

A MC/DC and Toggle Coverage Measurement Tool for FBD Program Simulation

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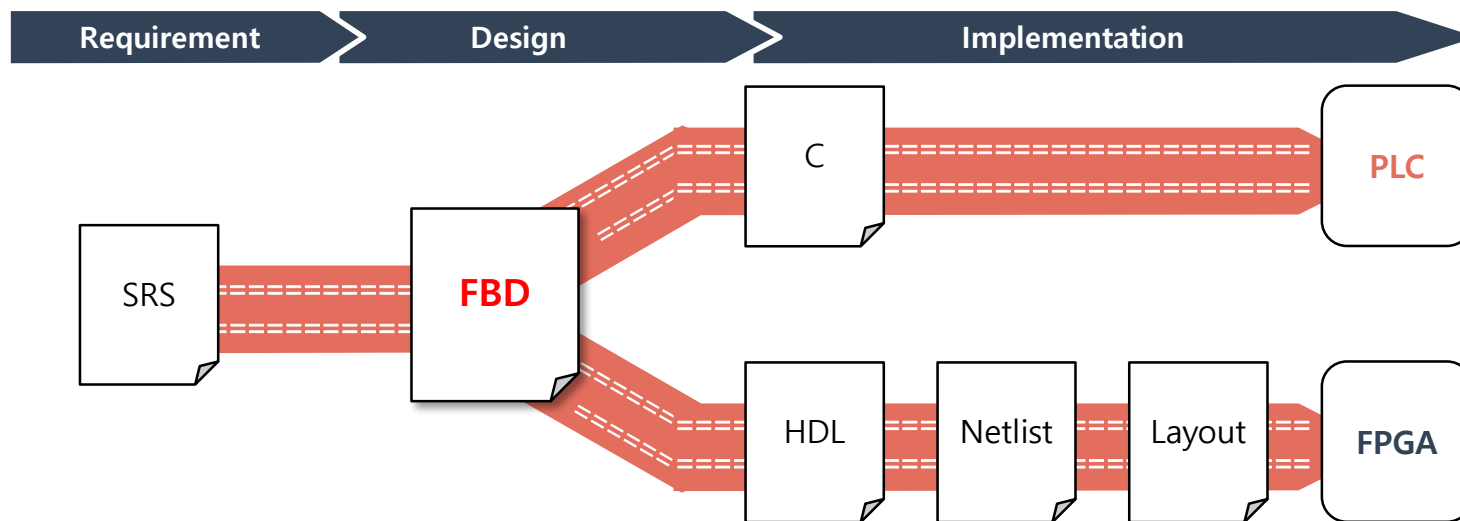
Functional Verification of FBD

- **Functional verification of FBD (Function Block Diagram) is important**

- **FBD** is a design model for **PLC** (and FPGA in the NuDE framework)

- **Detection errors early (design phase) → Can reduce costs and increase quality**

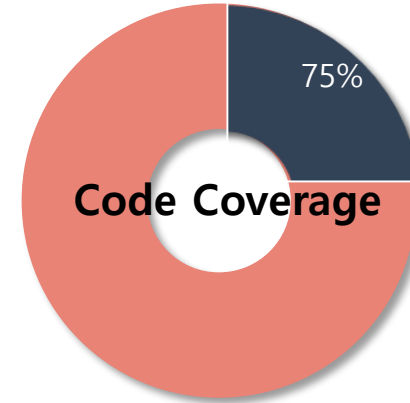
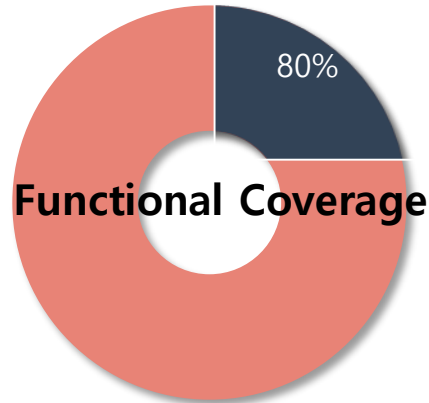
- **Software design errors are often only detected during final test or after delivery**



< The NuDE framework >

How Adequately the Testing has been Performed?

“Test Done = Test Plan Executed and All Codes Executed”



Functional Coverage

- = **Requirements Coverage**
- This coverage will be defined by the user
- User will define the coverage points for the functions to be covered
- 100% of functional coverage is always required

Code Coverage

- = **Structural Coverage**
- How many lines are executed, how many times expressions, branches executed, etc.
- Code coverage is collected by the simulation/testing tools.
- Users use code coverage to reach those corner cases which are not hit by the test cases.
 - Unfortunately, errors and bugs are often found in the corner cases.
- To assure a high quality of functional verification, code coverage is important as well as functional coverage

Introduction

- We applied two code coverages to FBDs

- (1) Toggle coverage , (2) MC/DC coverage

- Defined coverage criteria for FBD simulation

- If the coverages is not 100%, it means that the verification may be **insufficient** or the FBD may have unintended **errors** or bugs.

- We developed a set of supporting CASE tools

- Developed two CASE tools 'FBDSim' and 'FBDCover'

- Can simulate FBDs and measure the code coverages of the FBD simulation

- Objective : measuring the coverages during simulation (a sequential/continuous operation environment, not a single execution)

Toggle Coverage & MC/DC Coverage

• Toggle Coverage

- One of the oldest measurements of coverage in hardware design
- Measures the bits of logic that have toggled during simulation
- Can be measured in logic simulation
- Ex) 1-to-0 and 0-to-1 → 100% toggle coverage

• MC/DC Coverage

- Control flow-based structural coverage of the most highest level, in practice
- Widely applied to C/Java programs

