TMACS: a Tool for Modeling, Manipulation, and Analysis of Concurrent Systems

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Abstract. This paper reports on an effort to build a tool for modeling, specification, and analysis of concurrent systems. The tool implements the CCS process language and can build labeled transition systems from CCS expressions. Furthermore, it can be used to reduce the state space of a labeled transition system and to check whether two labeled transition systems exhibit the same behaviour, using strong and weak bisimulation equivalence. It can parse Henessy-Milner logic formulas and also implements the 'strong until' and 'weak until' operators. The tool has the functionality needed to perform modeling, specification, and verification, illustrated on two classical examples in the concurrency theory: the Alternating Bit Protocol and Peterson's mutual exclusion algorithm.

Keywords: CCS, labeled transition system, bisimulation equivalence, minimization, comparison, formal verification, Hennessy-Milner logic.

1 Introduction

Due to the increasing complexity of the real-life systems, manual analysis is very hard and often impossible. Therefore, having computer support for modeling, analysing, and verifying system behaviour is of an essential importance. This implies that the systems' properties and behaviour need to be described by formal methods with an explicit formal semantics.

One of the process languages used to formally describe and analyse any collection of interacting processes is the Calculus of Communication Systems (CCS), process algebra introduced by Robin Milner and based on the message-passing paradigm [1][2]. CCS, like any process algebra, can be exploited to describe both specifications of the expected behaviours of the processes and their implementations [3]. The standard semantic model for CCS and various other process languages is the notion of labeled transition systems, a model first used by Keller to study concurrent systems [4]. In order to analyze process behaviour and establish formally whether two processes offer the same behavior, different notions of behavioral equivalences over (states of) labeled transition systems have been proposed [5].

One of the key behavioral equivalences is the strong bisimilarity [6] which relates processes whose behaviours are indistinguishable from each other [7]. Weak bisimilarity [1][8] is a looser equivalence that abstracts away from internal (non-observable) actions. These and other behavioral equivalences can be employed to reduce the size of the state space of a labeled transition system and to check the equivalence between the behaviours of two labeled transition systems. This finds an extensive application in model checking and formal verification[9][5].

The notion of Hennessy-Milner logic [10] is used to characterize the behavioural properties of systems modeled semantically as labeled transition systems. As a more powerful language for specifying properties of processes, the extension of the Hennessy-Milner logic with recursive definitions of formulas [11] is often employed. It entails the 'strong until' and 'weak until' operators to allow for recursive definitions [5].

This paper presents TMACS, a tool that can be used to automate the process of modeling, manipulation and analysis of concurrent systems described by the CCS process language. TMACS stands for Tool for Modeling, manipulation, and Analysis of Concurrent Systems. It is given as a Java executable jar library [12] with very simple Graphical User Interface (GUI). The tool is functional enough to be able to satisfy the basic requirements for modeling, specification, and verification. TMACS can parse CCS expressions, generate labeled transition system from CCS in Aldebaran format [13], reduce a labeled transition system to its canonical form with respect to strong or weak bisimilarity and check whether two labeled transition systems are strongly or weakly bisimilar. Additionally, it can parse Hennessy-Milner formulas and implements the Hennessy-Milner logic operators for recursive definitions.

1.1 Related work

Different tools for modeling, specification and verification of concurrent reactive systems have been developed over the past two decades. Probably the most famous and most commonly used ones, especially in the academic environment, are the Edinburgh Concurrency Workbench (CWB) [14] and micro Common Representation Language 2 (mCRL2) [15].

The Edinburgh Concurrency Workbench (CWB) is a tool for analysis of cuncurrent systems, which allows for equivalence, preorder and model checking using a variety of different process semantics. It also allows defining of behaviours in an extended version of CCS and perform various analysis of these behaviours, such as checking various semantic equivalences, e.g. strong and weak bisimilarity check. We used CWB to validate our tool, e.g. for checking CCS validity and also for testing algorithms for strong and weak bisimularity of labeled graphs. Although CWB covers much of the functionality of our tool and more, CWB has a command interpreter interface that is more difficult to work with, unlike our tool that has a Graphical User Interface (GUI), and is very intuitive. As far as we know the CWB does not have the functionality for exporting labeled transition system graphs in Aldebaran format, that our tool has.

