Testing and Experimental Evaluation of VERDS Version 1.30

1 Introduction

This document contains an experimental evaluation of *verds* version 1.30. There are two parts of the evaluation: one is an experimental comparison of the TBD-based boolean diagram model checking implemented in *verds* (version 1.30)[1] with the BDD-based model checking implemented in NuSMV (version 2.5.0)[2]; the other is an experimental comparison of the QBF-based bounded semantics model checking implemented in *verds* with boolean diagram model checking implemented in *verds*. The experimental evaluation is done on a Linux platform with 128 GB memory. For convenience, the TBD-based boolean diagram model checking implemented in *verds* is referred to as *verds-bd* , and the QBF-based bounded semantics model checking implemented in *verds* is referred to as *verds*-QBF. For convenience, the invocation of NuSMV with the option -dcx for not generating counterexamples is referred to as NuSMV.

2 VERDS-BD versus NuSMV

This section contains an experimental comparison of *verds-bd* with NuSMV. The comparison is based on two types of random boolean programs (with variable number of global and local variables)[3].

Brief Summary Comparing with the general BDD based symbolic model checking algorithm implemented in NuSMV, *verds-bd* has advantages in the evaluation with both types of random programs combined with each of 24 properties: with respect to the first type of programs, *verds-bd* has advantages in all 24 cases; with respect to the second type of programs, *verds-bd* has advantages in 20 of the 24 cases. Of the 48 subtypes, 4 involve only AG properties, comparing with an ad hoc algorithm for handling AG properties implemented in NuSMV, *verds-bd* has advantages in 3 of the 4 sets of cases, while NuSMV has advantages in 1 of the 4 cases. Moreover, in most cases where *verds-bd* has advantages, the differences seem to yield a coefficient of an exponential factor in the number of boolean variables (when testing a property with a set of models of different sizes).

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[1] http://lcs.ios.ac.cn/∼zwh/verds/
[2] http://nusmv.irst.itc.it/
[3] http://lcs.ios.ac.cn/∼zwh/verds/

2.1 Types of Random Programs and Types of Properties

Two sets of random programs and 24 properties are formulated for the experimental evaluation.

Programs with Concurrent Processes The parameters of the first set of random boolean programs are as follows:

a: number of processes
b: number of all variables
c: number of share variables
d: number of local variables in a process

The shared variables are initially set to a random value in $\{0, 1\}$, and the local variables are initially set to 0. For each process, the shared variables and the local variables are assigned the negation of a variable randomly chosen from these variables.

Examples An example of such programs in the input format of $NuSMV$ is shown in Figure 1 of Appendix A. The corresponding program in the input format of *verds* (called *verds* verification model, or VVM for short) is shown in Figure 2 of Appendix A.

Programs with Concurrent Sequential Processes The parameters of the second set of random boolean programs are as follows, in addition to a, b, c, d specified above.

t: number of transitions in a process
p: number of parallel assignments in each transition

Besides the b boolean variables, for each process, there is a local variable representing program locations, with e possible values. The shared variables are initially set to a random value in $\{0, 1\}$, and the local variables are initially set to 0. For each transition of a process, p pairs of shared variables and local variables are randomly chosen among the shared variables and the local variables, such that the first element of such a pair is assigned the negation of the second element of the pair. Transitions are numbered from 0 to $t - 1$, and are executed consecutively, and when the end of the sequence of the transitions is reached, it loops back to the execution of the transition numbered 0.

Examples An example of such programs in the input format of $NuSMV$ is shown in Figure 3 of Appendix A. The corresponding program in VVM is shown in Figure 4 of Appendix A.

Types of Properties 24 properties are formulated for testing. The properties involve AG, AF properties and properties specified with different combinations of the operators with one or two levels of nesting (with two levels of nesting when AX or EX is involved). Properties p_{01} to p_{12} are shown as follows, in which v_i are global variables. Properties p_{13} to p_{24} are similar to p_{01} to p_{12} with the difference of $\wedge$ and $\bigvee$ replaced by respectively $\vee$ and $\bigwedge$.

p_{01} :	$AG(\bigvee_{i=1}^{c} v_i)$
p_{02} :	$AF(\bigvee_{i=1}^{c} v_i)$
p_{03} :	$AG(v_1 \rightarrow AF(v_2 \wedge \bigvee_{i=3}^{c} v_i))$
p_{04} :	$AG(v_1 \rightarrow EF(v_2 \wedge \bigvee_{i=3}^{c} v_i))$
p_{05} :	$EG(v_1 \rightarrow AF(v_2 \wedge \bigvee_{i=3}^{c} v_i))$
p_{06} :	$EG(v_1 \rightarrow EF(v_2 \wedge \bigvee_{i=3}^{c} v_i))$
p_{07} :	$A(v_1\, U\, A(v_2\, U\, \bigvee_{i=3}^{c} v_i)$
p_{08} :	$A(v_1\, U\, E(v_2\, U\, \bigvee_{i=3}^{c} v_i)$
p_{09} :	$A(v_1\, U\, A(v_2\, R\, \bigvee_{i=3}^{c} v_i)$
p_{10} :	$A(v_1\, U\, E(v_2\, R\, \bigvee_{i=3}^{c} v_i)$
p_{11} :	$A(AXv_1\, R\, AX\, A(v_2\, U\, \bigvee_{i=3}^{c} v_i)$
p_{12} :	$A(EXv_1\, R\, EX\, E(v_2\, U\, \bigvee_{i=3}^{c} v_i)$

2.2 Experimental Data for Two Selected Properties

For brevity, we chose to present the experimental data for two properties for each type of the random programs. The two properties are selected by looking at the one $NuSMV$ performs relatively best, and at the one *verds-bd* performs relatively best, with respect to the ratios of the average times of their performance on the 20 test cases. Additional details are presented in Appendix B.

For the programs with concurrent processes, we let b vary over the set of values $\{12, 24, 36\}$, $a = 3$, $c = b/2$, and $d = c/a$. For the programs with concurrent sequential processes,we let b vary over the set of values $\{12, 16, 20\}$, $a = 2$, $c = b/2$, $t = c$, $p = 4$, and $d = c/a$. Each of the 20 properties is tested on 20 test cases for each value of b.

The data are shown as follows, in which the numbers represent times in seconds. The left part of the table is the data obtained using the command "NuSMV -dcx filename" . The right part of the table is the data obtained using the command "verds filename".

model/property	b	min	max	aver	min	max	aver	ratio
$1/p_{11}$	12	0.0	0.0	0.0	0.0	0.1	0.0	0.83
	24	0.5	20.4	4.6	0.3	33.6	5.0	0.92
	36	29.4	1038.1	326.0	11.7	1028.7	175.7	1.86
$1/p_{02}$	12	0.0	0.0	0.0	0.0	0.0	0.0	4.21
	24	0.4	15.7	3.8	0.0	0.1	0.1	61.43
	36	26.1	945.7	282.3	0.2	2.6	0.8	356.56
$2/p_{11}$	12	0.1	0.6	0.2	0.1	5.8	2.0	0.11
	16	0.8	7.4	2.7	0.5	107.9	16.3	0.16
	20	11.1	192.0	62.8	2.7	644.7	176.4	0.36
$2/p_{02}$	12	0.1	0.2	0.1	0.0	0.0	0.0	4.09
	16	0.7	3.7	1.8	0.1	0.1	0.1	15.78
	20	9.2	82.1	37.8	0.4	0.8	0.6	65.20

Let $\tau(b,i)$ be the time for verification of the i-th ($i \in \{1,...,20\}$) test case with b variables, and let $lt.aver$ and $rt.aver$ denote the $aver$ value in respectively the left part and the right part of the table. The explanation of the meaning of different columns of the data is as follows.

$$
\begin{array}{ll}
min(b) & = \min_{1\leq i\leq 20} \tau(i,b) \\
min(b) & = \max_{1\leq i\leq 20} \tau(i,b) \\
aver(b) & = \sum_{1\leq i\leq 20} \tau(i,b)/20 \\
ratio(b) & = lt.aver(b)/rt.aver(b)
\end{array}
$$

The 4 properties are true in respectively 13, 60, 47, and 60 cases and false in respectively 47, 0, 13, and 0 cases.

2.3 On AG Properties

Properties p_{01} and p_{13} are of the form $AG\psi$. As AG properties are a very important type of properties that is simple and may be handle by specialized techniques, we have also compared *verds-bd* with an ad hoc algorithm implemented in NuSMV, using the command "NuSMV -AG -dcx filename". The experimental data for p_{01} and p_{13} are as follows.

model/property	b	min	max	aver	min	max	aver	ratio
$1/p_{01}$	12	0.0	0.0	0.0	0.0	0.0	0.0	0.97
	24	0.3	14.0	3.4	0.1	19.2	3.2	1.06
	36	24.5	865.2	247.4	7.8	249.4	89.4	2.77
$1/p_{13}$	12	0.0	0.0	0.0	0.0	0.0	0.0	2.76
	24	0.3	14.6	3.5	0.0	0.3	0.1	36.63
	36	24.5	872.3	253.4	0.2	3.0	1.1	232.70
$2/p_{01}$	12	0.0	0.1	0.1	0.0	0.0	0.0	2.50
	16	0.3	1.1	0.7	0.1	62.1	10.5	0.06
	20	2.4	10.2	5.6	0.4	450.8	31.4	0.18
$2/p_{13}$	12	0.0	0.1	0.1	0.0	0.1	0.1	1.10
	16	0.3	1.1	0.7	0.2	0.5	0.3	2.36
	20	2.4	10.2	5.7	1.2	2.7	1.8	3.18

The first 6 lines are data for the first type of programs and the last 6 lines are data for the second type of programs. The 4 properties are true in respectively 0, 0, 6, and 0 cases and false in respectively 60, 60, 54, and 60 cases. "NuSMV -AG -dcx" performs better in one of the four cases in this comparison.

2.4 Summary

Two types of programs are tested. One is programs with concurrent processes and the other programs with concurrent sequential processes. The experimental evaluation shows that the plain implementation of boolean diagram model checking has clear advantages over the BDD based symbolic model checking implemented in NuSMV, a well known model checking tool [1]. Although NuSMV has advantages in 4 of 24 cases with the second type of random programs, the advantages decrease when the size of the problem increases. On the other hand, in most cases where *verds-bd* has advantages, the differences seem to yield a coefficient of an exponential factor in the number of boolean variables (when testing a property with a set of models of different sizes). 4 of the 48 properties are AG properties, comparing with an ad hoc algorithm for handling AG properties implemented in NuSMV, *verds-bd* has advantages in 3 of the 4 sets of cases, while NuSMV has advantages in 1 of the 4 cases.

Note: The implementation of boolean diagram model checking is a plain one in the sense that there are no cone of influence reduction, no use of partitioned transition relation, and no use of sophisticated relational product computation (the implemented computation is straightforward: first conjunction and then abstraction). It is expected that the integration of the aforementioned techniques [2] will greatly increase the efficiency of boolean diagram model checking.

Note: The contents of the input files to the two tools *verds* and $NuSMV$ are syntactically different. To minimize the possible disturbance of the efficiency caused by the difference, we have ensured that the variables in the respective files are defined in the same order.

