HANDLING STATE SPACE EXPLOSION IN COMPONENT-BASED SYSTEMS: A REVIEW

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ABSTRACT. Component-based design is a different way of constructing systems which offers numerous benefits, in particular, decreasing the complexity of system design. However, deploying components into a system is a challenging and error-prone task. Model checking is one of the reliable methods that automatically and systematically analyses the correctness of a given system. Its brute-force check of the state space significantly expands the level of confidence in the system. Nevertheless, model checking is limited by a critical problem so-called Sate Space Explosion (SSE). To benefit from model checking, appropriate methods to reduce SSE, is required. In two last decades, a great number of methods to mitigate the state space explosion have been proposed which have many similarities, dissimilarities, and unclear concepts in some cases. This research, firstly, aims at present a review and brief discussion of the methods of handling SSE problem and classify them based on their similarities, principle and characteristics. Second, it investigates the methods for handling SSE problem in verifying Component-based system (CBS) and provides insight into CBS verification limitations that have not been addressed yet. The analysis in this research has revealed the patterns, specific features, and gaps in the state-of-the-art methods. In addition, we identified and discussed suitable methods to soften SSE problem in CBS and underlined the key challenges for future research efforts.

1. Introduction

Component-based design is a different way of constructing systems which offers numerous benefits, in particular, decreasing the complexity of system design. However, deploying components into the system is a challenging and error-prone task. Errors may lead to destructive results. Sometimes only one error can lead to crash entire system, like the error that defected Arian-5 rocket. There are a lot of safety-critical systems similar to Arian-5 that errors into them result in disastrous outcomes such as nuclear power stations, avionic software, aircraft flight control, and traffic control.

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One of the well-known approaches to verify systems is model checking [34]. Model checking is a brute-force verification method that is able to automatically and systematically analyze the state space and formal properties of a given system to demonstrate if its properties satisfied completely or not. This approach has proposed independently by Clarck and et al. [34] and Sifakis and et al. [91]. The brute-force check of the state space significantly expands the level of confidence in the system.

However, model checking limited by a critical problem so-called state space explosion (SSE). SSE is serious and restricted the amount of state space that can be checked by the model checker. The advantages promised by model checking encouraged the researcher communities to alleviate its drawbacks. Fighting this obstacle became the major direction in the model checking research and massive collection of methods have been presented to settle this serious problem.

The diversity of these methods motivated us to provide insight into the methods for alleviating SSE problem by following steps: 1- reviewing and briefly describing all the methods that address SSE problem; 2- classifying them based on their principles and characteristics; 3- underlying the key features and challenges of the methods; 4- identifying and discussing the methods for tackling SSE problem which have been used in CBS in order to both gaps analyzing and identifying suitable methods for SSE reduction in CBS. To complete these steps sufficiently, we formulated 6 research questions (RQs) which are defined in section 2. Answering these questions aid in enhancing comprehension, determining the suitability of SSE reduction methods, and propose and design an improved new method.

Our study shares similarities with surveys presented in [85, 92] for dealing with SSE problem, but has some differences in the sense that we cover both explicit and implicit methods. In addition we collect richer collection of SSE reduction methods, each method explained and their success factor and challenges identified. Moreover, we discussed the SSE problems in component-based systems which they have not covered. Other review papers like [47], are more based on the tool sets which is out of our scope.

The remainder of the paper is arranged as follow: In section 2 we identify our research questions and research process. Section 3 provides an explanation of basic concepts about SSE that used in this paper. Section 4 defines, classifies and explains different methods for alleviating SSE problem. In addition, in this section the key factors and limitation of these methods have been summing up in tables. Totally, we answer the RQs (1, 2, 3) in this section. Section 5 discusses tackling SSE problem in CBS and identify their key challenges. In this section, the answers for RQs (4, 5, 6) can be found. Section 6 discusses and concludes the results.

2. Research method

In these work, we follow some steps of SLR (like formulating RQs, identifying keywords and databases, inclusion and exclusion criteria) to collect and analyses literatures. This section shows how we applied these steps and the results are presented in the next sections.

First, we introduce a set of research questions (RQs) that are going to be answered by our research. Table 1 presents the RQs. The RQs are based on two major points of view: 1- all general mitigation methods for SSE problem of model checking and formal verification (RQ 1,2,3), 2- the methods that particularly have been applied in CBS (RQ 4,5,6).

Answer to these RQs support us to prepare an effective overview of the state-of-the-art and understand the concepts and theories behind the methods to alleviating SSE problem.

NO	Research questions	Motivation
RQ1	Which mitigation methods have been proposed in the literature for SSE problem in model checking and formal verification?	To understand the current state of the art methods for mitigating SSE problem.
RQ2	How the methods try to mitigate SSE problem?	To enhance understanding of their theories and concepts, and recognizing the different between SSE reduction methods easily.
RQ3	What are the success factors and kinds of challenges for SSE reduction methods?	To identify the kinds of success factors and potential challenges that might be faced in using specific SSE reduction methods.
RQ4	Which SSE reduction methods are more frequently discussed in the literature for CBS?	To determine the kinds of SSE reduction methods that can be apply to verify CBS.
RQ5	How do they tackle SSE in CBS? Which success factors and challenges are discussed in the literature about them?	To enhance understanding of their theories, concepts, success factors, and challenges. More- over, to identify how challenges could fail or limit the verification process of CBS.
RQ6	What is the most sufficient method to verify CBS?	To identify which method should we choose to verify CBS.

Table 1: Research questions

Moreover, finding answers for aforestated RQs help us to set up a classification for common SSE reduction methods. Then we briefly explain the classification and present an overview of that in section 3.

To shape our research process, we have used the book of "Model checking" by E. Clarke and et al. [34], and "Specification and verification of concurrent systems in Cesar" by Sifakis and et al. [91], as basis together with other studies published by those authors like [25, 29, 35]. One of the reason that we have selected these books and studies because their authors are known as the first scientists who present model checking. The books, significantly introduce formal verification, model checking, and methods for mitigation of SSE. We construct the initial paper collection by including the papers cited in the above books and all the papers in which present, review, survey, or employ those methods. We have iteratively searched in widely known electronic database/library resources like ACM digital library, IEEEexplore, Science direct, Web of science, Springer link, Google scholar, Citeceer until we were sure no more relevant and suitable paper can be found. Moreover, we used some online videos of the aforementioned authors in our research.