The micro Common Representation Language 2 (mCRL2), successor of μCRL, is a formal specification language that can be used to specify and analyse the behaviour of distrubuted systems and protocols. Its accompanying toolset contains extensive collection of tools to automatically translate any mCRL2 specification to a linear process, manipulate and simulate linear processes, generate the state space associated with a linear process, manipulate and visualize state spaces, etc. All mCRL2 tools can be used from the command line, but mCRL2 has an enhanced Graphical User Interface (GUI) as well which makes it very user-friendly and easy to use. We used mCRL2 also to validate and test our tool, e.g. for testing the algorithms for minimization and comparison of labeled graphs using strong and weak bisimularity. However, to our knowledge, mCRL2 does not provide the possibility to define systems' behaviour in the CCS process language nor to specify systems' properties using Hennessy-Milner logic. Also, even though mCRL2 supports minimization modulo strong and weak bisimulation equivalence, it does not output the computed bisimulation, feature that we have implemented in our tool.

In addition it is worth mentioning some other similar tools as well: the Mobiility Workbench (MWB) - tool for manipulating and analyzing mobile concurrent systems [16], Construction and Analysis of Distributed Processes (CADP) - toolbox for the design of communication protocols and distributed systems [17], the Labelled Transition System Analyser (LTSA) - a verification tool for concurrent systems [18], etc.

1.2 Outline

The contributions of this paper are organized as follows. In Section 2 we introduce some of the basic terminology used throughout the report. Section 3 is devoted to the implementation of the CCS process language and generation of labeled transition systems as a semantic model of process expressions, and it also discusses some of the choices made during the implementation. Section 4 describes the process of reducing the size of the state space of a labeled transition system as well as checking the equivalence between two labeled transition systems with respect to behavioural equivalences such as strong bisimilarity and observational equivalence (weak bisimilarity). It includes implementation details of two algorithms for computing strong bisimulation equivalence, the naive algorithm [5] and the advanced algorithm due to Fernandez [19]. It also entails a description of the saturation technique together with a respective algorithm for saturating a labeled transition system which reduces the problem of computing weak bisimulation equivalence to computing strong bisimilarity over the saturated systems [5]. Section 5 explains how the implementation of Hennesy-Milner Logic (HML) works and gives implementation details for the 'strong until' and 'weak until' operators. Next, in Section 6, we illustrate the application of TMACS for modeling, specification and verification of two classical examples in the concurrency theory: the Alternating Bit Protocol [20][21] and Peterson's mutual exclusion algorithm [22]. Finally, we give some conclusions and some directions for future development of the tool in Section 7. We also include four appendices. Appendix A contains the experimental results we got with analysis of the running times of our implementations of the two algorithms for computing bisimulation equivalence. Appendix B shows the syntax diagram for the grammar that recognizes CCS expressions, while Appendix C presents the grammar for Hennessy-Milner logic expressions. Finally, Appendix D includes some visual illustration of the tool's usage via screenshots of the graphical application.

2 Preliminaries

In this section, we give some formal definitions of the basic terminology used throughout the report [5][23].

Definition 1. *(Calculus of Communicating Systems): Calculus of Communicating Systems is algebraic theory to formalize the notion of concurrent computation. Commonly known as CCS.*

Definition 2. *(Labelled transition system): A labelled transition system is a five tuple* $A = (S, Act, \rightarrow, s, T)$ *where*

- S *is set of states,*
- Act *is a set of actions, possibly multi-actions,*
- $\rightarrow \subseteq S \times Act \times S$ *is a transition relation,*
- $s \in S$ *is the initial state,*
- $T \subseteq S$ *is the set of terminating states.*

Definition 3. *(Strong bisimulation equivalence): Let* $A_1 = (S_1, Act, \rightarrow_1, s_1, T_1)$ *and* $A_2 = (S_2, Act, \rightarrow_2, s_2, T_2)$ *be labelled transition systems. A binary relation* $R \subseteq S_1 \times S_2$ *is called a strong bisimulation relation iff for all* $s \in S_1$ *and* $t \in S_2$ *such that* sRt *holds, it also holds for all actions* $a \in Act$ *that:*

1. *if* $s \xrightarrow{a}_1 s'$ *then there is a* $t' \in S_2$ *such that* $t \xrightarrow{a}_2 t'$ *with* $s'Rt'$*,*
2. *if* $t \xrightarrow{a}_2 t'$ *then there is a* $s' \in S_1$ *such that* $s \xrightarrow{a}_1 s'$ *with* $s'Rt'$*, and*
3. $s \in T_1$ *if and only in* $t \in T_2$*.*