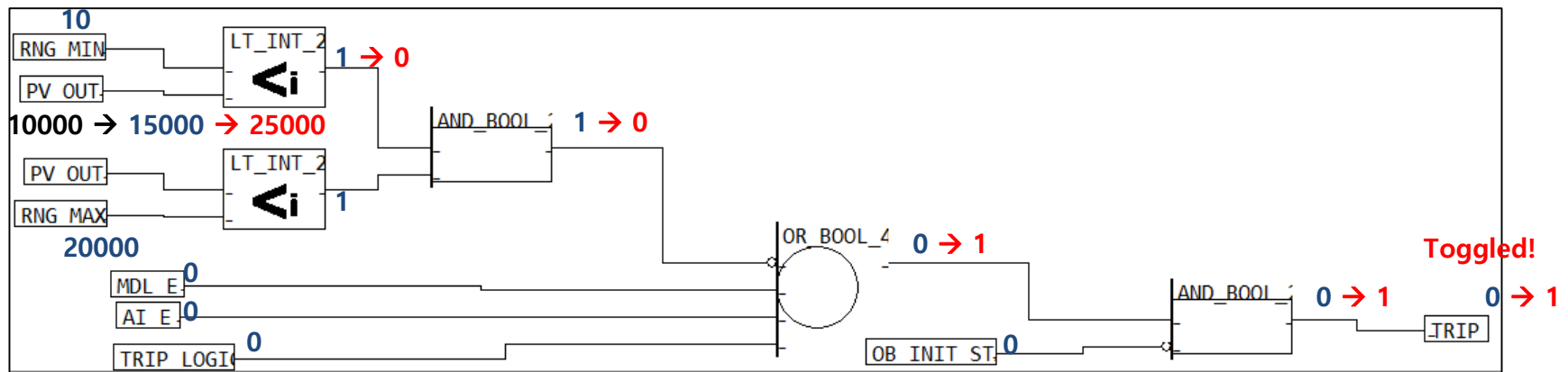
| Case # | A | B | OUT | A | B |
|--------|---|---|-----|---|---|
| 1 | T | T | T | O | O |
| 2 | T | F | F | | O |
| 3 | F | T | F | O | |
| 4 | F | F | F | | |

100% MC/DC
 → (T,T), (F,T), (T,F)

Toggle Coverage in FBDs

- Toggle Coverage in the FBD

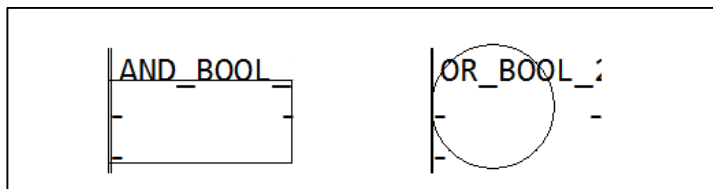
- Two application targets : (1) Output toggle, (2) Block toggle
 - (1) Output toggle : an output is toggle during the simulation
 - (2) Block toggle : a function block's output is toggle during the simulation
- Ex) If an output is not toggled, we may doubt that
 - the output variable is not tested → simulation may be **insufficient**.
 - the output variable is unreachable → the logic may have **dead codes** → a logic-fix requires



MC/DC Coverage in FBDs

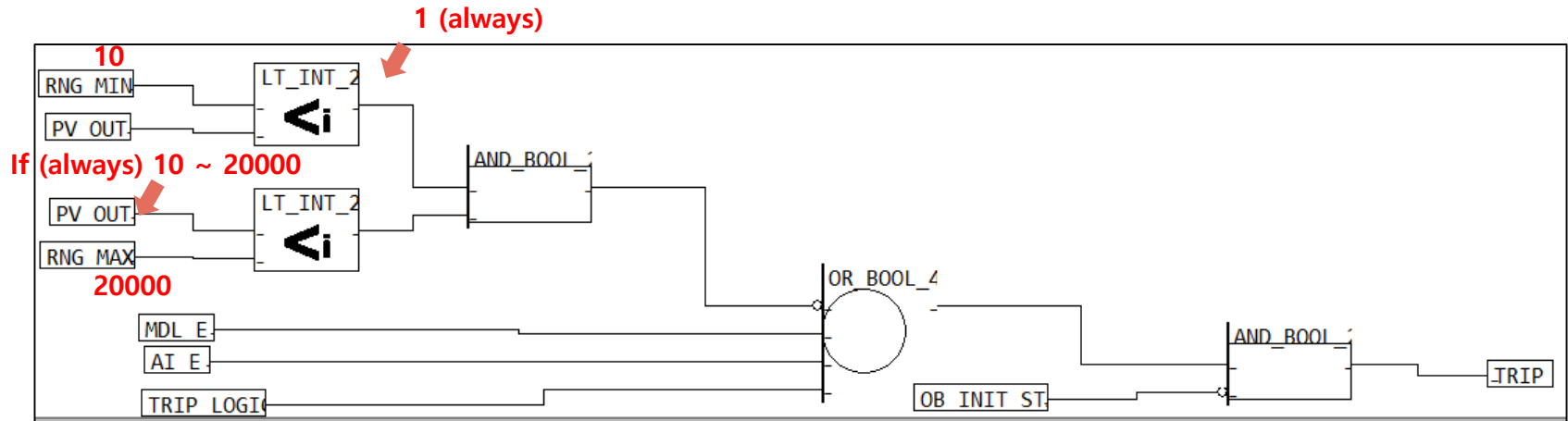
- MC/DC Coverage in the FBD

- Based on the typical MC/DC principle
- Measure the MC/DC coverage of a function block
- Ex) If any block does not cover 100% MC/DC coverage, we may doubt that
 - the block is not tested → simulation may be **insufficient**
 - the block is unreachable → the logic may have **dead codes** → a logic-fix requires



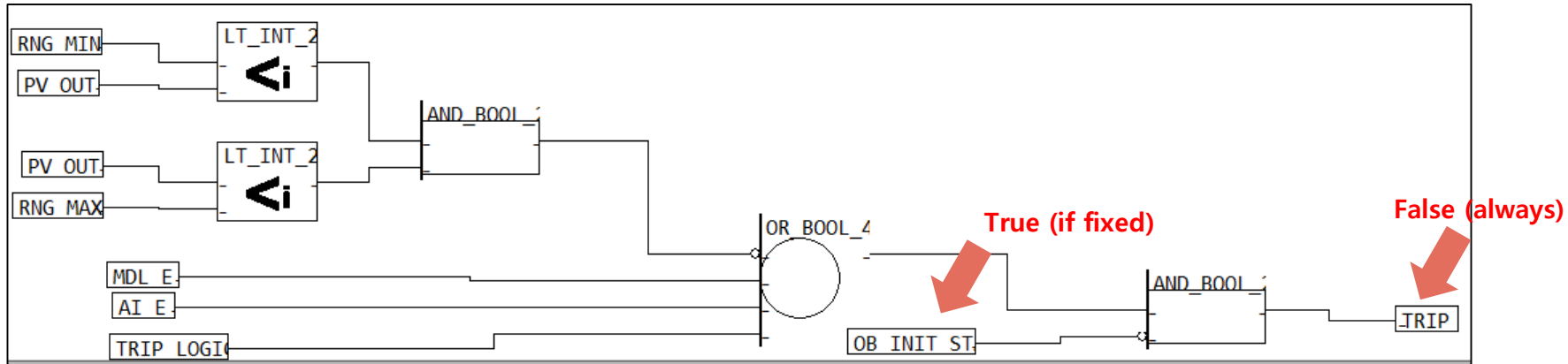
| | Inputs | MC/DC |
|-----|----------|-------------------|
| AND | IN1, IN2 | (0,1) (1,0) (1,1) |
| OR | IN1, IN2 | (0,0) (0,1) (1,0) |