During each iteration of searching in the resources, mostly used keywords and search strings for the RQ (1, 2, 3) were ("model checking OR formal verification" AND "State space explosion problem") or ("model checking OR formal verification" AND "the name

General inclusion criteria 1- Research papers, white papers, conferences, technical reports, Doctorate dissertation, books, hands books. 2- Studies and on-line videos of wellknown authors in model checking and formal verification. Specific inclusion criteria for RQs 1- The studies analyzes/addresses state space explosion in formal verification and model checking (RQ1) 2- The studies provide discussion about mitigation methods for the SSE problem, its success factors and challenges (RQ2 and 3)3- The studies analyze/discuss/present verification in CBS (RQ4) 4- The studies provide discussion about mitigation methods for the SSE problem in CBS verification, their success factors and challenges (RQ5 and 6) Exclusion criteria 1- Duplicate report of same study. 2- Short paper with few sources. 3- The papers were not understandable. 4- Studies like theorem proving that focuses on formal methods than model checking.

Table 2: Inclusion and exclusion criteria

of each mitigation methods for state space explosion, for example, assume-guarantee"). For RQ (4, 5, 6), we added "component-based system" to the above search strings. After each iteration, a preliminary review based on inclusion and exclusion criteria to achieve an appropriate paper collection has been applied. Both include and exclude criteria represented in table 2.

In the last phase, our review paper covered 114 papers, where 33 of them included in conferences; 19 of the papers presented in technical report, proceedings, symposiums, and workshops; 54 of the papers were published in the journals; 6 of the papers were books, and hand books; 1 of the papers was a tutorial for a tool package and 1 of them related to database search and snowballing [64].

3. Main Concepts

To comprehend the discussion of SSE problem, an outline of important terminologies and main concepts that we used in this paper is prepared. Thus, in this section we characterize some definitions including model checking, system model, temporal logic, system properties, state space explosion.

tikzstylesq=[draw,text=violet,minimum width=10pt, line width=2pt] *Model checking* is a tuple:

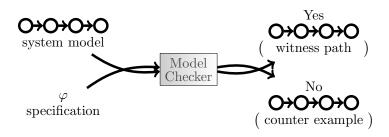


Figure 1: Model Checking

$$MODELCHECKING = < M, S >$$
 (3.1)

Where \mathbb{M} is a system model and \mathbb{S} is formal specification. Let m is a state of the system model $m \in \mathbb{M}$, then model checking search all states m in \mathbb{M} and returns witness path if they satisfy \mathbb{S} , $(\forall m \in \mathbb{M}) \models \mathbb{S}$. Otherwise, model checking produces counterexample.

System model is a conceptual model to represent and describe a system. In model checking, a system model originally is represented by Kripke structure, but it can use other graph like representation such as state chart [94], and Petri net [74]. Using graph like representation by individual states is one of the main representation paradigms in model checking so-called explicit-state model checking. Figure 4 shows an explicit-state system model based on kripke structure. Another representation paradigm is implicit model checking. In implicit model checking states are not individually represented, but a quantified propositional logic formula is used to represent the graph.

Formal specification in model checking represented by propositional temporal logic which is a kind of logic to describe and reason about the ongoing properties of the system being modeled in terms of time. There are two types of operations that temporal logic supports: First, logical operators such as \neg, \lor, \land , and second operators refer to modalities like Until, Next, Globally. The set of operators which express properties in only a single future position for every point in running time called *Linear Temporal Logic (LTL)*. As shown in the figure 2, LTL checks only one sequence of events in a single run and does not switch to another run during checking. On the other hand, there are another type of temporal logic called *Computational Tree Logic (CTL)* that is able to checks all possible paths in a single run. For example in figure 3 (b) the gray nodes are all possible paths, which CTL can switch to any of them during one single execution. It is checking by operator **A**. CTL operators can support one sequence of events in one run as well. For example, the gray color path in 3 (a) is the only path that will be checked in one run by operator **E**.

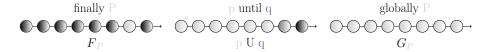


Figure 2: Example of LTL operators [35]

System property is defined by temporal logic. Some common system properties are reachability properties (some particular position in a system model that can be met), Safety properties (under particular circumstances, an event will not happen in any way, like: without the key a car won't start.), liveness (under certain circumstances, some event will

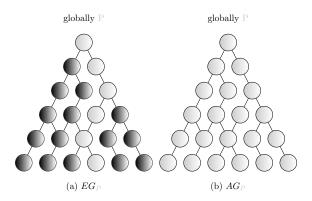


Figure 3: Example of CTL operators[35]

eventually happen, like: if we press the button of an elevator, it is bound to arrive ultimately.), *fairness* (under certain circumstances an event will or will not happen infinitely often, like: the gate will be raised infinitely often.) [34].

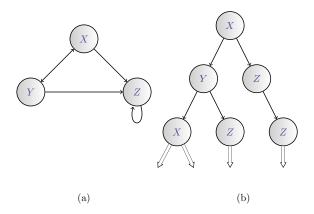


Figure 4: A kripke structure and its computation tree [34]

State Space Explosion. Let a given system having a processes and each process has m states (same states). Therefore, the size of state space of these n processes might be m^n . Thus, the amount of state space of a given system may increase exponentially with the size of its states (processes) and consequently exceed the memory capacity of the system.

Example 1: In figure 4 a Kripke structure and its corresponding computation tree are shown. It indicates the state space strongly depends on system variable and processes of a system and may grow up exponentially.

4. Classification of state space reduction methods

SSE problem is a bottleneck in model checking. The amount of a system's state space (even a finite system) strongly depends on its components and prone to increase in size exponentially. Consequently, it quickly exceeds the memory capacity of the computer and restricts the size that a model checker can check. Accordingly, memory is the main concern that the methods for tackling SSE problem are attempt to address. Memory concern can be

overcome in several aspects, for example, expanding memory capacity, reducing the states that need to be stored in memory, released memory from the redundant and repeated states, and etc. Generally, a method can not cover all the aspects, some find and omit redundancy, while others may focus on memory expansion. Due to this fact, we can simply classify these methods according to the aspects that they can cover. The classification has five dimensions summarized below:

- Memory handling. The memory handling dimension identifies the methods that directly engaged in memory expansion and management.
- Heuristics and probabilistic reasoning. This dimension identifies the methods that are able to find an approximation of the exact solution. They are the fastest way to find a close solution when the exact answer can not be computed.
- Scaling down the state space. The dimension of scaling down the state space identifies the methods that try to reduce the size of states to be stored in the memory. The reduction can be based on compression, symmetry and similarity omission, using Binary Decision Diagram BDD, or hash table.
- **Bottom-up approach**. The bottom-up approach dimension identifies the methods that start verification as early as the whole state space is constructed.
- **Divide-and-conquer approach**. Divide-and-conquer dimension identifies the methods which decompose the state space into small parts and address each small parts separately.