Definition 4. *Let* P *and* Q *be CCS processes or, more generally, states in a labeled transition system. For each action* a, $P \overset{a}{\Rightarrow} Q$ *iff:*

- *Either* $a \neq \tau$ *and there are processes* P' *and* Q' *such that* $P \left(\xrightarrow{\tau}\right)^* P' \xrightarrow{a} Q' \left(\xrightarrow{\tau}\right)^* Q$*,*
- *Or* $a = \tau$ *and* $P \left(\xrightarrow{\tau}\right)^* Q$*,*

where $\left(\xrightarrow{\tau}\right)^*$ *denotes the reflexive and transitive closure of the relation* $\xrightarrow{\tau}$*.*

Definition 5. *(Weak bisimulation equivalence/Observational equivalence): A binary relation R over the set of states of a labeled transition system is a weak bisimulation (observational equivalence) iff, whenever $s_1 R s_2$ and a is an action (including τ):*

- *If $s_1 \xrightarrow{a} s_1'$ then there is a transition $s_2 \overset{a}{\Rightarrow} s_2'$ such that $s_1' R s_2'$;*
- *If $s_2 \xrightarrow{a} s_2'$ then there is a transition $s_1 \overset{a}{\Rightarrow} s_1'$ such that $s_1' R s_2'$;*

Two states s and s' are observationally equivalent (or weakly bisimilar), written $s \approx s'$, iff there is a weak bisimulation equivalence that relates them.

Definition 6. *(Saturation): Let $T \subseteq S \times Act \times S$ be a labeled transition system. Then*

$$\begin{aligned} T^* &= \left\{ (p,a,q) \,|\, p \overset{a}{\Rightarrow} q \right\} = \\ &= T \cup \left(\xrightarrow{a} \right)^* \cup \left\{ (p,a,q) \,|\, a \neq \tau \wedge (\exists p', q' \in A)\, p \left(\xrightarrow{\tau} \right)^* p' \xrightarrow{a} q' \left(\xrightarrow{\tau} \right)^* q \right\} \end{aligned}$$

is a saturation of T.
Two labeled transition systems are weakly bisimilar iff their saturated labeled transition systems are strongly bisimilar.

Definition 7. *(Hennessy-Milner): The set of Hennessy-Milner formulas over a set of actions Act is given by the following abstract syntax:*

$$F, G ::= tt | ff | F \wedge G | F \vee G | \langle a \rangle F | [a] F$$

where $a \in Act$ and tt and ff denote true and false, respectively. If $A = \{a_1, ..., a_n\} \subseteq Act\,(n \geq 0)$, we use use the abbreviation $\langle A \rangle F$ for the formula $\langle a_1 \rangle F \vee ... \vee \langle a_n \rangle F$ and $[a] F$ for the formula $[a_1] F \wedge ... \wedge [a_n] F$. (If $A = \emptyset$ then $\langle a \rangle F = ff$ and $[a] = tt$.)

3 CCS parsing and labeled transition system generation

Given a set of action names, the set of CCS processes is defined by the following BNF grammar:

$$P ::= \emptyset \mid a.P_1 \mid A \mid P_1 + P_2 \mid P_1 | P_2 \mid P_1[b/a] \mid P_1 \backslash a \tag{1}$$

Two choices were considered for the problem of building a parser. The first choice was to build a new parser, which required much more resources and the second choice was to define a grammar and to use a parser generator (compiler-compiler, compiler generator) software to generate the parser source code. In formal language theory, a context-free grammar (CFG) is a grammar in which every production rule has the form:

$$V \to w$$

where V e is a nonterminal symbol, and w is a string of terminal and/or nonterminal symbols (w can be empty). Obviously, the defined BNF grammar for describing the CCS process is a CFG. Deterministic context-free grammars (DCFGs) are grammars that can be recognized by a deterministic pushdown automaton or equivalently, grammars that can be recognized by a LR (left to right) parser [24][25]. DCFGs are a proper subset of the context-free grammar family [24]. Although, the defined grammar is a non-deterministic context-free grammar, modern parsers have a look ahead feature, which means that the parser will not make a parsing decision until it reads ahead several tokens. This feature alows us to use a parser generator software, that will generate LR or LL parser which is able to recognize the non-deterministic grammar.