3 VERDS-QBF versus VERDS-BD

This section contains an experimental comparison of *verds*-QBF with verds−bd. The comparison is based on the same types of random boolean programs as those presented in the previous section.

Brief Summary Based on the test cases, the experimental evaluation shows that the bounded semantics model checking does not have advantage in verifying any of the properties that start with AG. On the other hand, the bounded semantics model checking has advantages in various degrees, ranging from a few percentage to a large percentage of test cases in different sets of test cases, with respect to the other verification and falsification problems (including falsification of AG properties). In summary, the bounded semantics model checking has advantage in more than 50 percent of the test cases, which are well distributed among verification and falsification of universal properties. In this sense, bounded semantics model checking and boolean diagram model checking may be considered complementary with their own advantages.

3.1 Experimental Data

For the programs with concurrent processes, we let b vary over the set of values $\{12, 24, 36\}$, $a = 3$, $c = b/2$, and $d = c/a$. For the programs with concurrent sequential processes,we let b vary over the set of values $\{12, 16, 20\}$, $a = 2$, $c = b/2$, $t = c$, $p = 4$, and $d = c/a$. Each of the 20 properties is tested on 20 test cases for each value of b.

For brevity, for each type of programs and each type of properties, a summary of the experimental data is presented as follows, where N is the number of test cases, T is the number of test cases in which the property is true, F is the number of test cases in which the property is false, adv is the number of cases in which *verds*-QBF has an advantage. The table on the top is the experimental data for the first type of programs, and the table on the bottom is that for the second type of programs. The experimental data are obtained using the command "verds -QBF filename"for bounded semantics model checking with *verds*-QBF and using the command "verds filename"for boolean diagram model checking with verds−bd. Additional details are presented in Appendix C.

property	adv/T	adv/F	adv/N
p_{01}	-	58/60	58/60
p_{02}	56/60	-	56/60
p_{03}	0/3	33/57	33/60
p_{04}	0/60	-	0/60
p_{05}	39/53	1/7	40/60
p_{06}	29/60	-	29/60
p_{07}	58/60	-	58/60
p_{08}	57/60	-	57/60
p_{09}	47/52	6/8	53/60
p_{10}	57/60	-	57/60
p_{11}	13/13	43/47	56/60
p_{12}	59/60	-	59/60
p_{13}	-	59/60	59/60
p_{14}	3/3	34/57	37/60
p_{15}	0/8	33/52	33/60
p_{16}	0/60	-	0/60
p_{17}	37/56	1/4	38/60
p_{18}	27/60	-	27/60
p_{19}	4/5	47/55	51/60
p_{20}	15/21	29/39	44/60
p_{21}	3/3	52/57	55/60
p_{22}	3/3	53/57	56/60
p_{23}	-	60/60	60/60
p_{24}	23/31	10/29	33/60
sum			1049/1440

p_{01}	0/53	2/7	2/60
p_{02}	60/60	-	60/60
p_{03}	0/10	2/50	2/60
p_{04}	0/60	-	0/60
p_{05}	4/46	0/14	4/60
p_{06}	1/60	-	1/60
p_{07}	60/60	-	60/60
p_{08}	60/60	-	60/60
p_{09}	36/54	0/6	36/60
p_{10}	52/60	-	52/60
p_{11}	33/47	3/13	36/60
p_{12}	50/60	-	50/60
p_{13}	-	60/60	60/60
p_{14}	4/4	1/56	5/60
p_{15}	0/10	4/50	4/60
p_{16}	0/60	-	0/60
p_{17}	4/48	0/12	4/60
p_{18}	1/60	-	1/60
p_{19}	8/8	44/52	52/60
p_{10}	13/18	28/42	41/60
p_{21}	4/4	50/56	54/60
p_{22}	4/4	48/56	52/60
p_{23}	-	59/60	59/60
p_{24}	9/16	34/44	43/60
sum			738/1440

Summary Two types of programs are tested. Based on the test cases, the experimental evaluation shows that the bounded semantics model checking does not have advantage in verifying any of the properties that start with AG. On the other hand, the bounded verification has advantage in various degrees with respect to the other verification and falsification problems (including falsification of AG properties).

Note The evaluation of the bounded semantics model checking uses *verds* for comparison, instead of the well known symbolic model checker $NuSMV$ [1], since *verds* is generally more efficient with respect to the test cases.

Note The efficiency also depends very much on the QBF-solving techniques. External QBF-solvers may be used to increase the efficiency of the verification. For ACTL formulas, special considerations are possible [3], and the use of SAT-solving techniques may be more efficient for this kind of problems.

References

1. A. Cimatti, E. M. Clarke, F. Giunchiglia, M. Roveri. NUSMV: A New Symbolic Model Verifier. CAV 1999: 495-499.
2. E. M. Clarke, O. Grumberg and D. Peled. Model Checking. The MIT Press. 1999.
3. W. Zhang. Bounded Semantics of CTL and SAT-based Verification. Lecture Notes in Computer Science 5885 (ICFEM 2009):286-305. Springer-Verlag. 2009.

A Examples of SMV and VVM Programs

Examples of SMV programs and VVM programs are presented. The contents are as follows:

Random concurrent processes A random SMV program with 6 global variables, 3 processes and 2 local variables for each of the processes, and the corresponding VVM program;

Random concurrent sequential processes A random SMV program with 6 global variables, 2 processes and 4 local variables (of which 3 are boolean variables) for each of the processes, and the corresponding VVM program.

```
MODULE main
VAR    v1:boolean; v2:boolean; v3:boolean;
       v4:boolean; v5:boolean; v6:boolean;
       v7:boolean; v8:boolean;
       p1:process p1t(v1,v2,v3,v4,v5,v6);
       p2:process p2t(v1,v2,v3,v4,v5,v6);
ASSIGN init(v1):=1; init(v2):=0; init(v3):=1;
       init(v4):=1; init(v5):=1; init(v6):=1;
       init(v7):=0; init(v8):=0;
       next(v1):=!v5; next(v2):=!v6; next(v3):=!v4;
       next(v4):=!v4; next(v5):=!v7; next(v6):=!v3;
       next(v7):=!v1; next(v8):=!v1;
SPEC   AG((v1=1|v2=1|v3=1|v4=1|v5=1|v6=1))

MODULE p1t(v1,v2,v3,v4,v5,v6)
VAR    v9:boolean; v10:boolean;
ASSIGN init(v9):=0; init(v10):=0;
       next(v1):=!v6; next(v2):=!v3; next(v3):=!v4;
       next(v4):=!v10; next(v5):=!v3; next(v6):=!v3;
       next(v9):=!v10; next(v10):=!v1;

MODULE p2t(v1,v2,v3,v4,v5,v6)
VAR    v11:boolean; v12:boolean;
ASSIGN init(v11):=0; init(v12):=0;
       next(v1):=!v3; next(v2):=!v6; next(v3):=!v12;
       next(v4):=!v2; next(v5):=!v5; next(v6):=!v3;
       next(v11):=!v11; next(v12):=!v5;
```

Fig. 1. A Program with Concurrent Processes

```
VVM
VAR    v1:(0..1); v2:(0..1); v3:(0..1); v4:(0..1); v5:(0..1); v6:(0..1);
INIT   v1=1; v2=0; v3=1; v4=1; v5=1; v6=1;
PROC   p0:p0t(v1,v2,v3,v4,v5,v6);
       p1:p1t(v1,v2,v3,v4,v5,v6); p2:p2t(v1,v2,v3,v4,v5,v6);
SPEC   AG((v1=1|v2=1|v3=1|v4=1|v5=1|v6=1))

MODULE p0t(v1,v2,v3,v4,v5,v6)
VAR    v7:(0..1); v8:(0..1);
INIT   v7=0; v8=0;
TRANS  TRUE: (v1,v2,v3,v4,v5,v6,v7,v8):=
             (1-v5,1-v6,1-v4,1-v4,1-v7,1-v3,1-v1,1-v1);

MODULE p1t(v1,v2,v3,v4,v5,v6)
VAR    v9:(0..1); v10:(0..1);
INIT   v9=0; v10=0;
TRANS  TRUE: (v1,v2,v3,v4,v5,v6,v9,v10):=
             (1-v6,1-v3,1-v4,1-v10,1-v3,1-v3,1-v10,1-v1);

MODULE p2t(v1,v2,v3,v4,v5,v6)
VAR    v11:(0..1); v12:(0..1);
INIT   v11=0; v12=0;
TRANS  TRUE: (v1,v2,v3,v4,v5,v6,v11,v12):=
             (1-v3,1-v6,1-v12,1-v2,1-v5,1-v3,1-v11,1-v5);
```

Fig. 2. A Program with Concurrent Processes in VVM

```
MODULE main
VAR    v1:boolean; v2:boolean; v3:boolean;
       v4:boolean; v5:boolean; v6:boolean;
       cp:{c0,c1,c2,c3,c4,c5}; v7:boolean; v8:boolean; v9:boolean;
       p1:process p1t(v1,v2,v3,v4,v5,v6);
ASSIGN init(v1):=1; init(v2):=0; init(v3):=1;
       init(v4):=1; init(v5):=1; init(v6):=1;
       init(cp):=c0; init(v7):=0; init(v8):=0; init(v9):=0;
       next(cp):=case cp=c0:c1; cp=c1:c2;
                 cp=c2:c3; cp=c3:c4; cp=c4:c5; cp=c5:c0; esac;
       next(v1):=case cp=c0:!v9; cp=c3:!v6; cp=c5:!v8; 1:v1; esac;
       next(v2):=case cp=c0:!v4; cp=c3:!v9; 1:v2; esac;
       next(v3):=case cp=c2:!v6; cp=c3:!v8; cp=c4:!v1; 1:v3; esac;
       next(v4):=case cp=c1:!v8; cp=c2:!v2; cp=c4:!v5; 1:v4; esac;
       next(v5):=case cp=c0:!v8; cp=c1:!v2;
                 cp=c2:!v8; cp=c3:!v7; 1:v5; esac;
       next(v6):=case cp=c1:!v1; cp=c5:!v4; 1:v6; esac;
       next(v7):=case cp=c0:!v6; cp=c2:!v1;
                 cp=c4:!v6; cp=c5:!v3; 1:v7; esac;
       next(v8):=case cp=c4:!v9; 1:v8; esac;
       next(v9):=case cp=c1:!v7; cp=c5:!v2; 1:v9; esac;
SPEC   AG((v1=1|v2=1|v3=1|v4=1|v5=1|v6=1))

MODULE p1t(v1,v2,v3,v4,v5,v6)
VAR    cp:{c0,c1,c2,c3,c4,c5}; v10:boolean; v11:boolean; v12:boolean;
ASSIGN init(cp):=c0; init(v10):=0; init(v11):=0; init(v12):=0;
       next(cp):=case cp=c0:c1; cp=c1:c2;
                 cp=c2:c3; cp=c3:c4; cp=c4:c5; cp=c5:c0; esac;
       next(v1):=case cp=c0:!v4; cp=c2:!v11; cp=c5:!v11; 1:v1; esac;
       next(v2):=case cp=c4:!v3; 1:v2; esac;
       next(v3):=case cp=c0:!v2; cp=c1:!v11;
                 cp=c2:!v4; cp=c5:!v2; 1:v3; esac;
       next(v4):=case cp=c3:!v3; 1:v4; esac;
       next(v5):=case cp=c1:!v1; cp=c2:!v10; 1:v5; esac;
       next(v6):=case cp=c2:!v2; cp=c4:!v1; cp=c5:!v4; 1:v6; esac;
       next(v10):=case cp=c0:!v11; cp=c1:!v6;
                 cp=c3:!v6; cp=c4:!v5; 1:v10; esac;
       next(v11):=case cp=c3:!v5; cp=c4:!v12; 1:v11; esac;
       next(v12):=case cp=c0:!v6; cp=c1:!v2;
                 cp=c3:!v1; cp=c5:!v5; 1:v12; esac;
```