A discussion about the classification is provided in detail in the first part of this section and an overview of it is represented in Figure 5. Each class divided into multiple subparts which are current methods for tackling SSE problem. To refine the description of our classification, we introduce some previous works. The RQ (1, 2) is fully answered in this part.

The second part of this section is about the RQ 3. The characteristics, key features and challenges of SSE reduction methods have been summing up in tables. Before each table, we describe our observation and conclusion.

4.1. Classification.

4.1.1. Memory handling. As mentioned before, memory is the main concern of the SSE reduction methods which can be addressed based on several aspects. Some of them directly engaged in memory and completely separated from the other methods like compressing the state space. These kinds of methods are based on following principles: 1- a proper memory management which increases the performance. Memory management is a process of controlling and incorporating programs by using a sufficient methodology to fragment, allocate, monitor, and release memory. 2- increasing memory capacity which is able to provide more space to store more data. It can by expanding external memory. Two methods that stand on the above explanation are discussed in the following:

Expanding external memory. The idea of using external memory with a proper algorithm, when RAM can not handle all data, might be one of the solutions to overcome SSE problem. External memory is able to provide much larger space. For the time being, the capacity of magnetic disks increased enormously with almost same cost. This fact motivates researchers to use external memory in model checking. Due to the fact that external memory cannot be accessed fast like internal memory, providing an efficient external memory algorithm is

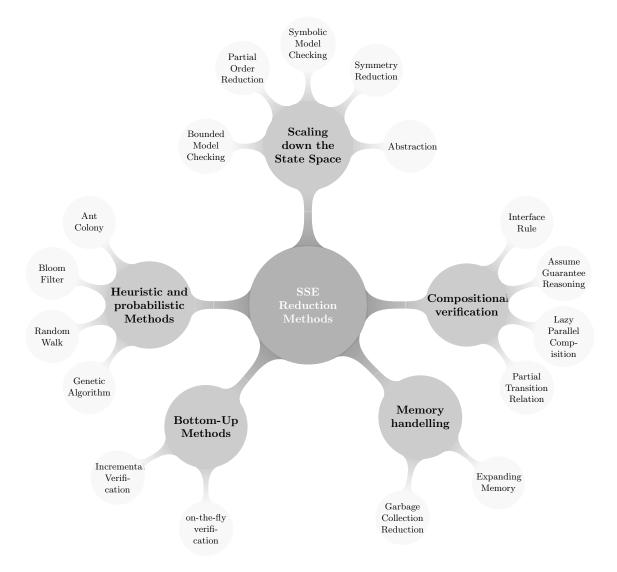


Figure 5: An overview of SSE reduction methods

the main concern in using this method. The algorithm must organize disk access carefully and precisely. The efficiency of the algorithm is determined via the amount of I/Os. In the other words, between the amount of I/Os and time efficiency has a relation in the sense that the time efficiency will be improved if the I/O actions reduced.

S. Edelkamp et al. [70] proposed layered duplicate detection to improve duplicate elimination in external memory model checking. This approach decides which states during searching in the state space should be stored in RAM, and which of them should be stored on disk. It turns out that it increases the efficiency of the running time and decrease the amount of disk storage.

W. Lijun et al. [112] proposed an I/O efficient methodology to provide a model checker based on extending memory. Their methodology is generally is based on NDF (or nested depth first). By combining the following three methods they have achieved a significant

improvement in time efficiency of I/O. The first method is sorting a hash table in linear time. In this method, the already visited states sorted in a hash table will be merged into a hash table which is saved and sorted into the external memory. Second method is detecting duplication in cache. Finally, third method refers to managing of the dynamic path. This methodology gives performance guarantees for I/O efficiency.

Garbage collection reduction. Garbage collection reduction is a memory management policy which inspired by using of garbage collection in real-life software systems to improve model checking methods. It deletes information about already visited-states and reclaims allocated memory while model checking is performed. Certainly, when garbage collection and memory reclaiming for idle memory does not utilize, the state space may grow and limit the verification. Garbage collection has some advantages, For example, it does not suffer from inefficient memory fragmentation and complex pointer analysis.

One of the classic collection algorithms is Mark and Sweep collection. In this algorithm, one state can be garbage collected when no more transition to it is available [73]. In the other words, it is based on reachability [61] and uses graph-search algorithms like depth-first search to indicate any state that must be marked as garbage.

The other collection algorithm is reference counting collection [3]. It discovers the garbages directly by monitoring and counting the pointers that point to each state. Disabling to reclaim the cycles of garbage is the major difficulty of this algorithm [61]. Additional algorithm to garbage collections is based on finding usability [78]. The most widely used of garbage collection are those programs are based on Java [72].

4.1.2. Heuristic and probabilistic reasoning. In many problems that do not have an exact solution, we wish to have at least an approximate answer. In this case using probabilistic reasoning can handle the situation. Probabilistic reasoning is able to find the approximate of the exact solution faster than other methods. The solution may not be optimum, but still valuable because it helps us in cases that the exact solution could not be achieved. Utilizing this kind of methods is a possible way to reduce the model checking effort. The rest of this section introduce two SSE reduction based on probabilistic reasoning.

Genetic algorithms. A genetic algorithm (GA) in computer science is a meta-heuristic optimizer that is based on population (a set of chromosomes) and encouraged by biologic evolution that is a subset of a larger category called evolutionary algorithms (EA). In some cases existing exact methods (the methods which try to find exact solution not approximate solution) fail to detect any exact and complete solution for a given problem or no any solution with lower complexity to them. Thus, it may be sufficient to find solutions approximately, or to provide faster coverage approaching solutions by using heuristics such as GA. In analyzing the use of GA or any EAs in model checking must consider the target is finding any solution (any error) not only the optimum solution. In addition, every reachable state of the entire system must be checked.

P. Godefroid and S. Khurshid investigated the utilize of GA in order to explore very large state space in check for finding errors such as deadlock and assertions violations [51]. They combined model checking and GA to guide searching during verification problem of a concurrent reactive system. When in the current state, there are more than one enable transitions, GA tries to explore which transition is the most fitted to be selected by a fitness function.

R. Yousefian et al. [113] explore the use of GA for model checking of the Graph Transformation Systems. In their work, an incomplete state space is created instead of creating entire state space to detect deadlock. Model checker only checks paths with low out going transition.

Random walk. Random walk defines a path includes a sequence of random steps to find errors in model checking. For certain type of graphs like Markov chain, random walk is able to decide reachability and predict error traces by a polynomial algorithms. The complexity of the algorithms is not better than some other methods for alleviating SSE problem, even it is worst. But, some advantages of it are of interest to researchers to use it in verification processes. First, its need for space is extremely low which is critical issue here. Second, parallel random walk is easy to implement and reduce the executing time. Despite the advantages, it does not guarantee the exploring all global states.