3.1 Generating the parser

ANTLR (ANother Tool for Language Recognition) [26] is a parser generator that was used to generate the parser for the CCS grammar. ANTLR uses LL(*) parsing and also allows generating parsers, lexers, tree parsers and combined lexer parsers. It also automatically generates abstract syntax trees (AST) [25], by providing operators and rewrite rules to guide the tree construction, which can be further processed with a tree parser, to build an abstract model of the AST using some programming language. A language is specified by using a context-free grammar which is expressed using Extended Backus Naur Form (EBNF) [25]. In short, an LL parser is a top-down parser which parses the input from left to right and constructs a Leftmost derivation of the sentence. An LL parser is called an LL(*) parser if it is not restricted to a finite k tokens of lookahead, but can make parsing decisions by recognizing whether the following tokens belong to a regular language. This is achieved by building temporary deterministic finite automaton, which are maintained and used until the parser makes a decision. This feature and some more optimization for the LL parser were published in recent years which made this kind of parser generators popular and favorable.

ANTLR was used to generate lexer, parser and a well defined abstract syntax tree which represents a tree representation of the abstract syntactic structure of the parsed sentence. The term abstract is used in a sense that the tree does not represent every single detail that exists in the language syntax, e.g., parentheses are implicit in the tree structure. From a development point of view it is much easier to work with trees than with a list of recognized tokens. One example of an AST is shown in Fig. 1 which is the result of parsing the expression:

$$A = (b.B \mid c.D \ + \ d.D) \backslash \{b, \ c\} \tag{2}$$

3.2 CCS domain model and labeled graph generation

Although working directly with abstract syntax trees and performing all algorithms on them is possible, it causes a limitation in future changes, where even a small change in the grammar and/or in the structure of the generated abstract

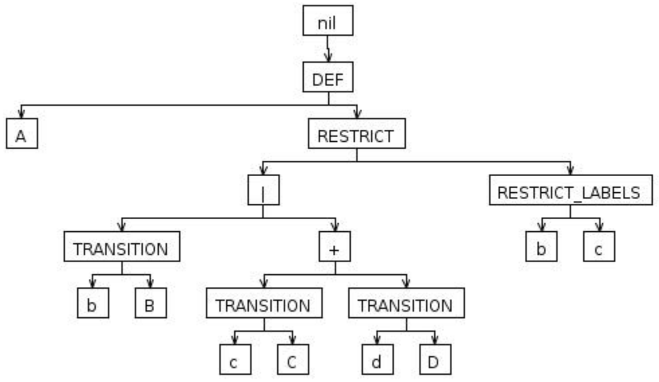

Fig. 1. Abstract syntaxt tree example

syntax trees causes a change in the implemented algorithms. Because of this, a specific domain model is built along with a domain builder algorithm, which has corresponding abstractions for all CCS operators, processes and actions. The input of the domain builder algorithm is an abstract syntax tree, and the output is a fully built domain model. The algorithms for constructing a labeled graph are implemented on the domain model because it is not expected for the domain model structure to change much in the future. The domain model is also a tree-like structure, so it is as easy to work with, as with the abstract syntax tree.

The algorithm for generation of labeled transition system is a recursive algorithm which traverses the tree structure of objects in the domain model and performs SOS rule every time it reaches an operation. In this fashion all SOS transformation are performed on the domain and as result a new graph structure is created which represents the labeled transition system which can be easily exported to a file in Aldebaran format.

3.3 Workflow of operations

In Fig. 2 the workflow of all operations that are executed for constructing a labeled transition system graph from a CCS expression are shown. Every operation is done as a standalone algorithm independent from the other operations, that has input and output shown in the figure. The modular design is deliberately chosen in order to help achieve better testing and maintenance of the source code.