Block Toggle Coverage (An Example of Insufficient Simulation)



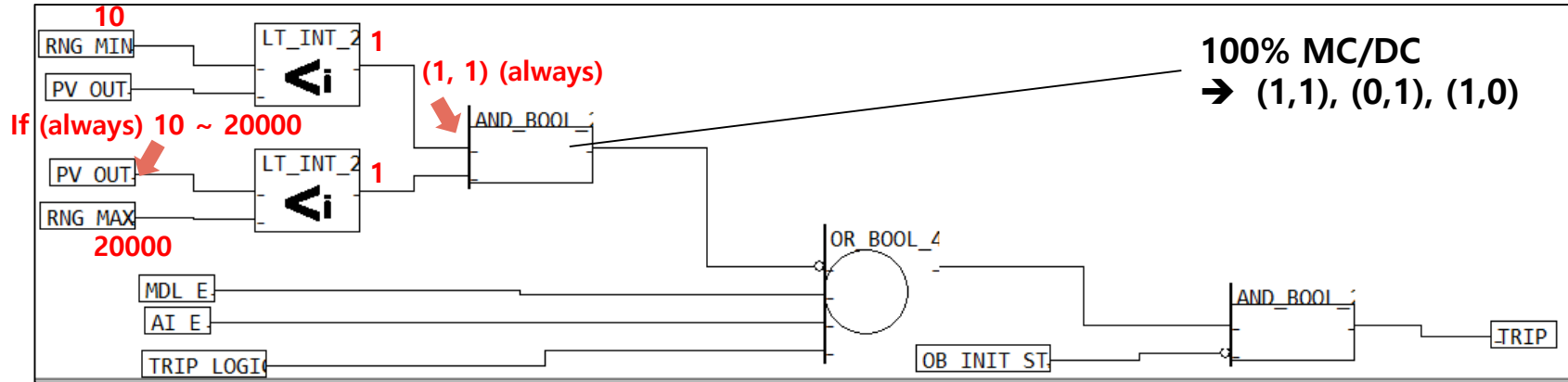
- **Insufficient simulation ?**
- **If the variable 'PV_OUT' is always located between MIN and MAX,**
 - The block 'LT_INT_2' is never toggled. → 0% toggle coverage
- **User can add more test cases to toggle the function block**
 - Ex) PV_OUT = 0~9 and next PV_OUT > 10 (again)
 - (0 → 1)
 - (1 → 0)

Output Toggle Coverage (An Example of Unreachable Code)



- **Unreachable ?**
- **If the variable 'OB_INT_ST' is always true?**
 - The output variable 'TRIP' is never toggled. → 0% toggle coverage
- **User can modify the logic**
 - Ex) remove 'AND_BOOL' block
 - Ex) change the 'OB_INT_ST' variable (i.e., constant) to an (simulation) input variable

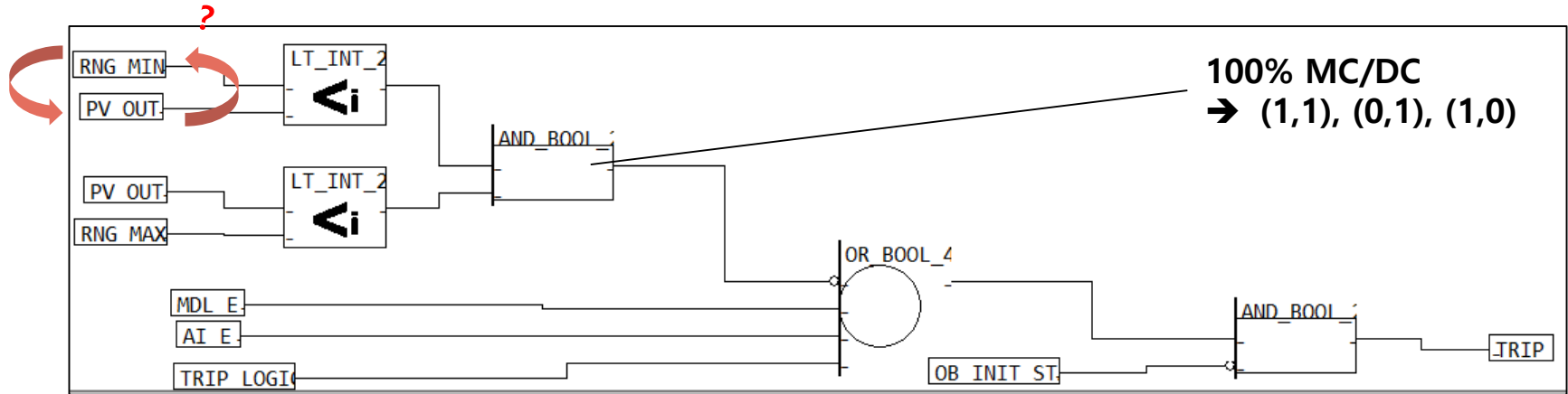
MC/DC Coverage (An Example of Insufficient Simulation)



- **Insufficient simulation ?**
- **If the variable 'PV_OUT' is always located between MIN and MAX,**
 - The input of 'AND_BOOL' is always (1, 1) → 33% MC/DC coverage
- **User can add more test cases to toggle the function block**
 - Ex) PV_OUT = 0~9 and PV_OUT = over 20000

| | |
|--------|--------|
| (0, 1) | (1, 0) |
|--------|--------|

MC/DC Coverage (An Example of Unreachable Code)

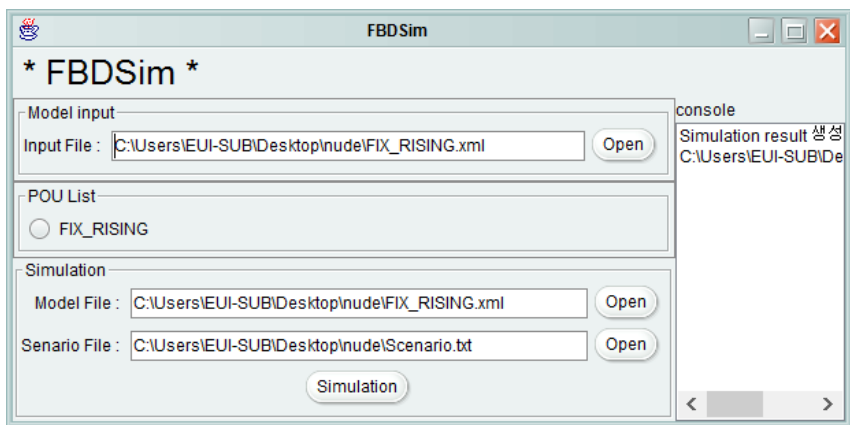


- **Unreachable ?**
- **If two inputs of the upper 'LT_INT_2' are exchanged (due to a logic error)**
 - It means "PV_OUT < MIN and PV_OUT < MAX"
 - The condition (1, 0) is never generated. → The max MC/DC is 66%
- **User may have a chance to identify the (hypothetical) error and fix the logic**