Fig. 3. A Program with Concurrent Sequential Processes

```
VVM
VAR    v1:(0..1); v2:(0..1); v3:(0..1); v4:(0..1); v5:(0..1); v6:(0..1);
INIT   v1=1; v2=0; v3=1; v4=1; v5=1; v6=1;
PROC   p0:p0t(v1,v2,v3,v4,v5,v6); p1:p1t(v1,v2,v3,v4,v5,v6);
SPEC   AG((v1=1|v2=1|v3=1|v4=1|v5=1|v6=1))

MODULE p0t(v1,v2,v3,v4,v5,v6)
VAR    cp:{c0,c1,c2,c3,c4,c5}; v7:(0..1); v8:(0..1); v9:(0..1);
INIT   cp=c0; v7=0; v8=0; v9=0;
TRANS  cp=c0: (v2,v7,v5,v1,cp):=(1-v4,1-v6,1-v8,1-v9,c1);
       cp=c1: (v9,v5,v6,v4,cp):=(1-v7,1-v2,1-v1,1-v8,c2);
       cp=c2: (v5,v7,v3,v4,cp):=(1-v8,1-v1,1-v6,1-v2,c3);
       cp=c3: (v2,v1,v5,v3,cp):=(1-v9,1-v6,1-v7,1-v8,c4);
       cp=c4: (v4,v3,v7,v8,cp):=(1-v5,1-v1,1-v6,1-v9,c5);
       cp=c5: (v6,v7,v9,v1,cp):=(1-v4,1-v3,1-v2,1-v8,c0);

MODULE p1t(v1,v2,v3,v4,v5,v6)
VAR    cp:{c0,c1,c2,c3,c4,c5}; v10:(0..1); v11:(0..1); v12:(0..1);
INIT   cp=c0; v10=0; v11=0; v12=0;
TRANS  cp=c0: (v1,v3,v12,v10,cp):=(1-v4,1-v2,1-v6,1-v11,c1);
       cp=c1: (v3,v12,v10,v5,cp):=(1-v11,1-v2,1-v6,1-v1,c2);
       cp=c2: (v5,v3,v1,v6,cp):=(1-v10,1-v4,1-v11,1-v2,c3);
       cp=c3: (v4,v12,v11,v10,cp):=(1-v3,1-v1,1-v5,1-v6,c4);
       cp=c4: (v2,v10,v11,v6,cp):=(1-v3,1-v5,1-v12,1-v1,c5);
       cp=c5: (v12,v1,v3,v6,cp):=(1-v5,1-v11,1-v2,1-v4,c0);
```

Fig. 4. A Program with Concurrent Sequential Processes in VVM

B Details of Experimental Evaluation I

This section contain experimental data with 2 types of random boolean programs: programs with concurrent processes and programs with concurrent sequential processes. Experimental data for each type of programs are further divided into a summary of the experimental data for all the 20 test cases, and experimental data that distinguish between models that satisfy a property and models that do not satisfy a property.

B.1 Programs with Concurrent Processes

For the programs with concurrent processes, we let b vary over the set of values $\{12, 24, 36\}$, $a = 3$, $c = b/2$, and by locating each process with the same number of local variables, we obtain $d = (b - c)/a = c/a$. Each property is tested on 20 test cases for each $b \in \{12, 24, 36\}$. The details are shown as follows.

p_{01}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	1.18
24	0.4	18.4	4.3	0.1	19.2	3.2	1.35
36	27.8	986.3	295.9	7.8	249.4	89.4	3.31

p_{02}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	4.21
24	0.4	15.7	3.8	0.0	0.1	0.1	61.43
36	26.1	945.7	282.3	0.2	2.6	0.8	356.56

p_{03}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.1	0.0	0.79
24	0.4	19.9	4.5	0.2	12.9	2.5	1.82
36	28.5	1226.8	335.6	2.2	383.0	80.6	4.16

p_{04}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	2.83
24	0.5	15.7	3.8	0.0	0.7	0.1	25.64
36	26.3	924.6	280.9	0.3	8.5	1.8	155.84

p_{05}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	1.19
24	0.4	18.9	4.2	0.1	8.1	1.4	3.08
36	26.7	1231.3	346.1	0.8	142.0	36.0	9.61

p_{06}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	2.29
24	0.4	16.4	4.0	0.0	0.9	0.2	23.08
36	29.3	970.8	300.5	0.3	10.8	2.1	142.83

p_{07}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	3.78
24	0.4	16.0	3.9	0.0	0.2	0.1	53.20
36	25.9	982.9	297.3	0.2	2.8	0.9	337.55

p_{08}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	2.85
24	0.4	16.1	3.9	0.0	0.4	0.1	35.02
36	27.4	956.2	300.2	0.3	3.4	1.2	242.75

p_{09}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	1.33
24	0.4	19.4	4.3	0.0	34.0	3.7	1.16
36	26.3	1023.8	296.4	0.3	674.6	71.2	4.16

p_{10}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	2.97
24	0.4	17.9	4.1	0.0	0.4	0.1	35.90
36	29.6	1129.0	332.9	0.3	4.2	1.3	250.32

p_{11}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.1	0.0	0.83
24	0.5	20.4	4.6	0.3	33.6	5.0	0.92
36	29.4	1038.1	326.0	11.7	1028.7	175.7	1.86

p_{12}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	1.77
24	0.4	16.2	4.0	0.1	0.9	0.2	19.29
36	30.2	955.2	312.7	0.5	11.3	2.4	129.73

p_{13}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	3.21
24	0.4	15.4	4.0	0.0	0.3	0.1	41.99
36	26.9	923.4	285.1	0.2	3.0	1.1	261.79

p_{14}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	3.22
24	0.4	16.8	4.0	0.0	0.3	0.1	39.86
36	27.2	1046.8	311.0	0.2	3.4	1.2	264.51

p_{15}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.1	0.0	0.75
24	0.4	20.0	4.5	0.2	13.0	2.5	1.81
36	29.9	1303.9	340.1	1.8	378.8	72.4	4.69

p_{16}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	2.71
24	0.4	15.9	4.0	0.0	0.7	0.2	26.50
36	26.9	932.9	282.9	0.3	8.5	1.9	152.17

p_{17}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	1.36
24	0.5	19.9	4.3	0.1	8.5	1.4	3.09
36	29.1	1305.9	348.2	0.9	201.1	40.4	8.61

p_{18}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	2.34
24	0.4	16.6	4.0	0.1	0.9	0.2	23.02
36	28.3	975.7	304.6	0.3	10.9	2.1	142.03

p_{19}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	2.73
24	0.4	18.3	4.2	0.0	0.5	0.1	30.78
36	31.6	1077.6	352.7	0.3	5.6	1.6	226.68

p_{20}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	1.27
24	0.5	18.4	4.4	0.0	33.6	3.8	1.17
36	28.5	1014.0	321.7	0.3	677.0	73.0	4.41

p_{21}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	2.66
24	0.5	17.0	4.2	0.0	0.5	0.1	30.63
36	30.2	1007.1	328.9	0.3	4.8	1.5	217.00

p_{22}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	3.29
24	0.5	16.2	4.0	0.0	0.3	0.1	39.10
36	28.2	1115.0	343.5	0.2	3.2	1.2	291.63

p_{23}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	1.58
24	0.5	17.5	4.2	0.1	1.1	0.2	18.34
36	31.5	1239.3	363.4	0.5	13.0	2.6	140.28

p_{24}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.1	0.0	0.87
24	0.4	17.4	4.3	0.1	38.8	4.5	0.95
36	27.6	964.1	299.9	0.5	695.7	83.2	3.60

Separating Data for Correct and Incorrect Models The experimental data are further divided into two groups for those test models that are true and for those models that are false, with respect to each of the properties. For each property, there are two tables, the first table is the experimental data obtained for the models that are evaluated to true, and the second table is the experimental data obtained for the models that are evaluated to false. The number in the leftmost column is the number of true (respectively false) models among the 20 models for each value of b.

p_{01}

T	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{01}

F	min	max	aver	min	max	aver	ratio
20	0.0	0.0	0.0	0.0	0.0	0.0	1.18
20	0.4	18.4	4.3	0.1	19.2	3.2	1.35
20	27.8	986.3	295.9	7.8	249.4	89.4	3.31

p_{02}

T	min	max	aver	min	max	aver	ratio
20	0.0	0.0	0.0	0.0	0.0	0.0	4.21
20	0.4	15.7	3.8	0.0	0.1	0.1	61.43
20	26.1	945.7	282.3	0.2	2.6	0.8	356.56

p_{02}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{03}

T	min	max	aver	min	max	aver	ratio
2	0.0	0.0	0.0	0.0	0.0	0.0	2.80
1	1.4	1.4	1.4	0.6	0.6	0.6	2.35
0	-	-	-	-	-	-	-

p_{03}

F	min	max	aver	min	max	aver	ratio
18	0.0	0.0	0.0	0.0	0.1	0.0	0.74
19	0.4	19.9	4.7	0.2	12.9	2.6	1.81
20	28.5	1226.8	335.6	2.2	383.0	80.6	4.16

p_{04}

T	min	max	aver	min	max	aver	ratio
20	0.0	0.0	0.0	0.0	0.0	0.0	2.83
20	0.5	15.7	3.8	0.0	0.7	0.1	25.64
20	26.3	924.6	280.9	0.3	8.5	1.8	155.84

p_{04}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{05}

T	min	max	aver	min	max	aver	ratio
16	0.0	0.0	0.0	0.0	0.0	0.0	1.33
18	0.4	18.9	4.4	0.1	8.1	1.5	2.97
19	26.7	1231.3	358.9	0.8	142.0	37.8	9.49

p_{05}

F	min	max	aver	min	max	aver	ratio
4	0.0	0.0	0.0	0.0	0.0	0.0	0.88
2	2.2	2.4	2.3	0.2	0.3	0.3	8.68
1	102.4	102.4	102.4	2.0	2.0	2.0	52.01

p_{06}

T	min	max	aver	min	max	aver	ratio
20	0.0	0.0	0.0	0.0	0.0	0.0	2.29
20	0.4	16.4	4.0	0.0	0.9	0.2	23.08
20	29.3	970.8	300.5	0.3	10.8	2.1	142.83