4 Minimization and comparison of labeled transition systems

Bisimulation equivalence (bisimilarity) [6] is a binary relation between labeled transition systems which associates systems that can simulate each other's be-

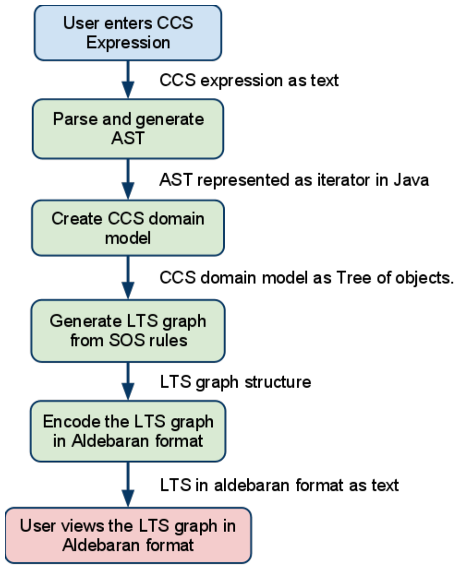
User enters CCS Expression
CCS expression as text
Parse and generate AST
AST represented as iterator in Java
Create CCS domain model
CCS domain model as Tree of objects.
Generate LTS graph from SOS rules
LTS graph structure
Encode the LTS graph in Aldebaran format
LTS in aldebaran format as text
User views the LTS graph in Aldebaran format

Fig. 2. Workflow of all operations for producing a labeled transition system graph from a CCS expression

haviour in a stepwise manner which enables comparison of different transition systems [9]. An alternative perspective is to consider the bisimulation equivalence as a relation between states of a single labeled transition system. Using the quotient transition system under such a relation, smaller models of the labeled transition system can be obtained [9].

The bisimulation equivalence finds its extensive application in many areas of computer science such as concurrency theory, formal verification, set theory, etc. For instance, in formal verification minimization with respect to bisimulation equivalence is used to reduce the size of the state space to be analyzed. Also, bisimulation equivalence is of particular interest in model checking, in specific to check the equivalence of an implementation of a certain system with respect to its specification model.

TMACS implements both options: reducing the size of the state space of a given labeled transition system and checking the equivalence of two labeled transition systems, using two behavioral equivalence relations: strong bisimilarity and observational equivalence (weak bisimilarity).

4.1 Minimization of a labeled transition system modulo strong bisimilarity

The process of reducing the size of the state space of a labeled transition system was implemented using an approach which consists of two steps:

1. Computing strong bisimulation equivalence (strong bisimilarity) for the labeled transition system;
2. Minimizing the labeled transition system to its canonical form using the strong bisimilarity obtained in the first step;

The first step, computing strong bisimulation equivalence, was implemented with two different methods: the so called naive method and a more efficient method due to Fernandez, both of which afterwards serve as minimization procedures.

The naive algorithm for computing bisimulation equivalence stems from the theory underlying Tarski's fixed point theorem. It is based on the fact that the strong bisimulation equivalence is the largest fixed point of the monotic function F as defined in [5] given by Tarsky's fixed point theorem. This algorithm has time complexity of $O(mn)$ for a labeled transition system with m transitions and n states.

Our implementation of the algorithm takes as an input a labeled transition system in aldebaran format, and generates the corresponding labelled graph as a list of nodes representing the states which use the following data structure:

– $S_p = \{(a, q)\}$ - set of pairs (a, q) for state p where a is an outgoing action for p and q is a state reachable from p with the action a

The algorithm then computes the strong bisimulation equivalence and outputs it as pairs of bisimilar states.

The algorithm due to Fernandez exploits the idea of the relationship between strong bisimulation equivalence and the relational coarsest partition problem solved by Paige and Tarjan [27]. It represents adaptation of the Paige-Tarjan algorithm of complexity $O(m \log n)$ to minimize labeled transition systems modulo bisimulation equivalence by computing the coarsest partition problem with respect to the family of binary relations $(T_a)_{a \in A}$ instead of one binary relation, where $T_a = \{(p, q) | (p, a, q) \in T\}$ is a transition relation for action $a \in A$ and T is a set of all transitions [19]. It has $O(m \log n)$ complexity for a labeled transition system with m transitions and n states.

Our implementation of Fernandez's algorithm takes a labeled transition system in Aldebaran format as an input, generates a labelled graph and then partitions the labeled graph into its coarsest blocks where each block represents a set of bisimilar states. Partition is a set of mutually exclusive blocks whose union constitutes the graph universe.