A successful and remarkable tool for randomization search in state space has been proposed by D. Owen et al. [82] which so-called LURCH. They compared the tool with SPIN and NuSMV and clued that LURCH can not be preferable as much as the others that have complete search. Nevertheless, futuristics and random search in LURCH can be useful to some system models that are too massive and cannot be explored completely.

Bloom filter. The two main schemes for probabilistic verification are hash compaction and bit state hashing which are using the data structure of Bloom filter. Bloom filter is an explicit and probabilistic method for verification activities. It stores compressed values in a hash table rather than storing fully state descriptors. During verification process some states with a non-zero probability way will be deleted. Therefore, some reachable states never be checked during verification process and may result in false positive outcomes.

An improved probabilistic method based on this method has been proposed by U. Stern and David L.Dill in [103]. They reduce the probability of deleting states by using a specific hashing design. The new design of hashing requires lower number of probes requires in the hash table. Another work of them for probabilistic is presented in [104].

P. C. Dillinger and P. Manolios [41] propose a method based on Bloom filter which is more accurate and shows that Bloom filter can play an important role in model checking.

Ant colony. Ant colony is another probabilistic method to optimize the problems which mostly used to find the optimum paths through graph like models. It can be also applied in model checking and verification. L. M. Duarte et al. [43] combine model checking and the ant colony to solve traveling sales man.

4.1.3. Scaling down the state space. Scaling down the size of the state space to be checked by model checkers is another way to alleviate SSE problem. Some general ideas are able to scale down the state space. To begin with, representing the state space by another way (implicitly) which consume less memory, like symbolic representation instead of defining them in the original shape (explicitly), truly compress the state space. In the comparison part of this section, in Table 3 the implicit and explicit methods has been indicated. Moreover, capturing and ignoring irrelevant or useless variables and informations in a system lead to

decrease the size of state space. Also, discovering duplicate states and avoid of regenerating them is another way of reducing state space.

The following are briefly discusses some methods for alleviating SSE problem for the class of scaling down the state space.

Symbolic model checking. This method utilizes to comprise the state space of a system by symbolically (implicitly) represents the state space. It considers large number of states at a single step and represents them as formulas instead of enumerating them once at a time. Therefore, the size of state space will be more smaller. It has been introduced by J. R. Burch et al. [24] based on Bryant's Binary Decision Diagram (BDD) for Mu-Calculus. BDD is a data structure used to canonically represent a Boolean formula that is essentially compressed even more than other data structures, and Mu-Calculus falls into one kind of logics called modal logic (a type of logic that is able to express modality like possibility, impossibility) which is able to define the properties in terms of graph-like patterns.

The methods has been used successfully for many problems such as deriving efficient decision procedures for CTL, and satisfiability of LTL. For example, a verification tool-set called ITS-tools by Y. Thierry-mieg [107] has been developed based on symbolic model checking which supports reachability property and two kinds of temporal logic CTL and LTL of concurrent specification. Another symbolic-based model checker has been provided by R. Cavada et al. [99] for verifying finite-states and infinite-states synchronous systems.

However, the BDD that is substantial part of symbolic model checking is extremely relies upon the variable's ordering which limited the use of symbolic model checking. To illustrate it more precisely, we use the following example:

Let two orders of a Boolean functions with 6 variables [20, 69, 21]:

$$1 - (a.b) + (c.d) + (e.f)$$
$$2 - (a.d) + (b.e) + (c.f)$$

This two boolean function has same number of variables, but they are different in ordering. The constructed BDD for both, as indicated in Figure 6, are not same because BDD is sensitive to ordering. For the first function the BDD has few nodes while for the second function it has more nodes.

Thus, reduced ordered binary decision diagrams (ROBDD) are used to reduce decision graph and provide more concise canonical representation for Boolean propositions. An improved variable ordering of BDD introduced by P. W. C Prasad et al. [90] that is based on graph topology. They demonstrated that using graph representation of a given Boolean function and computing shortest path among the variables can improve ROBDD. Further work to improve ROBDD presented by P. K. Sharma et al. [99] to get the most optimum size of ROBDD. However, computing an optimum order for ROBDD generally falls into NP-Complete problem category proved by B. Bolling et al. in [19] and B. Bolling in [18].

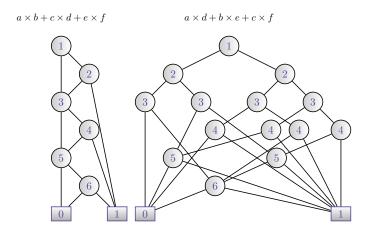


Figure 6: Ordering Dependency [69]

Bounded model checking (BMC). This method has been proposed in [15, 17] to deal with complexity of model checking and provide error traces. In this method the length of the trace to be explored is limited via a fixed amount of states $k \in int$. Then it checks through it to reveal error states. If an error location could not be reached inside the bound, the amount of k will be increased and the process will be repeated until one error is found. The selected k has to be large enough, otherwise, the method is not able to be completed [16]. However, if k be small enough, it outperforms BDD based model checking [30]. Discovering the k's length needs a few by-hand manipulation, whilst BDD in symbolic model checking requires a great or even manual effort to find an optimum ordering. In addition, BMC can handle much more clauses and variables than BDD methods [16].

Bounded model checking is the most important industrial application of Boolean satisfiability (SAT) solver [68]. SAT solver provides a platform for searching and reasoning based on propositional logic that is able to solve complex problems with million variables and constraints [110]. Some recent works used successfully SAT-based BMC to verify security critical systems [4], concurrent systems [88], and multi agent systems [111].

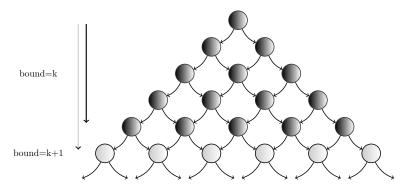


Figure 7: Bounded model checking [102]

BMC can be also based on Satisfiability Modulo Theories (SMT) [5, 6]. Using SMT allows us to compact the formula when arrays and vectors are involved. SMT has two

approaches: eager and lazy [8]. The eager approach provides a way to translate the original formula into an equal satisfiable formula. The lazy approach is combination of SAT and τ -theory (SAT + τ -theory [97]). It has been developed and used by wide range of communities and domains[38, 1, 88, 63]. SAT testing falls into NP-complete problems [30]. An explicit version of BMC have been proposed in the literature in [77].