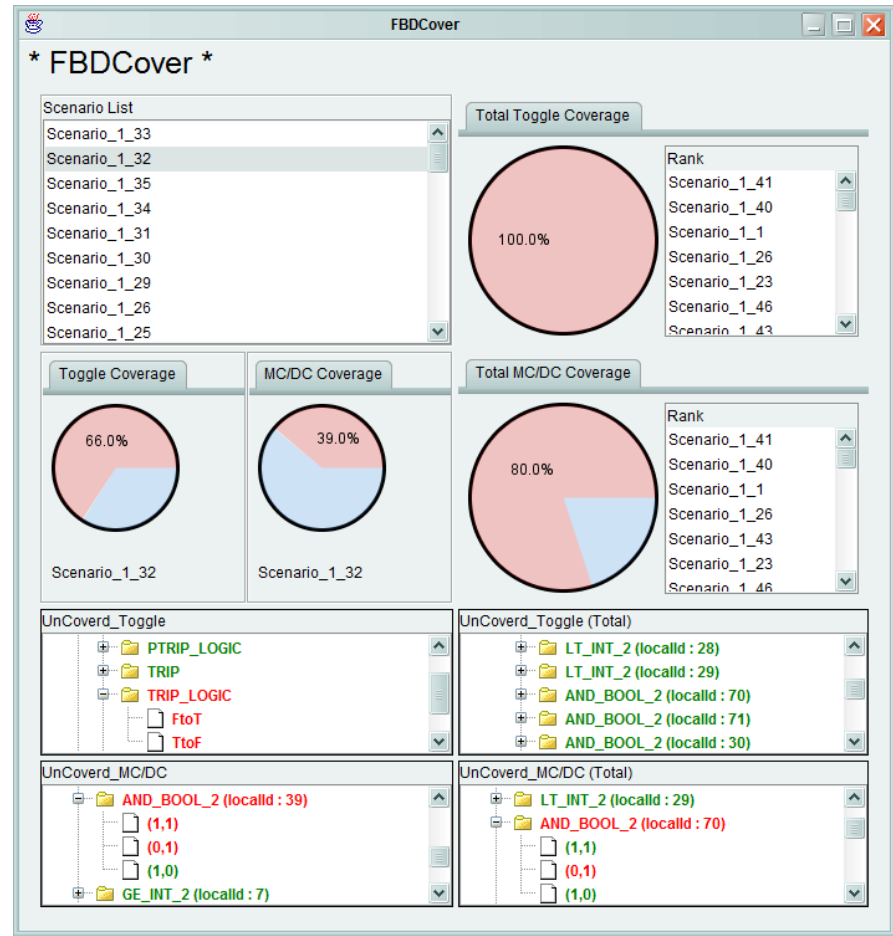
THE TOOL DEVELOPMENT

The Tool Development

- We develop two tools: (1) FBDSim (2) FBDCover



FBDSim

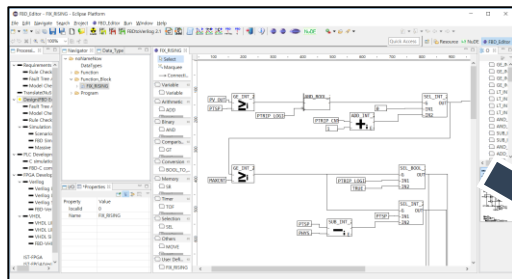


FBDCover

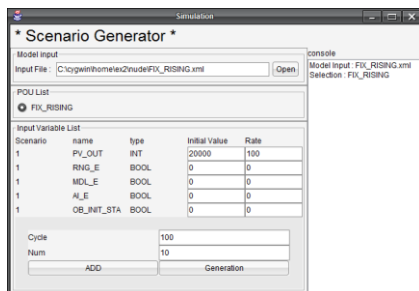
FBDSim

- **FBD Simulation Tool**

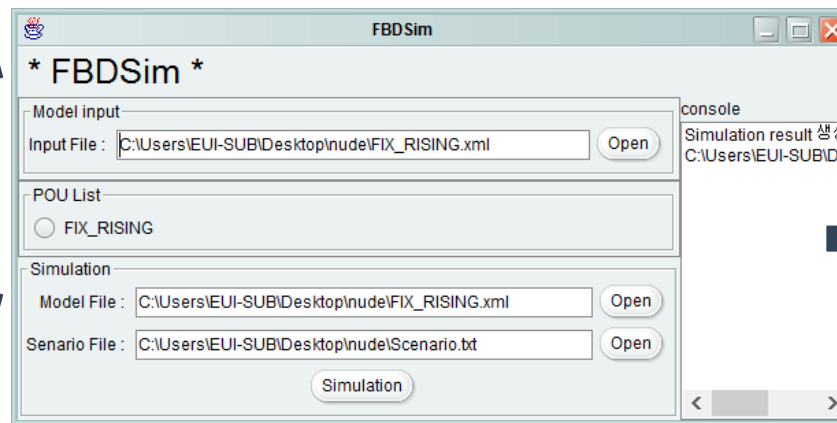
- **Input: (1) FBD program in PLCopen TC6 XML format , (2) Simulation scenario**
- **Output: (1) Simulation result, (2) Coverage information**
- **Embedded in FBD Editor**



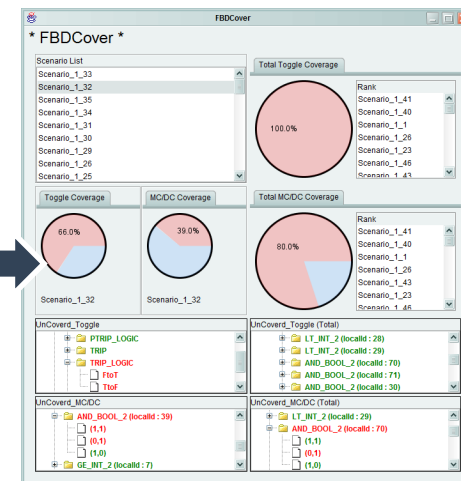
FBD Editor



Scenario Generator



FBDSim



FBDCover

FBDCover

- Coverage Measurement Tool**

- Input:**
 - Coverage information from FBDSim
- Output:**
 - Graphical coverage result
- Embedded in FBD Editor**
- Notifies ranks of scenarios**
- Notifies uncovered elements**

The screenshot displays the FBDCover application window with the following components:

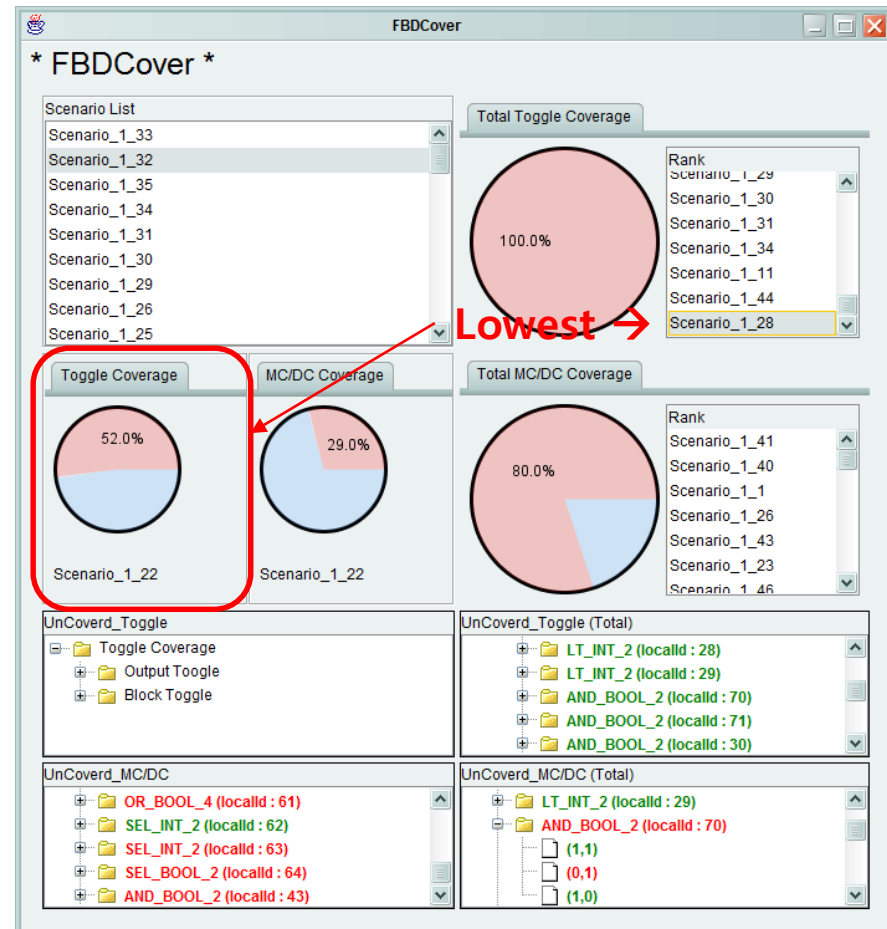
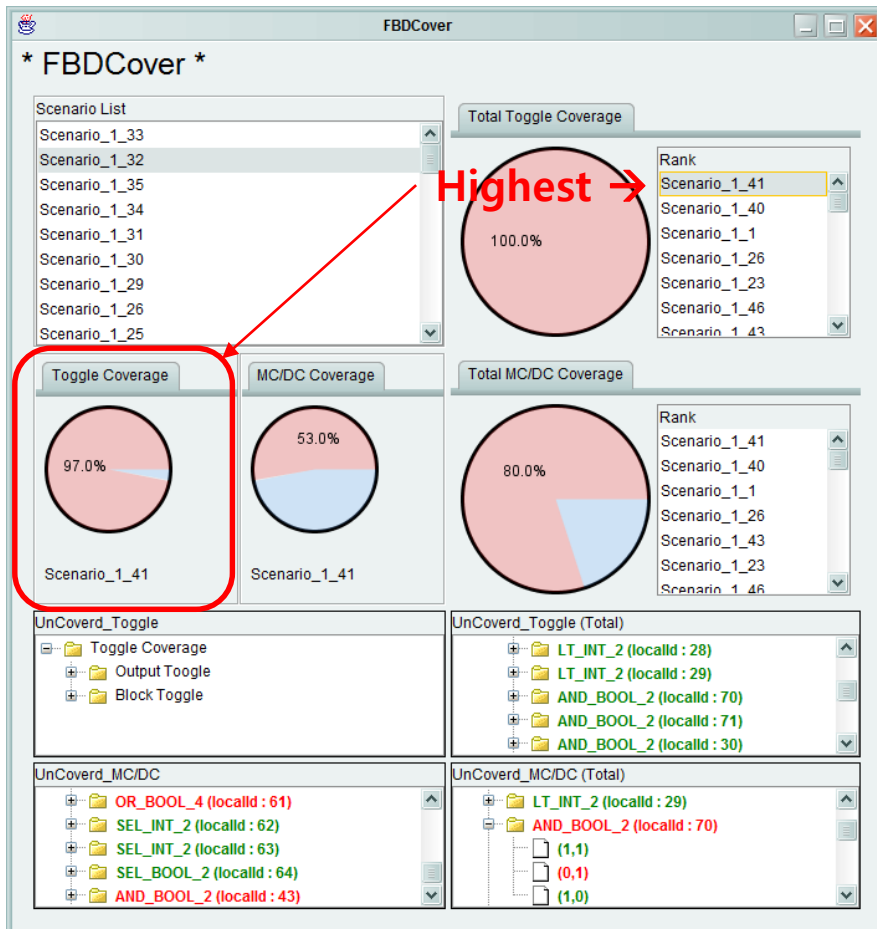
- Scenario List:** A list of scenarios including Scenario_1_33, Scenario_1_32, Scenario_1_35, Scenario_1_34, Scenario_1_31, Scenario_1_30, Scenario_1_29, Scenario_1_26, and Scenario_1_25.
- Total Toggle Coverage:** A pie chart showing 100.0% coverage for the selected scenario.
- Ranking:** A list of scenarios ranked by coverage, with Scenario_1_32 at the top.
- Toggle/MCDC Coverage of a scenario:** Two pie charts for Scenario_1_32 showing 66.0% Toggle Coverage and 39.0% MC/DC Coverage.
- Total MC/DC Coverage:** A pie chart showing 80.0% coverage.
- UnCoverd_Toggle:** A tree view showing uncovered toggle elements like PTRIP_LOGIC, TRIP, and TRIP_LOGIC (with sub-elements FtoT and TtoF).
- UnCoverd_MC/DC:** A tree view showing uncovered MC/DC conditions like AND_BOOL_2 (localId: 39) and GE_INT_2 (localId: 7).