To define graph states and transitions we used the following terminology represented by suitable data structures:

– $T_a[p] = \{q\}$ - an a-transition from state p to state q
– ${T_a}^{-1}[q] = \{p\}$ - an inverse a-transition from state q to state p
– ${T_a}^{-1}[B] = \cup \left\{{T_a}^{-1}[q], q \in B\right\}$ - inverse transition for block B and action a
– W - set of sets called splitters that are being used to split the partition
– infoB(a, p) - info map for block B, state p and action a

Having computed the strong bisimulation equivalence, the next step in the reduction of the state space of the labeled transition system uses the bisimulation equivalence obtained in the first step in order to minimize the labeled graph. This reduction is implemented as follows:

1. If a pair of states (p, q) is bisimilar, then the two states are merged into one single state $k = p \cup q$;
2. All incoming transitions $r \overset{a}{\to} p$ and $s \overset{a}{\to} q$ are replaced by transitions $r \overset{a}{\to} k$ and $s \overset{a}{\to} k$;
3. All outgoing transitions $p \overset{a}{\to} r$ and $q \overset{a}{\to} s$ are replaced by transitions $k \overset{a}{\to} r$ and $k \overset{a}{\to} s$;
4. The duplicate transitions are not taken into consideration.

The procedure is repeated for all pairs of bisimilar states.

This process of reduction with respect to strong bisimilarity is illustrated below in Fig. 3. The results obtained by applying both algorithms for computing strong bisimulation equivalence are given in Table 1. These results are then used as a basis for the reduction of the graph to its minimal form: all mutually bisimilar states are merged into a single state and their transitions are updated accordingly.

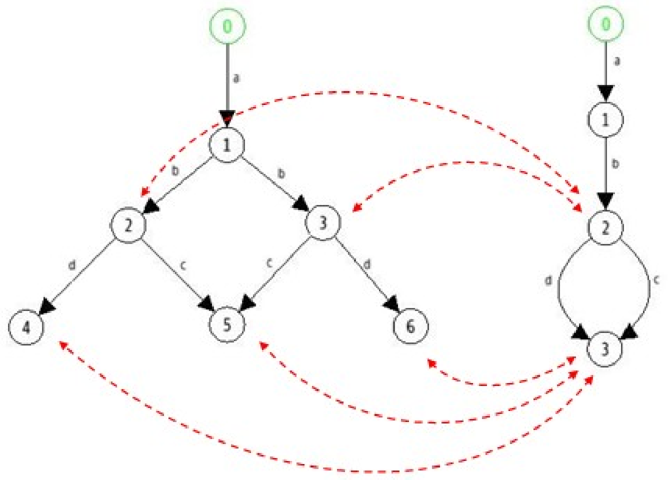

Fig. 3. Example of a labeled transition system graph and its minimial form modulo strong bisimilarity. The red dashed arrows depict the mapping of the states using the computed bisimulation equivalence. States 2 and 3 are merged into state 2 in the minimal graph, and states 4,5 and 6 are merged into state 3 in the minimal graph.

Algorithm	Bisimulation algorithm output
Naive	(2, 3), (3, 2), (4, 5), (5, 4), (4, 6), (6, 4), (5, 6), (6, 5), (0, 0), (1, 1), (2, 2), (3, 3), (4, 4), (5, 5), (6, 6)
Fernandez	{0}, {1}, {2}, {3}, {4, 5, 6}

Table 1. Computing strong bisimularity for the example labeled graph from Fig.3

4.2 Minimization of a labeled transition system modulo weak bisimilarity

The minimization of a labeled transition system modulo observational equivalence (weak bisimilarity) is reduced to the problem of minimization modulo strong bisimilarity, using a technique called saturation. Intuitevely, saturation amounts to first precomputing the weak transition relation and then constructing a new pair of finite processes whose original transitions are replaced by the weak transitions [5]. Once the algorithm for saturation is run and the original labeled transition system is saturated, the computation of weak bisimilarity amounts to computing strong bisimilarity of the saturated labeled transition system.

The algorithm for saturation in our tool was implemented as follows: The set of triples R can be partitioned in $2n$ sets with:

$$\begin{aligned} T_{\tau p} &= \{(p,\tau,q) \mid (p,\tau,q) \in T\}, \text{and} \\ T_{ap} &= \{(p,\tau,q) \mid a \neq \tau \wedge (p,\tau,q) \in T\} \end{aligned}$$

for every $p \in S$.

By the definition of $T_{\tau p}$ and T_{ap} it can be seen that

$$\bigcup_{p\in S} (T_{\tau p} \cup T_{ap}) = T,$$

and also, their pairwise intersection is empty.