Partial order reduction. This method attempts to cut down the state space of concurrent asynchronous systems [50]. In asynchronous processes, interleaving model of executions must consider all possible orders of events for the sake of preventing the omission of important ones. Some of these ordering result in the same state, as what is shown in figure 8. To avoid of this, partial order reduction avoids of analyzing all sequences and consider only an incomplete set of events. Its methodology is not distinguishing between traces that only differ by their orders. For example, in figure 8 to reach s' from s, it does not matter α is run first or β . The set of events includes only representatives of enable transition. Some approaches of partial order reduction introduced in stubborn sets [108], ample sets [2], persistent sets [46], unfolding methods [76], and sleep sets [29].

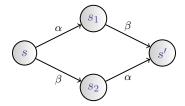


Figure 8: Some ordering results in a same state[33]

Normally, the reduced model of partial order reduction is explicit and produced by utilizing methods based on modified depth-first search [109] or breath-first search. It can be combined with other methods such as on-the-fly model checking [86] or symbolic model checking [2]. This method reduces the memory usage and time requirements. One of the key factors which effects on the efficiency of this methods is the number of enable transitions, which may change a predicate in the verified property [93]. In complex systems, the number of these transitions increase and few reduction can be constructed.

Abstraction. Abstraction is a methods to handle more state space by abstracting away the entire state space. It is based on a fact that states indicate computations in series of objects and obvious relationships that normally many similar behaviors are between them. The abstraction methods can interpret these objects in another universe of abstraction to avoid exploring all of them. However, the result of its execution must be same as the original one [40]. In [34], abstraction is defined as follow: let S_i is $i_t h$ state over the set of all states $S_1...S_n$. Abstraction will give a surjection $h = (h_1,...h_n)$ that groups and maps each state to corresponding abstract state. In [32], E. Clarke et al. indicated that the abstraction can be done based on the following aspects: an equivalence modulo of an integer to address mathematics operations, symbolic abstraction, and single bit abstraction to address bit-by-bit logical operations.