p_{06}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{07}

T	min	max	aver	min	max	aver	ratio
20	0.0	0.0	0.0	0.0	0.0	0.0	3.78
20	0.4	16.0	3.9	0.0	0.2	0.1	53.20
20	25.9	982.9	297.3	0.2	2.8	0.9	337.55

p_{07}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{08}

T	min	max	aver	min	max	aver	ratio
20	0.0	0.0	0.0	0.0	0.0	0.0	2.85
20	0.4	16.1	3.9	0.0	0.4	0.1	35.02
20	27.4	956.2	300.2	0.3	3.4	1.2	242.75

p_{08}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{09}

T	min	max	aver	min	max	aver	ratio
14	0.0	0.0	0.0	0.0	0.0	0.0	1.65
18	0.4	15.6	3.5	0.0	17.3	2.2	1.64
20	26.3	1023.8	296.4	0.3	674.6	71.2	4.16

p_{09}

F	min	max	aver	min	max	aver	ratio
6	0.0	0.0	0.0	0.0	0.0	0.0	0.93
2	2.8	19.4	11.1	1.4	34.0	17.7	0.63
0	-	-	-	-	-	-	-

p_{10}

T	min	max	aver	min	max	aver	ratio
20	0.0	0.0	0.0	0.0	0.0	0.0	2.97
20	0.4	17.9	4.1	0.0	0.4	0.1	35.90
20	29.6	1129.0	332.9	0.3	4.2	1.3	250.32

p_{10}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{11}

T	min	max	aver	min	max	aver	ratio
3	0.0	0.0	0.0	0.0	0.0	0.0	0.90
7	0.5	20.4	6.0	0.3	25.1	5.2	1.16
3	123.9	455.1	239.9	12.5	182.1	72.5	3.31

p_{11}

F	min	max	aver	min	max	aver	ratio
17	0.0	0.0	0.0	0.0	0.1	0.0	0.82
13	0.6	17.4	3.8	0.3	33.6	4.9	0.78
17	29.4	1038.1	341.2	11.7	1028.7	193.9	1.76

p_{12}

T	min	max	aver	min	max	aver	ratio
20	0.0	0.0	0.0	0.0	0.0	0.0	1.77
20	0.4	16.2	4.0	0.1	0.9	0.2	19.29
20	30.2	955.2	312.7	0.5	11.3	2.4	129.73

p_{12}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{13}

T	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{13}

F	min	max	aver	min	max	aver	ratio
20	0.0	0.0	0.0	0.0	0.0	0.0	3.21
20	0.4	15.4	4.0	0.0	0.3	0.1	41.99
20	26.9	923.4	285.1	0.2	3.0	1.1	261.79

p_{14}

T	min	max	aver	min	max	aver	ratio
2	0.0	0.0	0.0	0.0	0.0	0.0	3.43
1	3.8	3.8	3.8	0.2	0.2	0.2	24.31
0	-	-	-	-	-	-	-

p_{14}

F	min	max	aver	min	max	aver	ratio
18	0.0	0.0	0.0	0.0	0.0	0.0	3.20
19	0.4	16.8	4.0	0.0	0.3	0.1	41.17
20	27.2	1046.8	311.0	0.2	3.4	1.2	264.51

p_{15}

T	min	max	aver	min	max	aver	ratio
5	0.0	0.0	0.0	0.0	0.0	0.0	2.57
2	1.3	2.9	2.1	0.2	0.6	0.4	5.15
1	435.2	435.2	435.2	10.8	10.8	10.8	40.31

p_{15}

F	min	max	aver	min	max	aver	ratio
15	0.0	0.0	0.0	0.0	0.1	0.0	0.66
18	0.4	20.0	4.8	0.3	13.0	2.7	1.75
19	29.9	1303.9	335.1	1.8	378.8	75.7	4.43

p_{16}

T	min	max	aver	min	max	aver	ratio
20	0.0	0.0	0.0	0.0	0.0	0.0	2.71
20	0.4	15.9	4.0	0.0	0.7	0.2	26.50
20	26.9	932.9	282.9	0.3	8.5	1.9	152.17

p_{16}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{17}

T	min	max	aver	min	max	aver	ratio
19	0.0	0.0	0.0	0.0	0.0	0.0	1.35
18	0.5	19.9	4.5	0.1	8.5	1.5	2.99
19	29.1	1305.9	361.0	0.9	201.1	42.4	8.51

p_{17}

F	min	max	aver	min	max	aver	ratio
1	0.0	0.0	0.0	0.0	0.0	0.0	2.00
2	2.2	2.5	2.3	0.2	0.4	0.3	7.25
1	104.3	104.3	104.3	2.3	2.3	2.3	44.97

p_{18}

T	min	max	aver	min	max	aver	ratio
20	0.0	0.0	0.0	0.0	0.0	0.0	2.34
20	0.4	16.6	4.0	0.1	0.9	0.2	23.02
20	28.3	975.7	304.6	0.3	10.9	2.1	142.03

p_{18}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{19}

T	min	max	aver	min	max	aver	ratio
4	0.0	0.0	0.0	0.0	0.0	0.0	2.18
1	3.5	3.5	3.5	0.2	0.2	0.2	18.68
0	-	-	-	-	-	-	-

p_{19}

F	min	max	aver	min	max	aver	ratio
16	0.0	0.0	0.0	0.0	0.0	0.0	2.90
19	0.4	18.3	4.2	0.0	0.5	0.1	31.68
20	31.6	1077.6	352.7	0.3	5.6	1.6	226.68

p_{20}

T	min	max	aver	min	max	aver	ratio
11	0.0	0.0	0.0	0.0	0.0	0.0	1.28
6	1.3	12.1	5.6	0.4	18.0	5.0	1.12
4	167.3	473.9	365.1	3.6	342.6	103.3	3.53

p_{20}

F	min	max	aver	min	max	aver	ratio
9	0.0	0.0	0.0	0.0	0.0	0.0	1.27
14	0.5	18.4	3.9	0.0	33.6	3.3	1.21
16	28.5	1014.0	310.8	0.3	677.0	65.4	4.75

p_{21}

T	min	max	aver	min	max	aver	ratio
2	0.0	0.0	0.0	0.0	0.0	0.0	3.62
1	4.0	4.0	4.0	0.2	0.2	0.2	20.42
0	-	-	-	-	-	-	-

p_{21}

F	min	max	aver	min	max	aver	ratio
18	0.0	0.0	0.0	0.0	0.0	0.0	2.59
19	0.5	17.0	4.2	0.0	0.5	0.1	31.41
20	30.2	1007.1	328.9	0.3	4.8	1.5	217.00

p_{22}

T	min	max	aver	min	max	aver	ratio
2	0.0	0.0	0.0	0.0	0.0	0.0	3.38
1	3.6	3.6	3.6	0.2	0.2	0.2	22.29
0	-	-	-	-	-	-	-

p_{22}

F	min	max	aver	min	max	aver	ratio
18	0.0	0.0	0.0	0.0	0.0	0.0	3.29
19	0.5	16.2	4.0	0.0	0.3	0.1	40.54
20	28.2	1115.0	343.5	0.2	3.2	1.2	291.63

p_{23}

T	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{23}

F	min	max	aver	min	max	aver	ratio
20	0.0	0.0	0.0	0.0	0.0	0.0	1.58
20	0.5	17.5	4.2	0.1	1.1	0.2	18.34
20	31.5	1239.3	363.4	0.5	13.0	2.6	140.28

p_{24}

T	min	max	aver	min	max	aver	ratio
15	0.0	0.0	0.0	0.0	0.0	0.0	0.89
10	1.1	11.8	3.9	0.3	19.6	3.8	1.03
6	119.7	457.4	310.4	5.9	370.7	103.4	3.00

p_{24}

F	min	max	aver	min	max	aver	ratio
5	0.0	0.0	0.0	0.0	0.1	0.0	0.80
10	0.4	17.4	4.7	0.1	38.8	5.3	0.89
14	27.6	964.1	295.4	0.5	695.7	74.6	3.96

B.2 Programs with Concurrent Sequential Processes

For the programs with concurrent sequential processes,we let b vary over the set of values $\{12, 16, 20\}$, $a = 2$, $c = b/2$, $e = c$, $f = 4$, and $d = (b - c)/a = c/a$. Each property is tested on 20 test cases for each $b \in \{12, 16, 20\}$. The details are shown as follows.

p_{01}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.2	0.1	0.0	0.0	0.0	4.33
16	0.6	7.8	2.6	0.1	62.1	10.5	0.25
20	8.9	79.1	37.4	0.4	450.8	31.4	1.19

p_{02}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.2	0.1	0.0	0.0	0.0	4.09
16	0.7	3.7	1.8	0.1	0.1	0.1	15.78
20	9.2	82.1	37.8	0.4	0.8	0.6	65.20

p_{03}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.8	0.4	1.1	7.8	2.9	0.12
16	1.2	14.0	6.0	9.7	84.8	28.0	0.21
20	20.3	1028.9	256.0	49.5	840.5	270.5	0.95

p_{04}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.4	0.2	0.5	1.3	0.8	0.23
16	0.9	5.4	2.7	1.8	7.0	4.0	0.68
20	13.8	150.1	61.1	20.6	88.3	45.1	1.36

p_{05}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.7	0.3	0.5	5.2	2.3	0.14
16	1.7	29.8	8.7	6.7	52.2	19.0	0.46
20	83.9	2429.2	534.5	27.0	349.9	147.5	3.62

p_{06}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.4	0.2	0.6	1.4	0.9	0.22
16	1.0	7.9	3.6	1.9	7.4	4.2	0.87
20	19.4	215.4	88.5	21.8	83.8	47.2	1.87

p_{07}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.3	0.1	0.0	0.2	0.1	2.28
16	0.7	3.7	1.8	0.1	0.2	0.2	11.78
20	9.2	83.2	37.9	0.4	0.9	0.7	55.69

p_{08}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.3	0.2	0.1	0.2	0.1	1.30
16	0.8	6.0	2.7	0.3	0.6	0.4	7.10
20	14.9	149.2	65.6	1.4	3.3	2.2	29.50

p_{09}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.4	0.2	0.0	2.8	1.4	0.17
16	0.7	5.2	2.8	0.1	26.7	11.7	0.24
20	9.1	796.5	99.4	0.6	396.6	105.4	0.94

p_{10}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.6	0.2	0.1	0.5	0.2	1.07
16	1.1	9.5	4.1	0.2	0.8	0.4	9.80
20	25.6	414.4	122.7	1.4	5.8	3.8	32.56

p_{11}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.6	0.2	0.1	5.8	2.0	0.11
16	0.8	7.4	2.7	0.5	107.9	16.3	0.16
20	11.1	192.0	62.8	2.7	644.7	176.4	0.36

p_{12}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.3	0.2	0.1	0.7	0.4	0.44
16	0.9	8.1	3.4	0.6	1.9	1.0	3.54
20	21.9	239.0	102.7	3.5	16.8	10.1	10.16

p_{13}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.3	0.1	0.0	0.1	0.1	1.93
16	0.7	5.7	2.4	0.2	0.5	0.3	8.28
20	14.3	143.3	64.2	1.2	2.7	1.8	35.77