The family of sets $T^*_{\tau p}$ can be iteratively constructed with:

$$\begin{aligned} T^0_{\tau p} &= T_{\tau p} \cup \{(p,\tau,p)\}, \\ T^i_{\tau p} &= T^{i-1}_{\tau p} \cup \left\{(p,\tau,r) \mid (\exists q \in S)\,(p,\tau,q) \in T^{i-1}_{\tau p} \wedge (q,\tau,r) \in T_{\tau q}\right\}, \text{and} \\ T^*_{\tau p} &= T^n_{\tau p} \end{aligned}$$

(Note: $\left|T^*_{\tau p}\right| \leq |S| = n$; when for some $k < n$, $T^k_{\tau p} = T^{k+1}_{\tau p}$, then $T^*_{\tau p} = T^k_{\tau p} = T^n_{\tau p}$)

With this step a reflexive, transitive closure is constructed:

$$T^*_\tau = \bigcup_{p\in A} T^*_{\tau p} = \left\{(p,\tau,q) \mid p \left(\overset{\tau}{\to}\right)^* q\right\}$$

The next step is to construct:

$$T'_{ap} = \bigcup_{p\in A} T'_{ap} = \left\{(p,a,q) \mid (\exists q' \in S)\,(p,a,q') \in T \wedge q' \left(\overset{\tau}{\to}\right)^* q\right\} : \qquad (3)$$

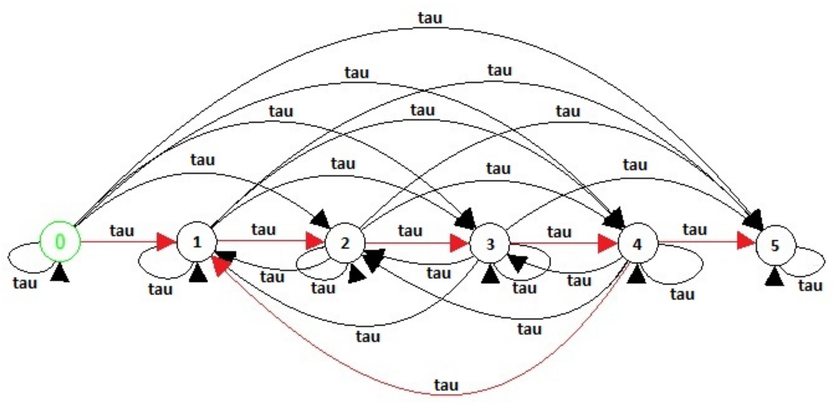

Fig. 4. Reflexive, transitive closure of τ. The original graph is depicted with red lines

$T_{ap}^{0} = T_{ap'}$,
$T_{ap}^{i} = T_{ap}^{i-1} \cup \left\{ (p,a,r) \mid (\exists q \in S)\,(p,a,q) \in T_{ap}^{i-1} \wedge (q,\tau,r) \in T_{\tau q}^{i-1} \right\}$ and
$T'_{ap} = T_{ap}^{n|Act|}$

(Note: $|T'_{ap}| \leq |S||Act| = n|Act|$, when for some $k < n|Act|$, $T_{ap}^{k} = T_{ap}^{k+1}$, then $T'_{ap} = T_{ap}^{k} = T_{ap}^{n|Act|}$)

For the third step,

$$T' = \bigcup_{p \in S} \left(T_{\tau p}^{*} \cup T'_{ap} \right)$$

needs to be partitioned again, defined by the destination in the triple:

$$T_{\tau q} = \{ (p,\tau,q) \mid (p,\tau,q) \in T' \}\text{, and}$$
$$T_{bq} = \{ (p,a,q) \mid a \neq \tau \wedge (p,a,q) \in T' \}$$

for every $p \in S$, and then construct:

$T_{bq}^{0} = T_{bq}$,
$T_{bq}^{i} = T_{bq}^{i-1} \cup \left\{ (p',a,q) \mid (\exists p \in S)\,(p,a,q) \in T_{bq}^{i-1} \wedge (p',\tau,p) \in T_{\tau p}^{*} \right\}$ and
$T_{bq}^{*} = T_{bq}^{n|Act|}$

Finally the saturated labeled transition system is:

$$T^{*} = \bigcup_{p \in S} \left(T_{\tau p}^{*} \cup T_{bp}^{*} \right) = \left(\xrightarrow{\tau} \right)^{*} \cup \left\{ (p,a,q) \mid a \neq \tau \wedge (\exists p', q' \in A)\, p \left(\xrightarrow{\tau} \right)^{*} p' \xrightarrow{a} q' \left(\xrightarrow{\tau} \right)^{*} q \right\}$$

Having computed the observational equivalence (weak bisimilarity) of the original labeled transition system, the process of its minimization is the same as the process for minimization modulo strong bisimilarity applied on the saturated labeled transition system.