As an example for the above kinds of abstraction consider following arithmetic modulo [32]:

```
(x \bmod i) + (y \bmod i) \bmod i \equiv x + y \pmod i

(x \bmod i) - (y \bmod i) \bmod i \equiv x - y \pmod i

(x \bmod i)(y \bmod i) \bmod i \equiv x y \pmod i
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To abstract the above modulo and determine the value modulo i, we can use the values modulo i of the subexpressions.

Another type of abstraction strategy is based on storage reduction of states has been studied by G. J. Holzman et al. [59] that intends to minimize the size of used memory during constructing state space. Moreover, another algorithm called *cone of influence* considers as an abstract methods that remove all variables from the system model. The variables are idle or do not have any influence on the system properties [34].

Symmetry reduction methods. Symmetry reduction method attempts to reduce the amount of state space. It is based on replacing sets of symmetrically similar states in a given model via a single representative class. Consider the figure 9 of a mutual-exclusion for two components a, b modeled by a Kripke structure. There are many obvious symmetries between the components. For example, when component a is in the critical section, component b is waiting, equivalently, when the state in b is in the critical section a is waiting. It is an adequate way in verification if we could find such equivalence states and check only one state from each class instead check all individual states.

A constructed model M' of system M under symmetry methods is called a quotient structure and a given property Fi holds for $M(fi \models M)$ if and only if Fi holds for $M'(Fi \models M')$. Symmetry reduction methods have two difficulties: orbit problem, and constructive orbit problem. Orbit problem sakes to find two states a and \bar{a} are in the equal orbit [31]. It is not known as NP-complete, but it is harder than isomorphism problems.

Constructive orbit problem (COP) is a representative function that replaces set of symmetrically similar states in a given model by a single representative which is minimal. This problem falls into NP-hard problems [7].

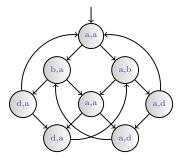


Figure 9: Mutual exclusion

Hash tables. A set of effective reachable states in contrast to the amount of possibly reachable states of a given state space is few. All effective states stored somewhere in the system's memory. One way to retrieve these sparse states, which can be visited before and needed several time during checking, is using hash tables. A hash table is an alternative to direct

addressing into ordinary array. This property of hash table provides a simple way to examine an arbitrary state in a given array in O(1) time [39]. It can be considered as yes-no methods that is able to improve the reachability analysis in verification processes.

G. J. Holzmann in [56] speeds up the process of generating an exhaustive list of all visited states during a search for errors and check new generation of state against all pre-analyzed states by a hash table. Through hash table the states can be accessed quickly and decrease the amount of state to check. To compact information more, they ignored storing the hash key itself (states) and only used the hash value (the address computed) to identify a state. The hashing discipline has been used improved the state storage and state comparison. Another example is SPIN model checker [58] that utilizing hash functions.

4.1.4. Bottom-up approach. Verification process can be done in a bottom-up manner before the entire state space constructed. The state space will be checked bit by bit and the global properties can be deduced by combining the result of them. In bottom-up approach one way is to delete the states that are already checked from memory and re-verify them when need. On the other hand, the verification information from the verified-states can be reuse and omit the effort of re-verifying. In contrast to compositional verification, bottom-up approaches do not need to do system decomposition. Two methods for alleviating SSE problem which are bottom-up discuss in bellow.

On-the-fly method. This method is an explicit method that is able to verify a system without storing the complete construction of state space in the memory. On-the-fly model checking starts checking from an initial state and searches adjacent states to gain local knowledge about the state space in a stepwise manner. The key factor here is storing only the current path and operates verification along constructing the state space of the system. In the other words, it does not postpone the verification until the state space construction to be completed. Therefore, the counterexample of the properties that do not hold can be found and generated as early as possible. This property considered as the most important advantages of the on-the-fly method [96].

Another advantage of this methods is that it reduces the memory requirements substantially, because it eliminates already visited states from memory. On the other hand, eliminating already verified states may increase the running time during searching for errors. Since this method does not store the already-visited states in the memory and may need to regenerate them over and over, then the time of exploring grows dramatically.

The methods itself often employs depth-first-search (DFS) algorithms for searching through the state space. The running time of this method relies upon the amount of states and number of transitions. The employed DFS algorithms are divided into two categories: Nested DFS and Strongly connected component (SCC). Nested DFS, firstly, searches for accepting states. Secondly, it searches for cycles around accepted states. Despite memory efficiency of this algorithm, it may lead to finding a very long trace of a counterexample. In [48], the authors proposed a method to achieve a minimal counterexample.

SCC-based on-the-fly methods find strongly connected component from initial state to a given state. If any violation found, then it produces a counterexample trace which is strongly connected and includes at least one component. In compare with nested DFS, it utilizes more memory, larger stack, and finally a longer counterexample. J. Geldenhuys introduced Tarjan's algorithm [106] to improve this kind of model checking. Geldenhuys and et al. [49] improved Tarjan's algorithm in term of finding accepting cycle sooner and producing a shorter counterexample. On-the-fly methods have been combined with other methods such as symmetry reduction [84].

Incremental verification. Incremental verification is one of those approaches that iteratively generate state space of the system and verify them until the overall properties of the system are satisfied. The key concept here is twofold: 1- preservation of the system properties when new increments are added; 2- providing an appropriate way to avoid of re-verifying the system when new increments in the higher level of verification are added. Therefore, it leads to reduce the whole of the verification effort. Incremental verification is discussed in detail in section 4. Some other works fall under this class is [11, 10] which illustrated in section 5.

4.1.5. Compositional Verification. Compositional verification is kind of divide-and-conquer approach which deals with the SSE problem. It divides a large and complex problem into sub-problems and verifies each part separately. Contrary to its name, this method decompose a given system into small components and then verify the local properties of each component. The result of verifying local properties of sub-systems employs to deduce the entire system property. Obviously, by using this approach the whole state space does not need to be constructed and the sub-systems are not big as the system itself, consequently, state space volume significantly will be reduced. In addition, it provides more insight into the system interactions. Compositional verification has several alternative methods which is explained below.

Interface rule. It makes an abstraction interface of component constraints and then proofs preservation of each local components by an interface rule. The idea behind using interface abstraction is that in the composition process only the properties are observable for other components should be checked. By hiding the rest of properties, a huge amount of states will be reduced. Interface theory provides strong logical operations which are sound. The soundness of that is proved in [14]. Figure 10 shows a general schema for interface rule method. P_1 and P_2 are two processes or two components which is equipped with their interface rules A_1 and A_2 .

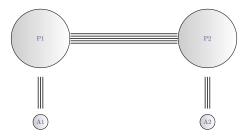


Figure 10: Abstraction

Partitioned Transition Relations. This method is based on image of states that produces a set of all successors of states A and pre-image which produces predecessor of set of states A' with a transition relation T [22]. Let the sets A and T are given by a Boolean formula then the image of A can be computed by the below formula:

$$\exists m[A(m) \land T(m, m')] \tag{4.1}$$

which existential m ($\exists m$) determines quantification over all variables in the set of variables m. In the first step, it constructs transition relation N_i of each component i during exploring the system model and then composes all individual results to produce global transition relation. By this way, the global transition relation will never be constructed explicitly. The formulas and steps that for synchronous systems is as follow:

$$\underbrace{\exists m_{\rho(n-1)}[\cdots \exists m_{\rho(1)}[\underbrace{\exists m_{\rho(0)}[A(m) \land T_{\rho(0)}(m,m')]}_{A_1} \land T_{\rho(1)}(m,m')]} \land \cdots \land T_{\rho(n-1)}(m,m')]}_{A_2}$$

$$\vdots$$

$$\vdots$$

$$A_n$$

$$(4.2)$$

Clearly, each step depends on the previous step and the final partitioning strongly depends on order that the variables qualified out. It can be computed by OBDD. However, finding an optimum ordering for OBDD is complex and it needs special algorithms to find an optimum ordering. In [23, 14], the authors have presented an algorithm to compute an optimum ordering of OBDD and improve the partition transition relations.