p_{14}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.2	0.1	0.0	0.2	0.1	1.28
16	0.7	7.4	2.7	0.2	0.6	0.3	8.44
20	14.5	142.2	64.8	1.2	5.5	3.1	21.23

p_{15}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.8	0.4	1.0	6.0	2.8	0.13
16	1.3	16.0	6.5	9.6	84.2	30.3	0.21
20	20.3	1007.9	292.9	50.2	845.7	277.9	1.05

p_{16}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.4	0.2	0.5	1.3	0.8	0.24
16	1.0	5.5	2.7	1.7	7.2	4.5	0.62
20	14.0	151.4	61.3	21.2	132.2	51.3	1.19

p_{17}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.7	0.3	0.5	4.0	2.1	0.16
16	1.8	27.4	9.0	6.7	51.8	20.4	0.44
20	82.6	2959.8	601.7	28.5	346.6	151.7	3.97

p_{18}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.4	0.2	0.6	1.4	0.9	0.23
16	1.3	8.0	3.8	1.9	7.6	4.7	0.81
20	19.9	218.1	88.6	22.0	135.2	55.1	1.61

p_{19}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.8	0.3	0.1	0.4	0.2	1.19
16	1.6	13.9	6.1	0.4	1.0	0.6	10.49
20	41.1	743.5	205.7	2.1	11.3	5.7	36.32

p_{20}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.6	0.3	0.1	2.3	1.4	0.21
16	1.1	14.7	5.6	0.2	27.6	11.9	0.47
20	25.5	2615.4	376.0	1.3	400.9	110.6	3.40

p_{21}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.5	0.2	0.1	0.3	0.2	1.19
16	1.1	10.8	4.5	0.4	0.9	0.5	8.40
20	29.9	351.3	137.5	2.0	5.9	4.2	33.02

p_{22}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.5	0.2	0.0	0.2	0.1	1.77
16	1.0	9.8	3.9	0.2	0.6	0.3	11.20
20	25.6	285.0	101.5	1.2	3.7	2.7	37.40

p_{23}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.6	0.2	0.2	0.9	0.5	0.48
16	1.3	13.6	5.7	0.7	2.4	1.2	4.83
20	37.5	635.0	190.8	4.2	22.8	13.4	14.22

p_{24}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.4	0.2	0.3	3.9	2.1	0.12
16	0.9	6.6	3.4	0.6	36.7	16.3	0.21
20	16.6	239.9	87.8	3.4	437.8	142.7	0.61

Separating Data for Correct and Incorrect Models The experimental data are further divided into two groups for those test models that are true and for those models that are false, with respect to each of the properties.

p_{01}

T	min	max	aver	min	max	aver	ratio
20	0.1	0.2	0.1	0.0	0.0	0.0	4.33
14	0.6	2.6	1.5	0.1	20.4	1.9	0.77
19	8.9	79.1	37.4	0.4	450.8	24.3	1.54

p_{01}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
6	3.8	7.8	5.2	15.2	62.1	30.6	0.17
1	38.7	38.7	38.7	165.9	165.9	165.9	0.23

p_{02}

T	min	max	aver	min	max	aver	ratio
20	0.1	0.2	0.1	0.0	0.0	0.0	4.09
20	0.7	3.7	1.8	0.1	0.1	0.1	15.78
20	9.2	82.1	37.8	0.4	0.8	0.6	65.20

p_{02}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{03}

T	min	max	aver	min	max	aver	ratio
6	0.1	0.7	0.3	1.5	4.5	2.7	0.11
3	5.7	6.9	6.4	13.6	31.6	21.5	0.30
1	83.2	83.2	83.2	374.7	374.7	374.7	0.22

p_{03}

F	min	max	aver	min	max	aver	ratio
14	0.2	0.8	0.4	1.1	7.8	3.1	0.13
17	1.2	14.0	5.9	9.7	84.8	29.1	0.20
19	20.3	1028.9	265.1	49.5	840.5	265.0	1.00

p_{04}

T	min	max	aver	min	max	aver	ratio
20	0.1	0.4	0.2	0.5	1.3	0.8	0.23
20	0.9	5.4	2.7	1.8	7.0	4.0	0.68
20	13.8	150.1	61.1	20.6	88.3	45.1	1.36

p_{04}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{05}

T	min	max	aver	min	max	aver	ratio
17	0.1	0.7	0.3	0.5	5.2	2.4	0.14
15	1.7	29.8	8.5	8.2	52.2	22.7	0.38
14	83.9	2429.2	611.6	27.0	254.2	138.2	4.43

p_{05}

F	min	max	aver	min	max	aver	ratio
3	0.1	0.4	0.3	1.0	1.4	1.2	0.25
5	2.3	15.0	9.1	6.7	10.7	7.8	1.16
6	86.2	577.9	354.4	34.8	349.9	169.2	2.09

p_{06}

T	min	max	aver	min	max	aver	ratio
20	0.1	0.4	0.2	0.6	1.4	0.9	0.22
20	1.0	7.9	3.6	1.9	7.4	4.2	0.87
20	19.4	215.4	88.5	21.8	83.8	47.2	1.87

p_{06}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{07}

T	min	max	aver	min	max	aver	ratio
20	0.1	0.3	0.1	0.0	0.2	0.1	2.28
20	0.7	3.7	1.8	0.1	0.2	0.2	11.78
20	9.2	83.2	37.9	0.4	0.9	0.7	55.69

p_{07}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{08}

T	min	max	aver	min	max	aver	ratio
20	0.1	0.3	0.2	0.1	0.2	0.1	1.30
20	0.8	6.0	2.7	0.3	0.6	0.4	7.10
20	14.9	149.2	65.6	1.4	3.3	2.2	29.50

p_{08}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{09}

T	min	max	aver	min	max	aver	ratio
17	0.1	0.4	0.2	0.0	2.8	1.4	0.18
18	0.7	5.2	2.5	0.1	26.7	11.1	0.23
19	9.1	796.5	102.0	0.6	396.6	103.2	0.99

p_{09}

F	min	max	aver	min	max	aver	ratio
3	0.1	0.2	0.2	1.3	1.7	1.5	0.13
2	4.6	4.7	4.6	15.3	19.5	17.4	0.27
1	49.4	49.4	49.4	146.4	146.4	146.4	0.34

p_{10}

T	min	max	aver	min	max	aver	ratio
20	0.1	0.6	0.2	0.1	0.5	0.2	1.07
20	1.1	9.5	4.1	0.2	0.8	0.4	9.80
20	25.6	414.4	122.7	1.4	5.8	3.8	32.56

p_{10}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{11}

T	min	max	aver	min	max	aver	ratio
15	0.1	0.3	0.2	0.1	5.8	1.4	0.13
16	0.8	4.7	2.4	0.5	42.6	7.6	0.31
16	11.1	140.9	54.9	2.7	644.7	143.4	0.38

p_{11}

F	min	max	aver	min	max	aver	ratio
5	0.2	0.6	0.4	3.4	4.6	4.1	0.09
4	1.2	7.4	3.9	21.4	107.9	51.0	0.08
4	38.3	192.0	94.3	181.2	491.3	308.4	0.31

p_{12}

T	min	max	aver	min	max	aver	ratio
20	0.1	0.3	0.2	0.1	0.7	0.4	0.44
20	0.9	8.1	3.4	0.6	1.9	1.0	3.54
20	21.9	239.0	102.7	3.5	16.8	10.1	10.16

p_{12}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{13}

T	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{13}

F	min	max	aver	min	max	aver	ratio
20	0.1	0.3	0.1	0.0	0.1	0.1	1.93
20	0.7	5.7	2.4	0.2	0.5	0.3	8.28
20	14.3	143.3	64.2	1.2	2.7	1.8	35.77

p_{14}

T	min	max	aver	min	max	aver	ratio
2	0.1	0.2	0.1	0.1	0.2	0.1	1.13
1	2.9	2.9	2.9	0.3	0.3	0.3	9.78
1	60.4	60.4	60.4	3.2	3.2	3.2	18.94

p_{14}

F	min	max	aver	min	max	aver	ratio
18	0.1	0.2	0.1	0.0	0.2	0.1	1.30
19	0.7	7.4	2.6	0.2	0.6	0.3	8.38
19	14.5	142.2	65.0	1.2	5.5	3.0	21.36

p_{15}

T	min	max	aver	min	max	aver	ratio
6	0.1	0.6	0.3	1.0	3.2	2.2	0.12
3	5.8	6.5	6.2	13.5	32.2	22.5	0.28
1	82.7	82.7	82.7	357.7	357.7	357.7	0.23

p_{15}

F	min	max	aver	min	max	aver	ratio
14	0.2	0.8	0.4	1.1	6.0	3.0	0.13
17	1.3	16.0	6.5	9.6	84.2	31.7	0.21
19	20.3	1007.9	304.0	50.2	845.7	273.7	1.11

p_{16}

T	min	max	aver	min	max	aver	ratio
20	0.1	0.4	0.2	0.5	1.3	0.8	0.24
20	1.0	5.5	2.7	1.7	7.2	4.5	0.62
20	14.0	151.4	61.3	21.2	132.2	51.3	1.19

p_{16}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{17}

T	min	max	aver	min	max	aver	ratio
19	0.1	0.7	0.3	0.5	4.0	2.1	0.16
15	1.8	27.4	8.9	8.9	51.8	24.4	0.36
14	82.6	2959.8	708.7	28.5	253.2	144.4	4.91

p_{17}

F	min	max	aver	min	max	aver	ratio
1	0.2	0.2	0.2	1.0	1.0	1.0	0.16
5	2.3	17.5	9.5	6.7	10.8	8.6	1.10
6	85.3	571.6	352.1	35.3	346.6	168.7	2.09

p_{18}

T	min	max	aver	min	max	aver	ratio
20	0.1	0.4	0.2	0.6	1.4	0.9	0.23
20	1.3	8.0	3.8	1.9	7.6	4.7	0.81
20	19.9	218.1	88.6	22.0	135.2	55.1	1.61

p_{18}

F	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{19}

T	min	max	aver	min	max	aver	ratio
4	0.2	0.4	0.3	0.2	0.3	0.2	1.34
2	4.0	5.6	4.8	0.5	0.5	0.5	8.99
2	110.7	187.2	148.9	3.5	5.6	4.6	32.49

p_{19}

F	min	max	aver	min	max	aver	ratio
16	0.1	0.8	0.3	0.1	0.4	0.2	1.15
18	1.6	13.9	6.2	0.4	1.0	0.6	10.64
18	41.1	743.5	212.0	2.1	11.3	5.8	36.66

p_{20}

T	min	max	aver	min	max	aver	ratio
7	0.2	0.6	0.4	0.5	2.0	1.4	0.29
6	2.7	14.7	8.1	3.7	25.6	14.2	0.57
5	32.6	2615.4	623.9	2.4	192.9	120.9	5.16

p_{20}

F	min	max	aver	min	max	aver	ratio
13	0.1	0.6	0.2	0.1	2.3	1.4	0.17
14	1.1	11.3	4.5	0.2	27.6	10.9	0.42
15	25.5	1570.2	293.4	1.3	400.9	107.1	2.74