Uncovered MC/DC condition

Ranks of FBDCover

• Highest rank scenario vs. Lowest rank scenario of toggle coverage

• Provide valuable information to improve simulation scenarios



Uncovered Elements of FBDCover

- Notify elements which are not simulated

- After improving the scenarios, user can re-simulate them seamlessly

The screenshot displays the FBDCover software interface. On the left, a ladder logic diagram shows two 'LT_INT_2' blocks. The top block is circled in red. Below it, a properties window for 'LT_INT_2' is shown, with 'localId' 28 circled in red. To the right, the main interface is titled '* FBDCover *' and contains several panels:

- Scenario List:** A list of scenarios including Scenario_1_33, Scenario_1_32, Scenario_1_35, Scenario_1_34, Scenario_1_31, Scenario_1_30, Scenario_1_29, Scenario_1_26, and Scenario_1_25.
- Total Toggle Coverage:** A pie chart showing 100.0% coverage. A rank list on the right includes Scenario_1_41, Scenario_1_40, Scenario_1_1, Scenario_1_26, Scenario_1_23, Scenario_1_46, and Scenario_1_43.
- Toggle Coverage:** A pie chart for Scenario_1_41 showing 97.0% coverage.
- MC/DC Coverage:** A pie chart for Scenario_1_41 showing 53.0% coverage.
- Total MC/DC Coverage:** A pie chart showing 80.0% coverage. A rank list on the right includes Scenario_1_41, Scenario_1_40, Scenario_1_1, Scenario_1_26, Scenario_1_43, Scenario_1_23, and Scenario_1_46.
- UnCoverd_Toggle:** A tree view showing 'LT_INT_2 (localId : 28)' with sub-items 'FtoT' and 'TtoF'. A red arrow points to this section.
- UnCoverd_MC/DC:** A tree view showing 'OR_BOOL_4 (localId : 61)', 'SEL_INT_2 (localId : 62)', 'SEL_INT_2 (localId : 63)', 'SEL_BOOL_2 (localId : 64)', and 'AND_BOOL_2 (localId : 43)'. Below this, a summary shows '(1,1)', '(0,1)', and '(1,0)'.

Additional annotations include a red circle around the 'LT_INT_2' block in the diagram and a red circle around the 'LT_INT_2 (localId : 28)' entry in the UnCoverd_Toggle panel. A red arrow points from the text 'LT_INT_2 block localId 28 (1 → 0) toggle' to the 'LT_INT_2 (localId : 28)' entry.

LocalId 28

LT_INT_2 block
LocalId 28
(1 → 0) toggle

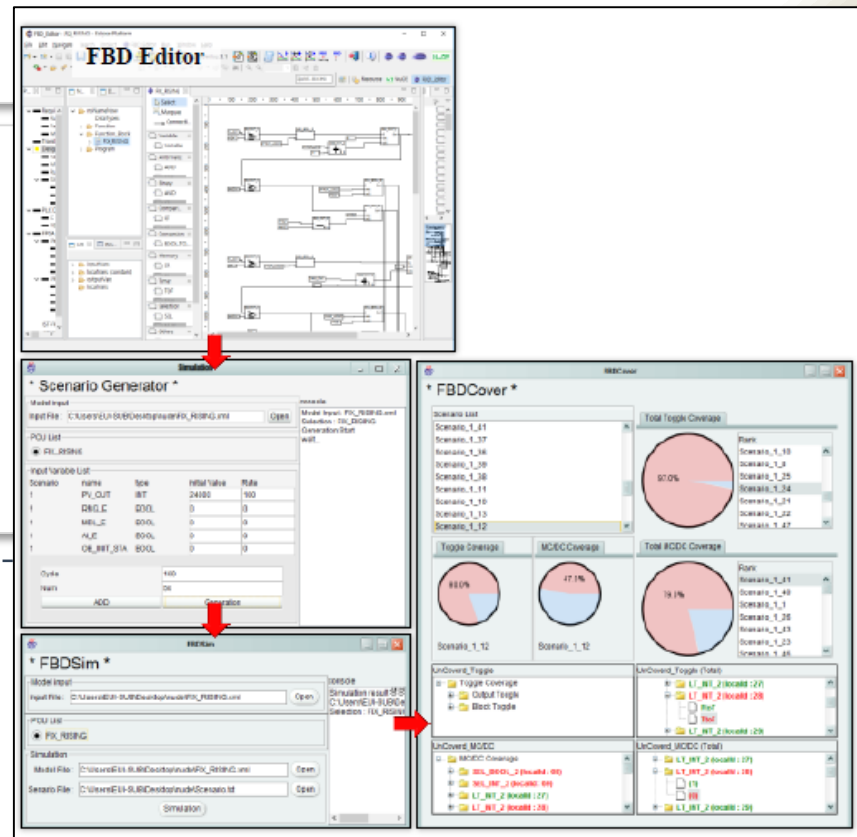
CASE STUDY

Case Study

- We performed a case study with an example replicating a KNICS APR-1400 RPS BP

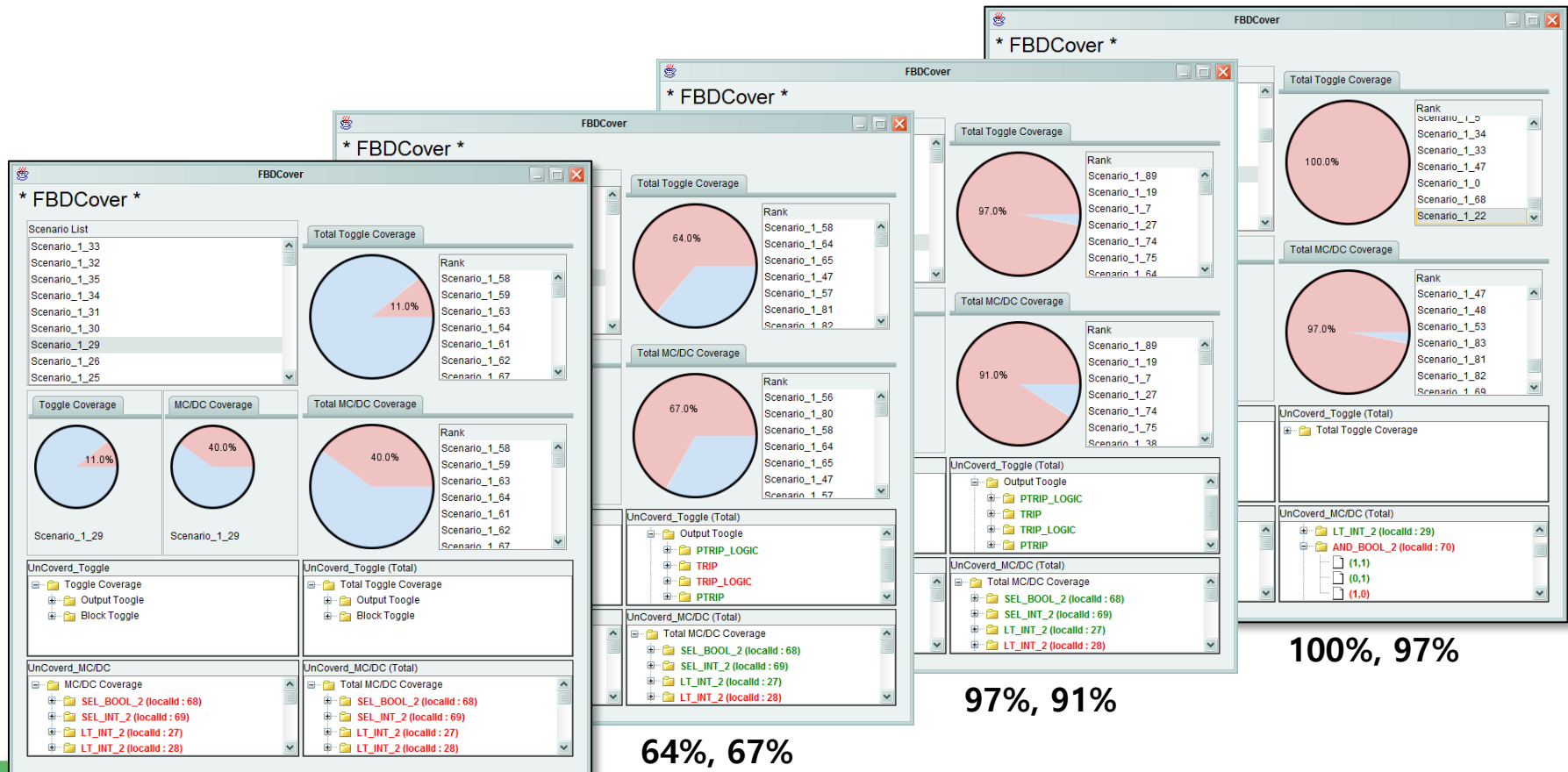
- 'FBDSim' automatically simulates a set of FBD scenarios and checks toggle and MC/DC coverage

