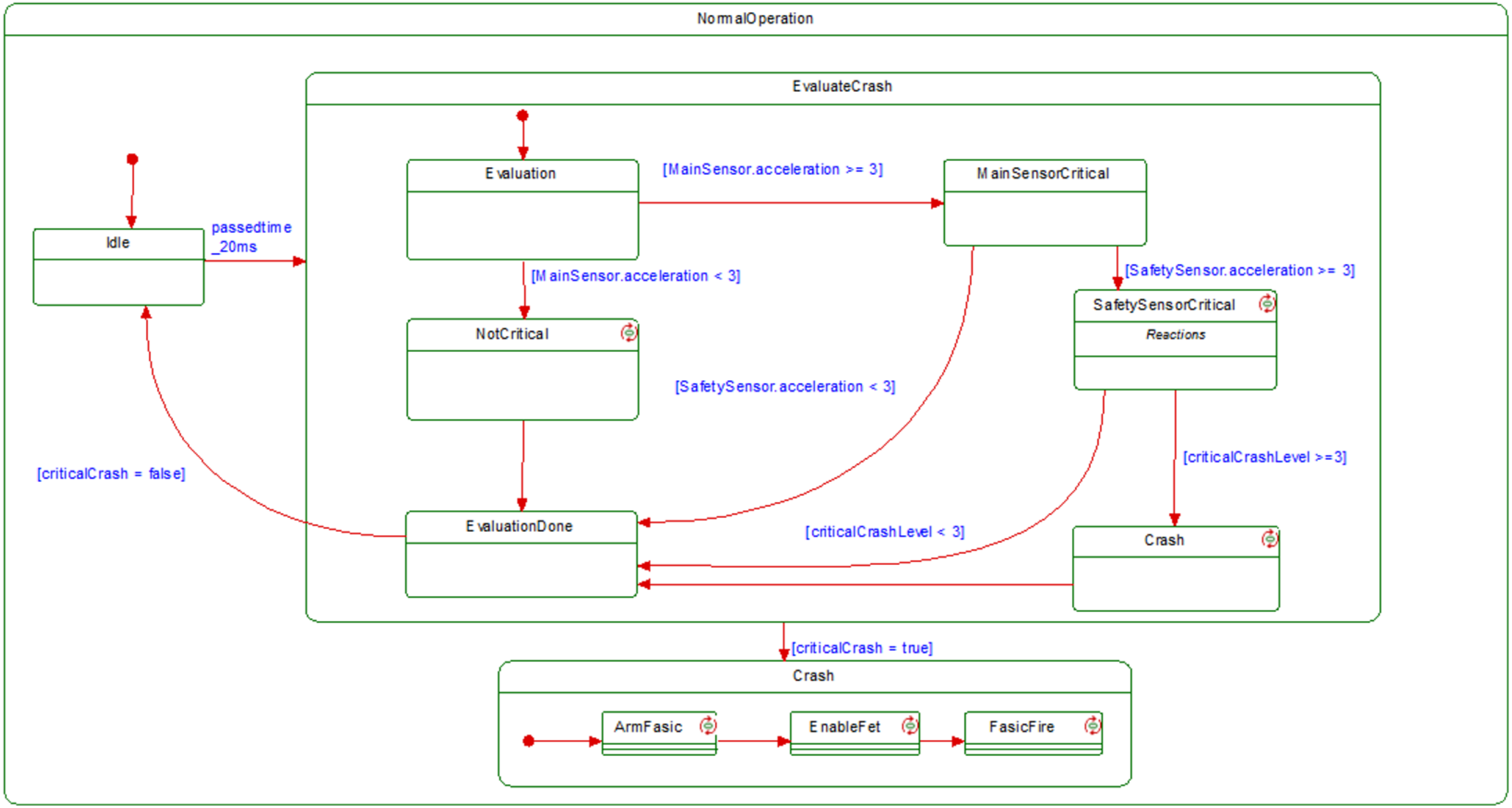
- **UML Model of an Airbag System**



- **Computation of** „Probability of an inadvertent deployment within 100h”

Example: Airbag System

- **Statechart of the Microcontroller**



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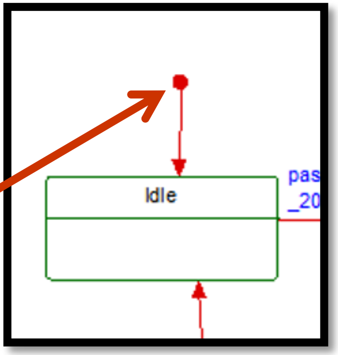
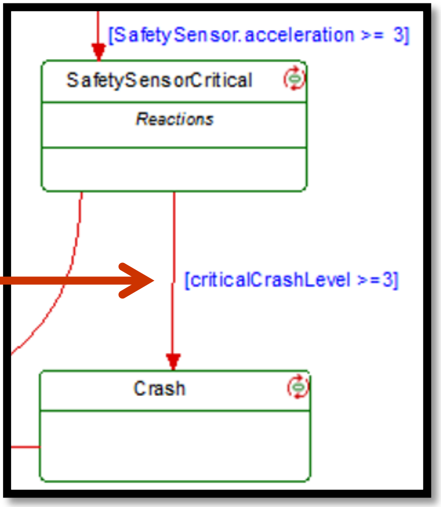
Example: Airbag System