p_{21}

T	min	max	aver	min	max	aver	ratio
2	0.2	0.3	0.2	0.2	0.2	0.2	1.00
1	4.4	4.4	4.4	0.5	0.5	0.5	8.62
1	137.5	137.5	137.5	4.4	4.4	4.4	31.35

p_{21}

F	min	max	aver	min	max	aver	ratio
18	0.1	0.5	0.2	0.1	0.3	0.2	1.22
19	1.1	10.8	4.5	0.4	0.9	0.5	8.38
19	29.9	351.3	137.5	2.0	5.9	4.2	33.11

p_{22}

T	min	max	aver	min	max	aver	ratio
2	0.2	0.3	0.2	0.1	0.2	0.1	1.57
1	3.8	3.8	3.8	0.3	0.3	0.3	11.01
1	112.1	112.1	112.1	2.9	2.9	2.9	38.10

p_{22}

F	min	max	aver	min	max	aver	ratio
18	0.1	0.5	0.2	0.0	0.2	0.1	1.80
19	1.0	9.8	3.9	0.2	0.6	0.3	11.21
19	25.6	285.0	101.0	1.2	3.7	2.7	37.36

p_{23}

T	min	max	aver	min	max	aver	ratio
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-
0	-	-	-	-	-	-	-

p_{23}

F	min	max	aver	min	max	aver	ratio
20	0.1	0.6	0.2	0.2	0.9	0.5	0.48
20	1.3	13.6	5.7	0.7	2.4	1.2	4.83
20	37.5	635.0	190.8	4.2	22.8	13.4	14.22

p_{24}

T	min	max	aver	min	max	aver	ratio
8	0.1	0.4	0.3	1.2	3.4	2.5	0.13
3	1.7	3.8	3.1	10.5	36.7	24.2	0.13
5	21.9	239.9	123.2	120.7	437.8	251.2	0.49

p_{24}

F	min	max	aver	min	max	aver	ratio
12	0.1	0.4	0.2	0.3	3.9	1.8	0.11
17	0.9	6.6	3.4	0.6	35.3	14.9	0.23
15	16.6	215.2	75.9	3.4	435.0	106.6	0.71

B.3 Summary

The experimental data for $b = 36$ for the first type of programs and $b = 20$ for the second type of programs are summarized in the following two tables. The tables show that the ratio vary from 1.86 to 356.86 for the first type of programs and from 0.36 to 65.20 for the second type of programs. In the latter case, NuSMV has advantage in 4 of the 24 cases.

	min	max	aver	min	max	aver	ratio
p_{01}	27.8	986.3	295.9	7.8	249.4	89.4	3.31
p_{02}	26.1	945.7	282.3	0.2	2.6	0.8	356.56
p_{03}	28.5	1226.8	335.6	2.2	383.0	80.6	4.16
p_{04}	26.3	924.6	280.9	0.3	8.5	1.8	155.84
p_{05}	26.7	1231.3	346.1	0.8	142.0	36.0	9.61
p_{06}	29.3	970.8	300.5	0.3	10.8	2.1	142.83
p_{07}	25.9	982.9	297.3	0.2	2.8	0.9	337.55
p_{08}	27.4	956.2	300.2	0.3	3.4	1.2	242.75
p_{09}	26.3	1023.8	296.4	0.3	674.6	71.2	4.16
p_{10}	29.6	1129.0	332.9	0.3	4.2	1.3	250.32
p_{11}	29.4	1038.1	326.0	11.7	1028.7	175.7	1.86
p_{12}	30.2	955.2	312.7	0.5	11.3	2.4	129.73
p_{13}	26.9	923.4	285.1	0.2	3.0	1.1	261.79
p_{14}	27.2	1046.8	311.0	0.2	3.4	1.2	264.51
p_{15}	29.9	1303.9	340.1	1.8	378.8	72.4	4.69
p_{16}	26.9	932.9	282.9	0.3	8.5	1.9	152.17
p_{17}	29.1	1305.9	348.2	0.9	201.1	40.4	8.61
p_{18}	28.3	975.7	304.6	0.3	10.9	2.1	142.03
p_{19}	31.6	1077.6	352.7	0.3	5.6	1.6	226.68
p_{20}	28.5	1014.0	321.7	0.3	677.0	73.0	4.41
p_{21}	30.2	1007.1	328.9	0.3	4.8	1.5	217.00
p_{22}	28.2	1115.0	343.5	0.2	3.2	1.2	291.63
p_{23}	31.5	1239.3	363.4	0.5	13.0	2.6	140.28
p_{24}	27.6	964.1	299.9	0.5	695.7	83.2	3.60
p_{01}	8.9	79.1	37.4	0.4	450.8	31.4	1.19
p_{02}	9.2	82.1	37.8	0.4	0.8	0.6	65.20
p_{03}	20.3	1028.9	256.0	49.5	840.5	270.5	0.95
p_{04}	13.8	150.1	61.1	20.6	88.3	45.1	1.36
p_{05}	83.9	2429.2	534.5	27.0	349.9	147.5	3.62
p_{06}	19.4	215.4	88.5	21.8	83.8	47.2	1.87
p_{07}	9.2	83.2	37.9	0.4	0.9	0.7	55.69
p_{08}	14.9	149.2	65.6	1.4	3.3	2.2	29.50
p_{09}	9.1	796.5	99.4	0.6	396.6	105.4	0.94
p_{10}	25.6	414.4	122.7	1.4	5.8	3.8	32.56
p_{11}	11.1	192.0	62.8	2.7	644.7	176.4	0.36
p_{12}	21.9	239.0	102.7	3.5	16.8	10.1	10.16
p_{13}	14.3	143.3	64.2	1.2	2.7	1.8	35.77
p_{14}	14.5	142.2	64.8	1.2	5.5	3.1	21.23
p_{15}	20.3	1007.9	292.9	50.2	845.7	277.9	1.05
p_{16}	14.0	151.4	61.3	21.2	132.2	51.3	1.19
p_{17}	82.6	2959.8	601.7	28.5	346.6	151.7	3.97
p_{18}	19.9	218.1	88.6	22.0	135.2	55.1	1.61
p_{19}	41.1	743.5	205.7	2.1	11.3	5.7	36.32
p_{20}	25.5	2615.4	376.0	1.3	400.9	110.6	3.40
p_{21}	29.9	351.3	137.5	2.0	5.9	4.2	33.02
p_{22}	25.6	285.0	101.5	1.2	3.7	2.7	37.40
p_{23}	37.5	635.0	190.8	4.2	22.8	13.4	14.22
p_{24}	16.6	239.9	87.8	3.4	437.8	142.7	0.61

C Details of Experimental Evaluation II

This section contain experimental evaluation based on 2 types of random boolean programs: programs with concurrent processes and programs with concurrent sequential processes. The maximum time for *verds*-QBF is set to 300 seconds. The sign $-$ in the tables either means timeout or the data are not available.

C.1 Programs with Concurrent Processes

For the programs with concurrent processes, we let b vary over the set of values $\{12, 24, 36\}$, $a = 3$, $c = b/2$, and by locating each process with the same number of local variables, we obtain $d = (b - c)/a = c/a$. Each property is tested initially on 20 test cases for each $b \in \{12, 24, 36\}$. The details are shown as follows, where the left part of the table is the data obtained for model checking with verds$-$bd, using the command "verds filename". The right part of the table is the data obtained for model checking with *verds*-QBF, using the command "verds -QBF filename".

The *ratio* is marked with 0.00 when the *max* of the right part of the table is not available (the time exceeds 300 seconds). *verdsbd* has advantage in cases where *ratio* < 1.00 (possibly except the case of p_{09}).

p_{01}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	3.33
24	0.1	19.2	3.2	0.0	0.0	0.0	247.00
36	7.8	249.4	89.4	0.0	0.2	0.1	1718.82

p_{02}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	1.87
24	0.0	0.1	0.1	0.0	0.0	0.0	18.86
36	0.2	2.6	0.8	0.0	0.0	0.0	173.99

p_{03}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.1	0.0	0.0	-	-	0.00
24	0.2	12.9	2.5	0.0	-	-	0.00
36	2.2	383.0	80.6	0.2	-	-	0.00

p_{04}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	-	-	-	0.00
24	0.0	0.7	0.1	-	-	-	0.00
36	0.3	8.5	1.8	-	-	-	0.00

p_{05}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	-	-	0.00
24	0.1	8.1	1.4	0.0	-	-	0.00
36	0.8	142.0	36.0	0.1	-	-	0.00

p_{06}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	0.48
24	0.0	0.9	0.2	0.0	0.5	0.2	1.12
36	0.3	10.8	2.1	0.1	8.5	1.7	1.24

p_{07}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	2.22
24	0.0	0.2	0.1	0.0	0.0	0.0	22.40
36	0.2	2.8	0.9	0.0	0.0	0.0	171.00

p_{08}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	2.69
24	0.0	0.4	0.1	0.0	0.0	0.0	40.44
36	0.3	3.4	1.2	0.0	0.0	0.0	255.00

p_{09}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	2.31
24	0.0	34.0	3.7	0.0	5.2	0.4	9.33
36	0.3	674.6	71.2	0.0	-	-	0.00

p_{10}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	2.17
24	0.0	0.4	0.1	0.0	0.0	0.0	28.44
36	0.3	4.2	1.3	0.0	0.0	0.0	218.00

p_{11}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.1	0.0	0.0	0.0	0.0	2.65
24	0.3	33.6	5.0	0.0	0.3	0.1	68.48
36	11.7	1028.7	175.7	0.0	3.8	0.6	294.77

p_{12}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	3.25
24	0.1	0.9	0.2	0.0	0.0	0.0	49.40
36	0.5	11.3	2.4	0.0	0.0	0.0	415.55

p_{13}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	3.31
24	0.0	0.3	0.1	0.0	0.0	0.0	28.89
36	0.2	3.0	1.1	0.0	0.0	0.0	224.52

p_{14}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	0.65
24	0.0	0.3	0.1	0.0	0.2	0.0	2.04
36	0.2	3.4	1.2	0.0	8.3	1.1	1.11

p_{15}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.1	0.0	0.0	-	-	0.00
24	0.2	13.0	2.5	0.0	-	-	0.00
36	1.8	378.8	72.4	0.3	-	-	0.00

p_{16}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	-	-	-	0.00
24	0.0	0.7	0.2	-	-	-	0.00
36	0.3	8.5	1.9	-	-	-	0.00

p_{17}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.3	0.0	0.35
24	0.1	8.5	1.4	0.0	-	-	0.00
36	0.9	201.1	40.4	0.1	-	-	0.00

p_{18}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	0.46
24	0.1	0.9	0.2	0.0	0.5	0.2	1.10
36	0.3	10.9	2.1	0.1	8.6	1.8	1.19

p_{19}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	1.30
24	0.0	0.5	0.1	0.0	0.0	0.0	23.48
36	0.3	5.6	1.6	0.0	0.0	0.0	154.84

p_{20}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	2.62
24	0.0	33.6	3.8	0.0	-	-	0.00
36	0.3	677.0	73.0	0.0	-	-	0.00

p_{21}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	1.66
24	0.0	0.5	0.1	0.0	0.0	0.0	28.28
36	0.3	4.8	1.5	0.0	0.0	0.0	185.95

p_{22}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	1.41
24	0.0	0.3	0.1	0.0	0.0	0.0	23.41
36	0.2	3.2	1.2	0.0	0.0	0.0	146.33

p_{23}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	3.90
24	0.1	1.1	0.2	0.0	0.0	0.0	56.41
36	0.5	13.0	2.6	0.0	0.0	0.0	310.28

p_{24}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.1	0.0	0.0	0.1	0.0	2.00
24	0.1	38.8	4.5	0.0	-	-	0.00
36	0.5	695.7	83.2	0.4	-	-	0.00