Lazy parallel composition. In this method for all processes, a restricted transition relation will be created. The restricted transition is more concise than the global transition relation itself [14]. Let R is a global transition relation and S is a set of states. R' can be a restricted transition relation for the image s if it always satisfies the bellow condition:

$$R'|_{s} = R|_{s} \tag{4.3}$$

The formula indicates that R and R' concur on transitions start from states in s, but R' has fewer nodes than R. This method simplifies the transition relation of each component by using the constrain operators before constructing the global transition relation.

$$R' = \bigwedge_{i..n} constraint(R_i, S)$$
(4.4)

R' must concur with the global relation transition R in the set of states S. As a result, producing successors of S by using restricted transition R' produces the same result as using R. The total formula and steps that they take in compare with partial transition relation method is as follow:

$$\exists m'[A(m') \land \underbrace{(T_1(m, m')|s}_{step1} \land \underbrace{T_2(m, m')|s}_{step2})] \tag{4.5}$$

In the above formula, it is obvious that every step is independent and it can be considered as an improvement of partition transition relations.

Assume-guarantee reasoning. It has been proposed by Pnueli [89] and verifies a single component of the system at a time. However, during verification a component needs to assume that the environment has a certain behavior, then if the other components of the system guarantee that behavior, it can be deduced that the behavior is hold for entire the system. Thus, two kinds of properties should be checked: First is specific assumptions about the environment behavior. Second, guarantee that the provided assumptions are hold. The basic rule of assume guarantee can be formulated as follow:

$$\frac{\langle true \rangle M' \langle g \rangle \quad \langle M \langle f \rangle}{\langle true \rangle M \parallel M' \langle f \rangle}$$

$$(4.6)$$

This method is discussed in detail in section 5.

State Space Explosion Reduction	explicit	implicit	State Space Explosion Reduction	explicit	implicit
Symbolic model checking		✓	Genetic algorithm	✓	_
Bounded model checking		\checkmark	Random walk	\checkmark	
Garbage collection	\checkmark		Ant colony	✓	
Partial order reduction	\checkmark		Bloom filter	\checkmark	
On-the-fly method	\checkmark		Incremental verification	\checkmark	\checkmark
Expanding memory	\checkmark	\checkmark	Interface rules		\checkmark
Symmetry reduction methods	\checkmark		Partition transition relation		\checkmark
Abstraction	\checkmark		Lazy parallel composition		\checkmark
Hash table	✓		Assume-guarantee reasoning	✓	\checkmark

Table 3: Explicit and Implicit methods

4.2. **Comparison.** The methods for mitigation SSE problem are trying to address the memory concern. For example, by using specific data structure like BDD, using heuristics, add more external memory, or divide the problem into sub problems. These methods are completely different and the only shared characteristics between them is the way of representing the state space. The way of representing state space can be considered as two main paradigms of model checking. This two paradigms are *explicit and implicit*. Table 3 compares the reviewed methods based on them.

The success factor and challenges of the reviewed methods are summing up in two separate tables. 6 and 5 are listed the success factor and challenges of each method respectively.

5. Handling SSE problem in CBS

Despite the fact that deciding properties like liveness and deadlock free in CBS is NP-hard [75, 79], model checking and formal verification have been utilized to evaluate the this kind of properties of CBS. A particular subset of CBS verification is concerned with addressing SSE problem. The methods that have been explained in previous section can be used in CBS. Figure 11, indicates the frequently used methods in CBS which includes assume-guarantee reasoning, interface rule, and incremental verification. The component-wise representation of the state space of these kinds of methods is one of the reason of their popularity in CBS. Assume-guarantee and interface rule are subsets of compositional

GLIG ELL DILL	G .c .
State Space Explosion Reduction	Specific features
Symbolic model checking	it supports 10^{20} state and beyond [22].
Bounded model checking	it requires lower by hand manipulation than other approaches like BDDs that need manual ordering [30].
Garbage collection	its managing memory and fragmenting is on the fly; it avoids suspending pointers being created [67].
Partial order reduction	it limits the searching of redundant interleaving [50].
On-the-fly method	it verifying individual traces rather than the whole state space; it is able to produce counter examples as early as possible [96].
Expanding memory	external memory capacity is infinite and not expensive.
Symmetry reduction methods	it replaces a set of symmetrically similar states in a given model by a single representative which is minimal, therefore the similar states and traces present only once [31].
Abstraction	it handles more states by removing states with similar behaviors [34].
Compositional verification	the entire state space of the system will not be built completely [14].
Hash table	it does not need to store the whole states; it improved nested depth-first- search [57]
Genetic algorithm	it uses an intelligent search instead of searching exhaustively into entire state space [113].
Random walk	its need for space is extremely low; it is able to be parallel.
Ant colony	coverage is guarantee [98].
Incremental verification	it can be done before the system construction completes; the counter examples can be found as early as possible [refer to section 4].

Table 4: Success features of SSE reduction methods

verification which is a divide and conquer approach. The philosophy behind these two methods is dividing a system into some sub-components, addressing the local properties

State Space Explosion Reduction	Challenges
Symbolic model checking	it uses BDDs which strongly depends on ordering of its input variables [19, 18]
Bounded model checking	it is capable to find only trivial properties and unable to check systems contains deep loops [42]; it can find long counter example while short counterexamples are easier to understand [95]
Garbage collection	it consuming computer resources [114, 54]; it is hard to predict the pauses that garbage collection has done [100]
Partial order reduction	it does not sensitive in ordering of ${\rm traces}[33].$
On-the-fly method	it needs to regenerate already visited states consequently lead to increase runtime [65].
Expanding memory	it leads to slower memory access, therefore it needs a proper Input/Output algorithm [112].
Symmetry reduction methods	it falls into NP-hard problems [7].
Abstraction	it needs a proper mapping function $[65]$.
Compositional verification	breaking down a system is hard to do [36, 37]; verifying the systems with long chain circularity is difficult [65]
Hash table	it assigns unique index number which may lead to hash collision and missing the error states [57]
Ant colony	it does not guarantee the exploring all global states, therefore it does not guar- antee to find global properties; time to coverage is uncertain [98]
Genetic algorithm	same as Ant colony
Random walk	same as Ant colony
Bloom filter	there is no guarantee to find global properties, it may lead to false positive results [103]
Incremental verification	it needs to generates rules to guarantee the preservation of properties and gen- erating rules to avoid of re-verifying the previous levels [refer to section 4]

Table 5: Challenges of methods for alleviating SSE problem

of a subset of components independently, and then deduce the entire properties of the system properties. Incremental verification falls into bottom-up approach that is able to exploit lower level verification information when small changes apply or components add. Table 6 represents the characteristics of these three method. In this section, we first describe these methods then discuss the suitable method for alleviating SSE problem for CBS.

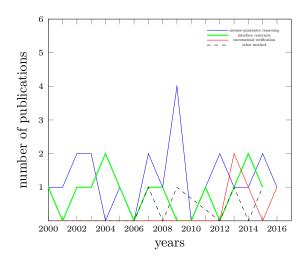


Figure 11: Number of Publications from 2000 to 2016

Assume-guarantee reasoning- needs three steps started by D, we call it Three-D: 1- Decomposing a given system S into its sub components $C_1, C_2, ..., C_n$, 2- Deriving assumption A_i about the environment for each C_i , 3- Defining rules to prove properties of C_i guarantees the requirements φ of system S under assumption A_i .

Step 1 is breaking up the entire system into the sub components. Applying divide and conquer methods over CBS which is already composed by multiple components may facilitate the decomposition step, but it is still a tedious task. J. M Cobleigh et.al [36, 37] determined that finding an appropriate decomposition of a given system to verify by such methods is hard to do.

Step 2 is the process of capturing the behavior that a given component C_i collects about its environment A_i . The most important key point here which yield assumption checking successful is detecting appropriate assumptions for every component. Thus, a challenging question arise here: How to detect appropriate assumption? The assumptions have been traditionally generated by users which strongly limited the assume-guarantee reasoning practically. Some proposals have been proposed to develop the assumptions automatically such as using learning assumptions [81, 52, 25].

Step 3 is defining rules to proof that the sub-component C_i guarantees its correct behavior of under assumption A_i . Having rules to decide about the correctness of assumption is necessary. Thus, this question must be answered precisely: How to develop this kind of proof rules? The rules can be provided based on a set of theoretic operations [26].

Another challenge of this methods is shown in the figure. 12. Suppose a system with three components Sum, Sub, and Multiple. It is compulsory to proof satisfaction of component Sum to verify component sub. Likewise, verifying component Multiple depends on Sum and Sub. This shows the problem of interdependent assumptions between components. Mutual interdependency between the components, like the dependency between component Sum and Multiple is another problem that called circularity. Tackling this problem needs a set of sound and complete rules. In [65] proof that solving long chain of circularity is difficult. Some recent works for tackling this problem are presented in [44, 45].