- We used our tool-set of
 - FBD Editor
 - Scenario Generator
 - FBDSim
 - FBDCover



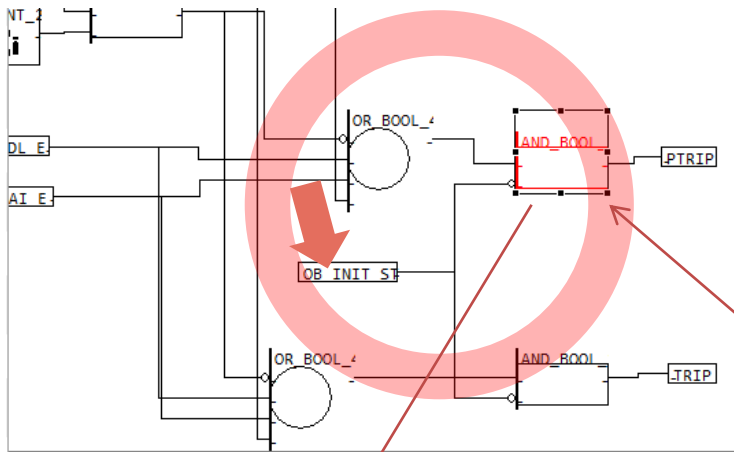
Case Study

- We found uncovered elements and improved the scenarios and then re-simulated with the scenarios.



Case Study (Example)

- We found that we missed to simulate the bypass, with the MC/DC coverage.



| Property | Value |
|----------------|------------|
| Excution_order | 0 |
| localId | 70 |
| Location | 960,2460 |
| Name | AND_BOOL_2 |

*** FBDCover ***

Scenario List

- Scenario_1_41
- Scenario_1_37
- Scenario_1_36
- Scenario_1_39
- Scenario_1_38
- Scenario_1_91
- Scenario_1_90
- Scenario_1_93
- Scenario_1_92

Total Toggle Coverage

100.0%

Rank

- Scenario_1_5
- Scenario_1_34
- Scenario_1_33
- Scenario_1_47
- Scenario_1_0
- Scenario_1_68
- Scenario_1_22

Toggle Coverage

40.0%

Scenario_1_22

MC/DC Coverage

49.0%

Scenario_1_22

Total MC/DC Coverage

97.0%

Rank

- Scenario_1_47
- Scenario_1_48
- Scenario_1_53
- Scenario_1_83
- Scenario_1_81
- Scenario_1_82
- Scenario_1_69

UnCoverd_Toggle

- Toggle Coverage
- Output Toggle
- Block Toggle

UnCoverd_Toggle (Total)

- Total Toggle Coverage

UnCoverd_MC/DC

- MC/DC Coverage
- SEL_BOOL_2 (localId : 68)
- SEL_INT_2 (localId : 69)
- LT_INT_2 (localId : 27)
- LT_INT_2 (localId : 28)

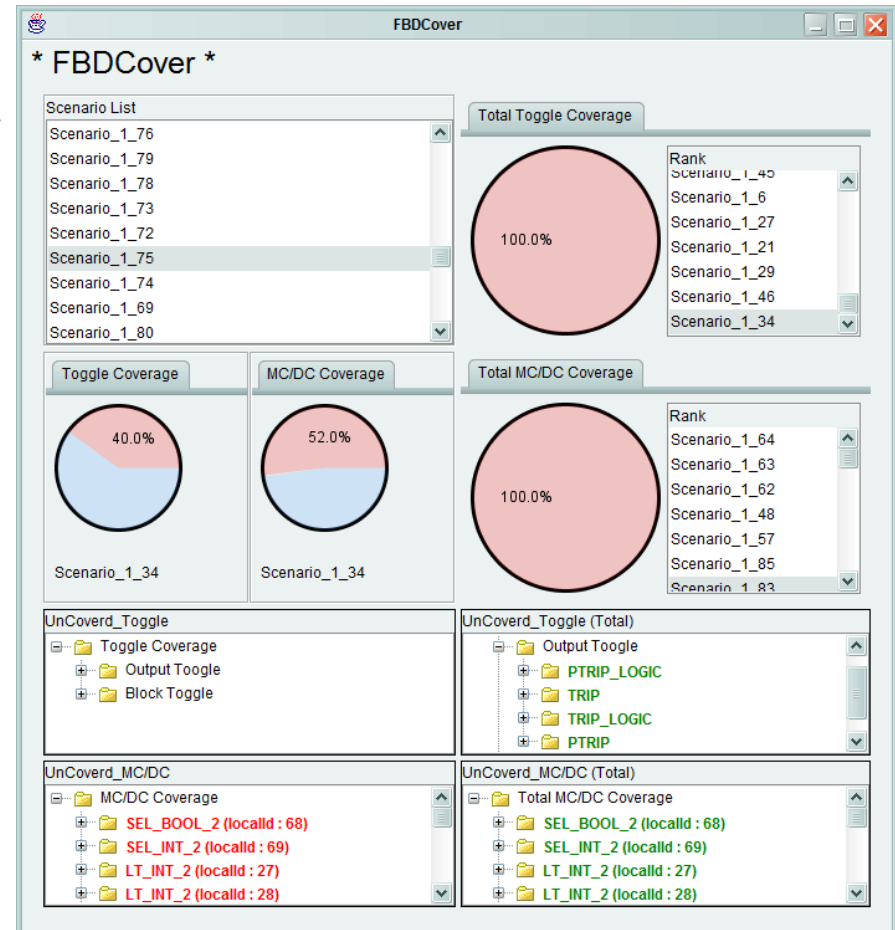
UnCoverd_MC/DC (Total)

- LT_INT_2 (localId : 29)
- AND_BOOL_2 (localId : 70)
 - (1,1)
 - (0,1)
 - (1,0)

Case Study (Example)

- Finally, we were able to get 100% toggle and MC/DC coverage.