A summary for $b = 36$ is as follows.

m/p	min	max	aver	min	max	aver	ratio
$1/p_{01}$	7.8	249.4	89.4	0.0	0.2	0.1	1718.82
$1/p_{02}$	0.2	2.6	0.8	0.0	0.0	0.0	173.99
$1/p_{03}$	2.2	383.0	80.6	0.2	-	-	0.00
$1/p_{04}$	0.3	8.5	1.8	-	-	-	0.00
$1/p_{05}$	0.8	142.0	36.0	0.1	-	-	0.00
$1/p_{06}$	0.3	10.8	2.1	0.1	8.5	1.7	1.24
$1/p_{07}$	0.2	2.8	0.9	0.0	0.0	0.0	171.00
$1/p_{08}$	0.3	3.4	1.2	0.0	0.0	0.0	255.00
$1/p_{09}$	0.3	674.6	71.2	0.0	-	-	0.00
$1/p_{10}$	0.3	4.2	1.3	0.0	0.0	0.0	218.00
$1/p_{11}$	11.7	1028.7	175.7	0.0	3.8	0.6	294.77
$1/p_{12}$	0.5	11.3	2.4	0.0	0.0	0.0	415.55
$1/p_{13}$	0.2	3.0	1.1	0.0	0.0	0.0	224.52
$1/p_{14}$	0.2	3.4	1.2	0.0	8.3	1.1	1.11
$1/p_{15}$	1.8	378.8	72.4	0.3	-	-	0.00
$1/p_{16}$	0.3	8.5	1.9	-	-	-	0.00
$1/p_{17}$	0.9	201.1	40.4	0.1	-	-	0.00
$1/p_{18}$	0.3	10.9	2.1	0.1	8.6	1.8	1.19
$1/p_{19}$	0.3	5.6	1.6	0.0	0.0	0.0	154.84
$1/p_{20}$	0.3	677.0	73.0	0.0	-	-	0.00
$1/p_{21}$	0.3	4.8	1.5	0.0	0.0	0.0	185.95
$1/p_{22}$	0.2	3.2	1.2	0.0	0.0	0.0	146.33
$1/p_{23}$	0.5	13.0	2.6	0.0	0.0	0.0	310.28
$1/p_{24}$	0.5	695.7	83.2	0.4	-	-	0.00

Number of cases in which verds-QBF has advanatages The data are also presented in a way that the number of cases in which *verds*-QBF has advantage and that in which NuSMV has advantage are explicitly shown, where N is the number of test cases, T is the number of test cases in which the property is true, F is the number of test cases in which the property is false, adv is the number of cases in which *verbs*-QBF has an advantage.

p_{01}

b	adv/T	adv/F	adv/N
12	-	18/20	18/20
24	-	20/20	20/20
36	-	20/20	20/20
sum	-	58/60	58/60

p_{02}

b	adv/T	adv/F	adv/N
12	16/20	-	16/20
24	20/20	-	20/20
36	20/20	-	20/20
sum	56/60	-	56/60

p_{03}

b	adv/T	adv/F	adv/N
12	0/2	9/18	9/20
24	0/1	15/19	15/20
36	-	9/20	9/20
sum	0/3	33/57	33/60

p_{04}

b	adv/T	adv/F	adv/N
12	0/20	-	0/20
24	0/20	-	0/20
36	0/20	-	0/20
sum	0/60	-	0/60

p_{05}

b	adv/T	adv/F	adv/N
12	6/16	0/4	6/20
24	15/18	1/2	16/20
36	18/19	0/1	18/20
sum	39/53	1/7	40/60

p_{06}

b	adv/T	adv/F	adv/N
12	4/20	-	4/20
24	12/20	-	12/20
36	13/20	-	13/20
sum	29/60	-	29/60

p_{07}

b	adv/T	adv/F	adv/N
12	18/20	-	18/20
24	20/20	-	20/20
36	20/20	-	20/20
sum	58/60	-	58/60

p_{08}

b	adv/T	adv/F	adv/N
12	17/20	-	17/20
24	20/20	-	20/20
36	20/20	-	20/20
sum	57/60	-	57/60

p_{09}

b	adv/T	adv/F	adv/N
12	12/14	4/6	16/20
24	16/18	2/2	18/20
36	19/20	-	19/20
sum	47/52	6/8	53/60

p_{10}

b	adv/T	adv/F	adv/N
12	17/20	-	17/20
24	20/20	-	20/20
36	20/20	-	20/20
sum	57/60	-	57/60

p_{11}

b	adv/T	adv/F	adv/N
12	3/3	13/17	16/20
24	7/7	13/13	20/20
36	3/3	17/17	20/20
sum	13/13	43/47	56/60

p_{12}

b	adv/T	adv/F	adv/N
12	19/20	-	19/20
24	20/20	-	20/20
36	20/20	-	20/20
sum	59/60	-	59/60

p_{13}

b	adv/T	adv/F	adv/N
12	-	19/20	19/20
24	-	20/20	20/20
36	-	20/20	20/20
sum	-	59/60	59/60

p_{14}

b	adv/T	adv/F	adv/N
12	2/2	4/18	6/20
24	1/1	15/19	16/20
36	-	15/20	15/20
sum	3/3	34/57	37/60

p_{15}

b	adv/T	adv/F	adv/N
12	0/5	8/15	8/20
24	0/2	13/18	13/20
36	0/1	12/19	12/20
sum	0/8	33/52	33/60

p_{16}

b	adv/T	adv/F	adv/N
12	0/20	-	0/20
24	0/20	-	0/20
36	0/20	-	0/20
sum	0/60	-	0/60

p_{17}

b	adv/T	adv/F	adv/N
12	4/19	0/1	4/20
24	15/18	1/2	16/20
36	18/19	0/1	18/20
sum	37/56	1/4	38/60

p_{18}

b	adv/T	adv/F	adv/N
12	3/20	-	3/20
24	11/20	-	11/20
36	13/20	-	13/20
sum	27/60	-	27/60

p_{19}

b	adv/T	adv/F	adv/N
12	3/4	8/16	11/20
24	1/1	19/19	20/20
36	-	20/20	20/20
sum	4/5	47/55	51/60

p_{20}

b	adv/T	adv/F	adv/N
12	10/11	6/9	16/20
24	4/6	12/14	16/20
36	1/4	11/16	12/20
sum	15/21	29/39	44/60

p_{21}

b	adv/T	adv/F	adv/N
12	2/2	13/18	15/20
24	1/1	19/19	20/20
36	-	20/20	20/20
sum	3/3	52/57	55/60

p_{22}

b	adv/T	adv/F	adv/N
12	2/2	14/18	16/20
24	1/1	19/19	20/20
36	-	20/20	20/20
sum	3/3	53/57	56/60

p_{23}

b	adv/T	adv/F	adv/N
12	-	20/20	20/20
24	-	20/20	20/20
36	-	20/20	20/20
sum	-	60/60	60/60

p_{24}

b	adv/T	adv/F	adv/N
12	14/15	3/5	17/20
24	6/10	4/10	10/20
36	3/6	3/14	6/20
sum	23/31	10/29	33/60

C.2 Programs with Concurrent Sequential Processes

For the programs with concurrent sequential processes,we let b vary over the set of values $\{12, 16, 20\}$, $a = 2$, $c = b/2$, $e = c$, $f = 4$, and $d = (b - c)/a = c/a$. Each property is tested on 20 test cases for each $b \in \{12, 16, 20\}$. The details are shown as follows.

p_{01}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	-	-	-	0.00
16	0.1	62.1	10.5	-	-	-	0.00
20	0.4	450.8	31.4	-	-	-	0.00

p_{02}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.0	0.0	0.0	0.0	0.0	6.58
16	0.1	0.1	0.1	0.0	0.0	0.0	16.39
20	0.4	0.8	0.6	0.0	0.0	0.0	51.47

p_{03}

b	min	max	aver	min	max	aver	ratio
12	1.1	7.8	2.9	1.4	-	-	0.00
16	9.7	84.8	28.0	13.6	-	-	0.00
20	49.5	840.5	270.5	-	-	-	0.00

p_{04}

b	min	max	aver	min	max	aver	ratio
12	0.5	1.3	0.8	-	-	-	0.00
16	1.8	7.0	4.0	-	-	-	0.00
20	20.6	88.3	45.1	-	-	-	0.00

p_{05}

b	min	max	aver	min	max	aver	ratio
12	0.5	5.2	2.3	1.0	-	-	0.00
16	6.7	52.2	19.0	115.2	-	-	0.00
20	27.0	349.9	147.5	-	-	-	0.00

p_{06}

b	min	max	aver	min	max	aver	ratio
12	0.6	1.4	0.9	1.0	-	-	0.00
16	1.9	7.4	4.2	59.5	-	-	0.00
20	21.8	83.8	47.2	-	-	-	0.00

p_{07}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.2	0.1	0.0	0.0	0.0	11.12
16	0.1	0.2	0.2	0.0	0.0	0.0	22.17
20	0.4	0.9	0.7	0.0	0.0	0.0	60.83

p_{08}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.2	0.1	0.0	0.0	0.0	24.23
16	0.3	0.6	0.4	0.0	0.0	0.0	53.84
20	1.4	3.3	2.2	0.0	0.0	0.0	205.79

p_{09}

b	min	max	aver	min	max	aver	ratio
12	0.0	2.8	1.4	0.0	-	-	0.00
16	0.1	26.7	11.7	0.0	-	-	0.00
20	0.6	396.6	105.4	0.0	-	-	0.00

p_{10}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.5	0.2	0.0	74.0	3.8	0.05
16	0.2	0.8	0.4	0.0	40.5	2.3	0.18
20	1.4	5.8	3.8	0.0	22.6	1.3	2.83

p_{11}

b	min	max	aver	min	max	aver	ratio
12	0.1	5.8	2.0	0.0	-	-	0.00
16	0.5	107.9	16.3	0.0	-	-	0.00
20	2.7	644.7	176.4	0.0	-	-	0.00

p_{12}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.7	0.4	0.0	-	-	0.00
16	0.6	1.9	1.0	0.0	-	-	0.00
20	3.5	16.8	10.1	0.0	-	-	0.00

p_{13}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.1	0.1	0.0	0.0	0.0	14.16
16	0.2	0.5	0.3	0.0	0.0	0.0	40.23
20	1.2	2.7	1.8	0.0	0.0	0.0	155.38