- **PRISM Code**

```
module MicroController

NormalOperation_active: [0..19] init 0;

// initial state
[](NormalOperation_active = 0)
     -> NormalOperation_active '= 1);

[](NormalOperation_active = 6)
    & (MicroController_criticalCrashLevel >=3 )
    -> ( NormalOperation_active '= 7) &
         ( MicroController_criticalCrash '=true);




endmodule
```

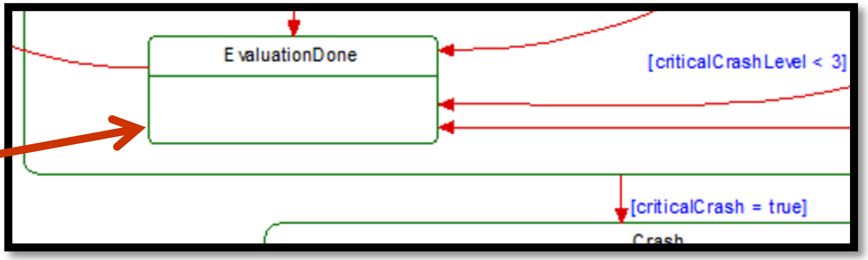


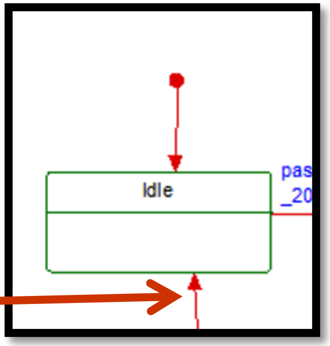


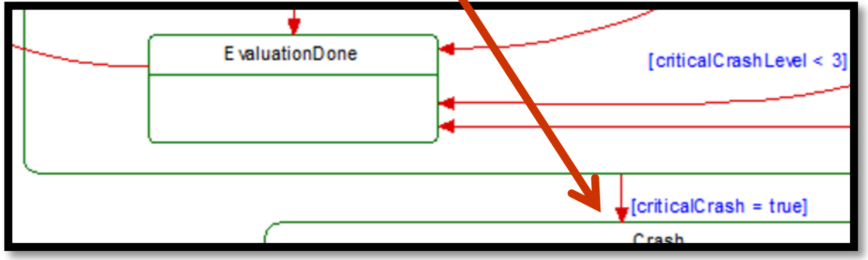
Example: Airbag System

- **C Code**

```
switch ( NormalOperation_active ) {
……… // some code
case EvaluationDone:
{
  if(IS_EVENT_TYPE_OF(OMNullEventId))
  {  //## transition 2
    if(criticalCrash = false)
    {
      EvaluateCrash_exit();
      NormalOperation_subState = Idle;
      rootState_active = Idle;
      res = eventConsumed;
    }
  }
  if(res == eventNotConsumed)
  {
    res = EvaluateCrash_handleEvent();
  }
}
break;
……… // some code
}
```







Evaluation

- **Computation of failure probabilities for the inadvertent deployment**

	CTMC λ = 1	**CTMC λ = 100**	**MDP (non-det.)**
Airbag (probability)	$2.0 \cdot 10^{-4}$	$2.7 \cdot 10^{-4}$	$9.98 \cdot 10^{-4}(\pm 8.32 \cdot 10^{-11})$
Airbag (time)	0.1 sec.	258.1 sec.	3.94 sec.
Radar (probability)	$8.8 \cdot 10^{-22}$	$8.231 \cdot 10^{-20}$	$4.81 \cdot 10^{-13}(\pm 1.39 \cdot 10^{-20})$
Radar (time)	22.57 min	68.88 min	277.27 min

- ASR: “Probability of wrong information being displayed to the air traffic manager within 1h”
- Model sizes:
  - Airbag: ≈ 7000 states + 50.000 transitions
  - ASR: ≈ 200 mio. states + 2 billion transitions

Conclusion

- **Summary: QuantUM Approach**
  - Quantitative model-based safety analysis
  - Automatic translation of UML / SysML models into model checking code
  - Non-determinism + continuous failure rates can now be handled while maintaining the computation error
  - Computation is adaptable to the purposes of the results
    - Certification or just coarse evaluation of design

- **Outlook**
  - Automatic Fault Tree generation for MDPs
  - Automatic Failure Mode and Effect Analysis
  - Result interpretation as UML sequence diagrams
  - Further integration into certification and validation standards
    - ISO26262, ARP 4754A