- Of course, it is not sufficient to assure that the program is free from bug or error.
- It is possible to fail with 100% code coverage.
- However, we always try to improve on the quality of verification with every possible means.
- The tool is helpful because it notify engineers about that there are uncovered elements.
 - The uncovered elements imply that the simulation is not sufficient or the FBD has unintended errors or bugs.



100%, 100%

Conclusions and Future Work

- We applied toggle and MC/DC coverage to the FBD.

- If the coverages are not 100%, user should analyze whether it is reasonable.
- If it is not reasonable, it means that the simulation may be insufficient or the logic may have unintended errors or bugs.

- We are trying to **evaluate** the efficiency/applicability of the coverages proposed.
- All condition coverage is also applicable.

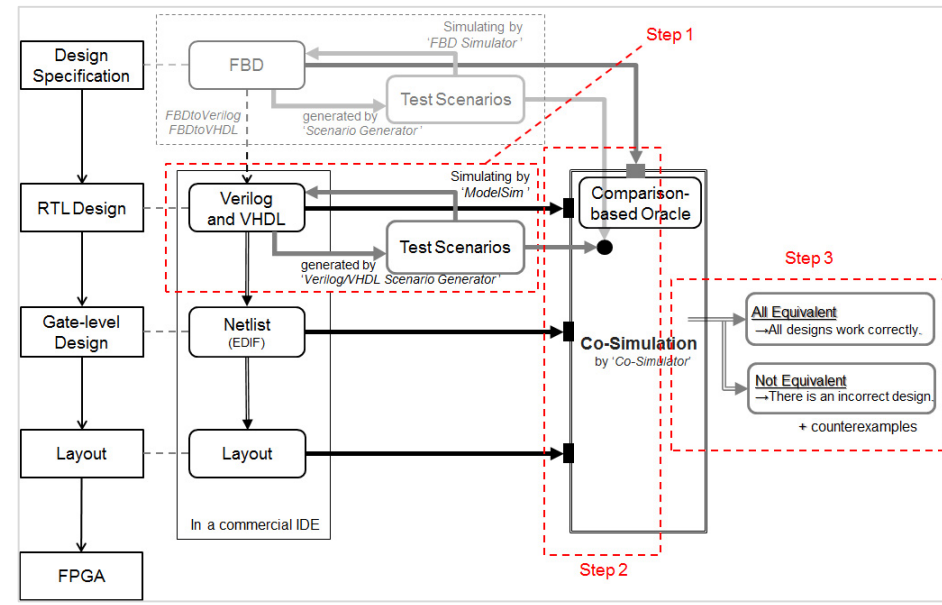
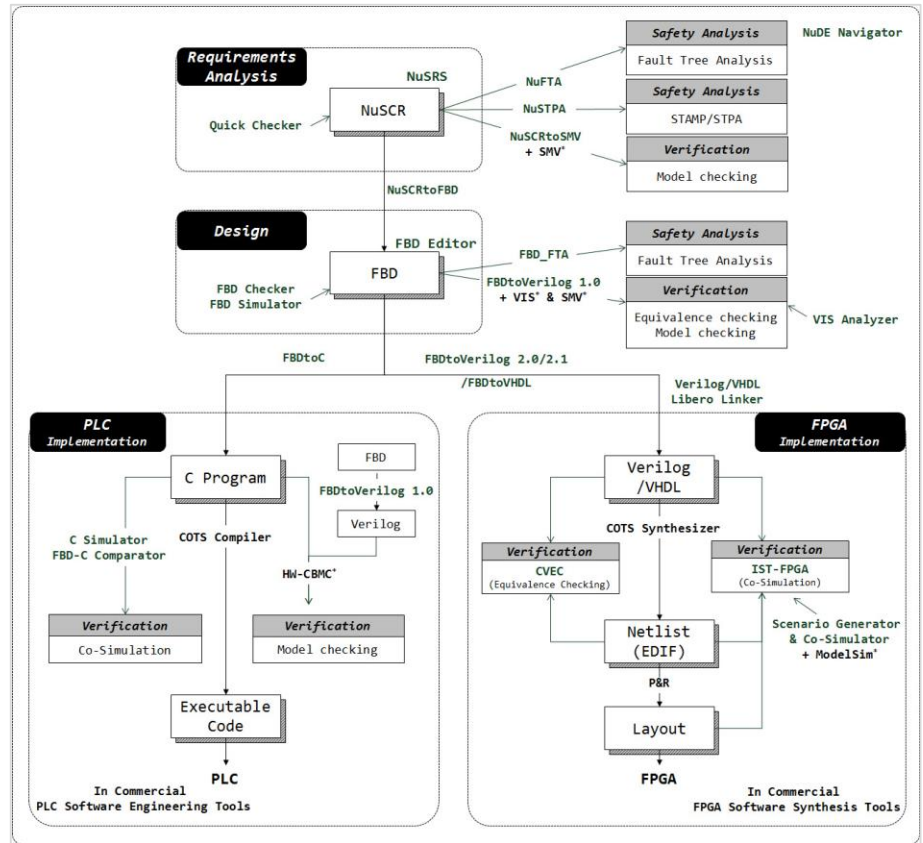
- We developed two CASE tools.

- We developed two CASE tools 'FBDSim' and 'FBDCover'
- We can simulate the FBD and measure the coverages of the simulation
- It produces a rank of scenarios and uncovered elements.

Conclusions and Future Work

- We are now planning to extend the coverage technique and tools to develop a full coverage-based scenario generation tool.

- NuDE 2.0
- IST-FPGA



Jaeyeob Kim, Eui-Sub Kim, Junbeom Yoo, Young Jun Lee and Jong-Gyun Choi, "An Integrated Software Testing Framework for FPGA-based Controllers in Nuclear Power Plants," Nuclear Engineering and Technology, Vol.48, No.2, pp.470-481, 2016.

THANK YOU

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