p_{14}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.2	0.1	0.0	-	-	0.00
16	0.2	0.6	0.3	0.0	-	-	0.00
20	1.2	5.5	3.1	0.0	-	-	0.00

p_{15}

b	min	max	aver	min	max	aver	ratio
12	1.0	6.0	2.8	1.3	-	-	0.00
16	9.6	84.2	30.3	11.2	-	-	0.00
20	50.2	845.7	277.9	-	-	-	0.00

p_{16}

b	min	max	aver	min	max	aver	ratio
12	0.5	1.3	0.8	-	-	-	0.00
16	1.7	7.2	4.5	-	-	-	0.00
20	21.2	132.2	51.3	-	-	-	0.00

p_{17}

b	min	max	aver	min	max	aver	ratio
12	0.5	4.0	2.1	1.0	-	-	0.00
16	6.7	51.8	20.4	-	-	-	0.00
20	28.5	346.6	151.7	-	-	-	0.00

p_{18}

b	min	max	aver	min	max	aver	ratio
12	0.6	1.4	0.9	0.9	-	-	0.00
16	1.9	7.6	4.7	54.2	-	-	0.00
20	22.0	135.2	55.1	240.0	-	-	0.00

p_{19}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.4	0.2	0.0	0.2	0.0	5.94
16	0.4	1.0	0.6	0.0	1.6	0.4	1.40
20	2.1	11.3	5.7	0.0	11.0	1.3	4.50

p_{20}

b	min	max	aver	min	max	aver	ratio
12	0.1	2.3	1.4	0.0	-	-	0.00
16	0.2	27.6	11.9	0.0	-	-	0.00
20	1.3	400.9	110.6	0.0	-	-	0.00

p_{21}

b	min	max	aver	min	max	aver	ratio
12	0.1	0.3	0.2	0.0	0.2	0.0	5.04
16	0.4	0.9	0.5	0.0	2.8	0.4	1.31
20	2.0	5.9	4.2	0.0	11.1	1.1	3.67

p_{22}

b	min	max	aver	min	max	aver	ratio
12	0.0	0.2	0.1	0.0	0.5	0.1	2.29
16	0.2	0.6	0.3	0.0	1.8	0.3	1.29
20	1.2	3.7	2.7	0.0	7.5	0.7	3.69

p_{23}

b	min	max	aver	min	max	aver	ratio
12	0.2	0.9	0.5	0.0	0.1	0.0	32.44
16	0.7	2.4	1.2	0.0	0.3	0.0	29.29
20	4.2	22.8	13.4	0.0	120.8	6.2	2.18

p_{24}

b	min	max	aver	min	max	aver	ratio
12	0.3	3.9	2.1	0.0	-	-	0.00
16	0.6	36.7	16.3	0.0	-	-	0.00
20	3.4	437.8	142.7	0.0	-	-	0.00

A summary for $b = 20$ is as follows.

m/p	min	max	aver	min	max	aver	ratio
$2/p_{01}$	0.4	450.8	31.4	-	-	-	0.00
$2/p_{02}$	0.4	0.8	0.6	0.0	0.0	0.0	51.47
$2/p_{03}$	49.5	840.5	270.5	-	-	-	0.00
$2/p_{04}$	20.6	88.3	45.1	-	-	-	0.00
$2/p_{05}$	27.0	349.9	147.5	-	-	-	0.00
$2/p_{06}$	21.8	83.8	47.2	-	-	-	0.00
$2/p_{07}$	0.4	0.9	0.7	0.0	0.0	0.0	60.83
$2/p_{08}$	1.4	3.3	2.2	0.0	0.0	0.0	205.79
$2/p_{09}$	0.6	396.6	105.4	0.0	-	-	0.00
$2/p_{10}$	1.4	5.8	3.8	0.0	22.6	1.3	2.83
$2/p_{11}$	2.7	644.7	176.4	0.0	-	-	0.00
$2/p_{12}$	3.5	16.8	10.1	0.0	-	-	0.00
$2/p_{13}$	1.2	2.7	1.8	0.0	0.0	0.0	155.38
$2/p_{14}$	1.2	5.5	3.1	0.0	-	-	0.00
$2/p_{15}$	50.2	845.7	277.9	-	-	-	0.00
$2/p_{16}$	21.2	132.2	51.3	-	-	-	0.00
$2/p_{17}$	28.5	346.6	151.7	-	-	-	0.00
$2/p_{18}$	22.0	135.2	55.1	240.0	-	-	0.00
$2/p_{19}$	2.1	11.3	5.7	0.0	11.0	1.3	4.50
$2/p_{20}$	1.3	400.9	110.6	0.0	-	-	0.00
$2/p_{21}$	2.0	5.9	4.2	0.0	11.1	1.1	3.67
$2/p_{22}$	1.2	3.7	2.7	0.0	7.5	0.7	3.69
$2/p_{23}$	4.2	22.8	13.4	0.0	120.8	6.2	2.18
$2/p_{24}$	3.4	437.8	142.7	0.0	-	-	0.00

Number of cases in which verds-QBF has advanatages The data are also presented in a way that the number of cases in which *verds*-QBF has advantage and that in which NuSMV has advantage are explicitly shown.

p_{01}

b	adv/T	adv/F	adv/N
12	0/20	-	0/20
16	0/14	2/6	2/20
20	0/19	0/1	0/20
sum	0/53	2/7	2/60

p_{02}

b	adv/T	adv/F	adv/N
12	20/20	-	20/20
16	20/20	-	20/20
20	20/20	-	20/20
sum	60/60	-	60/60

p_{03}

b	adv/T	adv/F	adv/N
12	0/6	1/14	1/20
16	0/3	1/17	1/20
20	0/1	0/19	0/20
sum	0/10	2/50	2/60

p_{04}

b	adv/T	adv/F	adv/N
12	0/20	-	0/20
16	0/20	-	0/20
20	0/20	-	0/20
sum	0/60	-	0/60

p_{05}

b	adv/T	adv/F	adv/N
12	4/17	0/3	4/20
16	0/15	0/5	0/20
20	0/14	0/6	0/20
sum	4/46	0/14	4/60

p_{06}

b	adv/T	adv/F	adv/N
12	1/20	-	1/20
16	0/20	-	0/20
20	0/20	-	0/20
sum	1/60	-	1/60

p_{07}

b	adv/T	adv/F	adv/N
12	20/20	-	20/20
16	20/20	-	20/20
20	20/20	-	20/20
sum	60/60	-	60/60

p_{08}

b	adv/T	adv/F	adv/N
12	20/20	-	20/20
16	20/20	-	20/20
20	20/20	-	20/20
sum	60/60	-	60/60

p_{09}

b	adv/T	adv/F	adv/N
12	12/17	0/3	12/20
16	10/18	0/2	10/20
20	14/19	0/1	14/20
sum	36/54	0/6	36/60

p_{10}

b	adv/T	adv/F	adv/N
12	16/20	-	16/20
16	17/20	-	17/20
20	19/20	-	19/20
sum	52/60	-	52/60

p_{11}

b	adv/T	adv/F	adv/N
12	10/15	2/5	12/20
16	11/16	1/4	12/20
20	12/16	0/4	12/20
sum	33/47	3/13	36/60

p_{12}

b	adv/T	adv/F	adv/N
12	18/20	-	18/20
16	15/20	-	15/20
20	17/20	-	17/20
sum	50/60	-	50/60

p_{13}

b	adv/T	adv/F	adv/N
12	-	20/20	20/20
16	-	20/20	20/20
20	-	20/20	20/20
sum	-	60/60	60/60

p_{14}

b	adv/T	adv/F	adv/N
12	2/2	1/18	3/20
16	1/1	0/19	1/20
20	1/1	0/19	1/20
sum	4/4	1/56	5/60

p_{15}

b	adv/T	adv/F	adv/N
12	0/6	2/14	2/20
16	0/3	2/17	2/20
20	0/1	0/19	0/20
sum	0/10	4/50	4/60

p_{16}

b	adv/T	adv/F	adv/N
12	0/20	-	0/20
16	0/20	-	0/20
20	0/20	-	0/20
sum	0/60	-	0/60

p_{17}

b	adv/T	adv/F	adv/N
12	4/19	0/1	4/20
16	0/15	0/5	0/20
20	0/14	0/6	0/20
sum	4/48	0/12	4/60

p_{18}

b	adv/T	adv/F	adv/N
12	1/20	-	1/20
16	0/20	-	0/20
20	0/20	-	0/20
sum	1/60	-	1/60

p_{19}

b	adv/T	adv/F	adv/N
12	4/4	15/16	19/20
16	2/2	12/18	14/20
20	2/2	17/18	19/20
sum	8/8	44/52	52/60

p_{20}

b	adv/T	adv/F	adv/N
12	6/7	9/13	15/20
16	5/6	8/14	13/20
20	2/5	11/15	13/20
sum	13/18	28/42	41/60

p_{21}

b	adv/T	adv/F	adv/N
12	2/2	17/18	19/20
16	1/1	15/19	16/20
20	1/1	18/19	19/20
sum	4/4	50/56	54/60

p_{22}

b	adv/T	adv/F	adv/N
12	2/2	16/18	18/20
16	1/1	14/19	15/20
20	1/1	18/19	19/20
sum	4/4	48/56	52/60

p_{23}

b	adv/T	adv/F	adv/N
12	-	20/20	20/20
16	-	20/20	20/20
20	-	19/20	19/20
sum	-	59/60	59/60

p_{24}

b	adv/T	adv/F	adv/N
12	6/8	9/12	15/20
16	2/3	13/17	15/20
20	1/5	12/15	13/20
sum	9/16	34/44	43/60

C.3 Summary

The data are grouped into 12 groups, one for each type of properties where p_i and p_{i+12} are considered as of the same type. Since p_{05} and p_{06} are existential properties (and there is only one initial state in the models), we present and interpret the data according to the verification and falsification of $\neg p_{05}$ and $\neg p_{06}$. The following is a summary of the experimental data.

properties	adv/T	adv/F	adv/N
p_{01}, p_{13}	0/53	179/187	179/240
p_{02}, p_{14}	123/127	35/113	158/240
p_{03}, p_{15}	0/31	72/209	72/240
p_{04}, p_{16}	0/240	-	0/240
$\neg p_{05}, \neg p_{17}$	2/37	84/203	86/240
$\neg p_{06}, \neg p_{18}$	-	58/240	58/240
p_{07}, p_{19}	130/133	91/107	221/240
p_{08}, p_{20}	145/159	57/81	202/240
p_{09}, p_{21}	90/113	108/127	198/240
p_{10}, p_{22}	116/127	101/113	217/240
p_{11}, p_{23}	46/60	165/180	211/240
p_{12}, p_{24}	141/167	44/73	185/240
sum	793/1247	994/1533	1787/2880

The bounded semantics model checking does not have advantage in verifying any of the properties that start with AG. The bounded bounded semantics model checking has advantage in various degrees in verifying the other 8 types of properties (no data for verification are available for $\neg p_{06}$) and in falsifying 11 types of properties (no data for falsification are available for p_{04}). The details of the experimental data do not indicate how the sizes of problems may affect the advantage/disadvantage of bounded verification. Rather, the type of the verification problems matters.