Other works based on assume-guarantee reasoning are an algorithm based on a prefixclosed set of traces [26], an algebraic theory [80, 27], an invariant based algorithm [13], an

SSE Reduction Technique	Challenges
Assume-guarantee Reasoning	decomposing system, detecting appropriate assumption, developing new rules to determine the correctness of assumptions, circularity
Interface-based verification	decomposing system, generating abstract constraint, refine the interface
Incremental verification	preserving of system properties when new increments are added, avoiding of re-verifying in the high level of verification

Table 6: Challenges of SSE reduction methods in component-based verification

algorithm named AGMC [55], an assume-guarantee verification for SOFA component model [83], a minimize assumption generation algorithm [87].

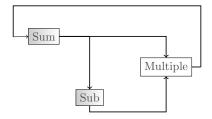


Figure 12: Interdependency between components

Interface rule reasoning- Interface rule which has been presented in [34] is a set of abstract constraints for each single components in the systems. It restricts the behavior of components and assures about the protection of local properties. The first challenging key is generating the abstract constraints. This method can be used in compositional verification strategies by decomposing the interface of the system into sub-parts which is representing the global properties. Then, inferring the global properties from the interface that the composition of individual components will satisfy. The second challenge of this method is decomposition.

The interface rules must include appropriate information to fulfill the compositional verification goal. It can be either traditionally prepared by users manually or generated automatically. Some works based on this method are discussed bellow.

Yan. Jin [65] propose a formal framework to specifying and verifying component based systems based on *Interface Automata (IA)*. IA has been used to describe interaction protocols of components and preserve the local properties of them to verify them independently. Another work on verifying component-based system via interface rule presented by Isazadeh. A *et al.* [62]. They have proposed a formal model to specify interface rule for communication protocols of components and then verify components according to this interface rule.

Sophie Quinton and Susanne Graf [9] have developed a framework for interface rule reasoning (in term of contract-based reasoning) for component-based design. In order to introduce such interface rule, they make benefit from a notation of I/A automata proposed by Henzinger and take into account sets of notation of contrasts about composability and compatibility.

Another work presented in [53] to compositional verification of component based in X-MAN. This work consists of two steps: 1- Vertical verification and Horizontal verification. Vertical verification guarantees that each atomic component satisfies its contracts (presented by an interface). 2- Horizontal verification which uses components contracts to verify the entire system. In this work they suppose that the interface rules has been already attached to each component in the repository. Other works in interface based verification are [105, 28, 60].

Incremental verification- as its name implies, incremental verification incrementally checks the system behavior. It can be done during design process. If a CBS is constructing incrementally, verification can be done during the construction and iteratively check properties of unfinished system until the system is completed. Thus, for incrementally verification of CBS it is vital to support incremental construction. In [71], property feasibility of incremental construction have been proved. Let system S constructed by inc_i increments from initial inc_0 where $inc_1 \subseteq inc_2 \subseteq inc_3$... and $inc_i \subseteq inc_{i+1}$ which means inc_{i+1} contains the behaviors of inc_i [71]. We say φ is the properties of the system S such that $\varphi_{inc_1} \subseteq \varphi_{inc_2} \subseteq \varphi_{inc_3} \subset ...$ where $\varphi_{inc_1} \subseteq \varphi_{inc_2}$ means the properties that satisfied in inc_i preserved in the next step of construction inc_{i+1} . Thus, preservation of the system properties when new increments are added is one of the key challenges in incremental verification.

Second, providing an appropriate way to avoid of re-verifying the system when new increments in the higher level of verification is required. Verifying the whole system after every small changes is not efficient. Therefore, providing a rule to deal with this issue can be consider as a effective improvement in formal verification, because it leads to reduce the whole verification effort significantly.

An incremental verification based on interaction invariants for component-based design has been proposed in [11, 12]. It is an invariant-based method for verification in BIP component-based model. The interaction invariants involve locations of multiple components and express constraints on global state space induced via interactions. A methods called Binary Behavioral Constraints (BBC) has been proposed to symbolically compute the interaction invariants. The methods completely defined the influence of interactions of a composite component on the other component's behavior. To reuse those invariants when new increments are added they decompose the BBC and use two new methods to enhance scalability. The verification method is pure synchronization and did not consider data exchange. Finally, the constraints and computations are represented by BDD. As we discuss in sec 4, BDD strongly depends on input ordering and without proper ordering, the BDD may grow up and quickly exceed the memory capacity. Despite proposing a sufficient technique to reduce the BDD, ordering BDD falls into NP-problems and does not have exact solution [19, 18]. A tool package called CUDD have been used to generate BBDs [101].

Other work concerning incremental verification for dynamic CBS is defined in [66]. This work can verify CBS whose components and structure change dynamically at runtime. The method, called INVEST, improved compositional verification by adding incremental strategy to reverify a system after any removal, modification, and addition of components.

Initially, the system will be verified by typical compositional vitrifaction and assume guarantee reasoning. The incremental verification executes when any changes occur in the system. The method is not completely incremental and combine with assume-guarantee reasoning.

6. Discussion and Conclusion

This work on one hand reviewed, briefly discussed, characterized, and classified existing methods of state space explosion reduction methods into five categories. On the other hand, investigated the methods for alleviating SSE problem that have been utilized in CBS. In section 3, RQ(1, 2, 3) have been answered completely. The state-of-the-art mitigation methods for SSE problem has been identified and explained. The success factors and challenges of them are summarized as well. All these informations led to set up a classification for common SSE reduction methods.

RQs (4, 5) have been discussed in section 4. We demonstrate common SSE reduction methods in CBS and their challenges to analyze which method is suitable for verifying CBS. It summarized in table 6. After discussing SSE reduction methods applied in CBS, now we are in the position to discuss RQ6.

Among the common methods for alleviating SSE problem in CBS, one choice is using compositional verification either assume-guarantee or interface rules. However, in such methods, the entire verification problem should be decomposed into smaller task of its components and check each of them individually. Then, after decomposition, some difficulties such as interdependency between components, circularity, finding assumptions will be raised. Utilizing such methods in order to verify CBS obviously has limited by several issues.

On the other hand, applying incremental verification in CBS may have some advantages. To begin with, such methods, omit the tedious task of breaking up the verification problem in the sense that verifying a system in a bottom-up manner and bit-wise during incremental construction reduce the verification effort, rather than decomposing the system after the entire construction is finished and then verify each part individually. The implementation of incremental construction and verification by [12, 71] has determined the possibility of this.

Another advantage of incremental verification is that counterexamples and error traces can be found as early as possible. In the other words, the counter examples can be created before the whole system constructed. It is very useful to reveal error states before going through the higher levels of constructing.

It is important to mention we are aware that all current component models are not intended to support incremental construction and it requires formalization for constructing CBS incrementally. This is the topic that we intend to investigate more as our future work.

Next topic that we intend to explore as our future work is finding a sufficient empirical way for utilizing incremental verification over CBS which can guarantee both preserving the system properties and reducing verification effort by re-using already verified states in the higher level of construction and verification. Obviously, it is the main target in using such methods and we are intending to achieve sufficient empirical way for it in the future.

The general clue for this research is that despite proposing many methods for solving the bottleneck of model checking, the state space explosion still remains an obstacle in worst case and have not been solved completely yet. This research is provide a basis for many stakeholders such as component based developers that need to select the most appropriate method for verifying their system, organizations that desire to creating model checker, researchers willing to set their research directions.

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