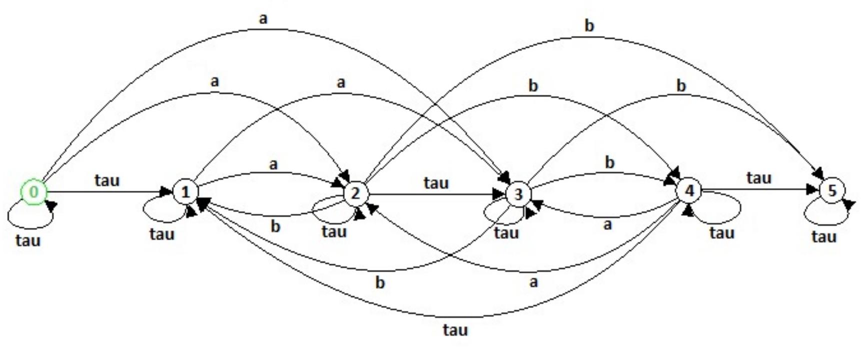

Fig. 5. Example saturated labeled transition system graph

4.3 Comparison of two labeled transition systems modulo strong bisimilarity

The idea for the implementation of the equivalence checking of two labeled transition systems modulo strong bisimilarity was based on the following fact: Two labelled transition systems are (strongly) bisimilar iff their initial states are bisimilar [23].

That means that in order to check whether two labeled transition systems are bisimilar it is enough to check whether their initial states are bisimilar. This can be done using the following approach:

1. The two labeled transition systems are merged into a single transition system
2. An algorithm for computing the strong bisimilarity is applied to the merged system
3. A check is performed to see if the initial states belong to the same bisimulation equivalence class

The correctness of the implementation was tested with the use of ltsconvert and ltscompare tools of mCRL2 [15].

4.4 Comparison of two labeled transition systems modulo weak bisimilarity

The comparison of two labeled transition systems modulo weak bisimilariy amounts to checking strong bisimilarity over the saturated labeled transition systems [5]. In another words, two labeled transition systems are weakly bisimilar iff their saturated labeled transition systems are strongly bisimilar. Following this fact, we implemented the comparison of two labeled transition systems modulo weak bisimilarity by applying the saturation algorithm over the original labeled graphs in order to obtain their saturated labeled graphs, after which the process of comparison of the saturated labeled transition systems modulo strong bisimilarity was applied as described above.

5 Hennessy-Milner logic and implementation of the 'strong until' and 'weak until' operators

Henessy-Milner logic [10] is a multimodal logic used to characterize the properties of a system which describe some aspects of the system's behaviour. Its syntax is defined by the following BNF grammar [23]:

$$\phi ::= tt \mid ff \mid \neg\phi \mid \phi \wedge \phi \mid \phi \vee \phi \mid \langle a \rangle\, \phi \mid \ [a]\, \phi \tag{4}$$

A single Hennessy-Milner logic formula can only describe a finite part of the overall behavious of a process. Therefore, the Henessy-Milner logic was extended to allow for recursive definitions by the introduction of two operators: the so called 'strong until' operator U^s and the so called 'weak until' operator U^w. These operators are expressed as follows [5]:

$$\begin{array}{l} F\ U^s\ G \overset{min}{=} G \vee (F \wedge \langle Act\rangle tt \wedge [Act]\, (F\ U^s\ G)) \\ F\ U^w\ G \overset{max}{=} G \vee (F \wedge [Act]\, (F\ U^w\ G)) \end{array} \tag{5}$$

The BNF grammar describing the set of HML formulas with recursion is as follows [31]:

$$\phi ::= tt \mid ff \mid \neg\phi \mid \phi \wedge \phi \mid \phi \vee \phi \mid \langle a \rangle\, \phi \mid \ [a]\, \phi \mid X \mid min\,(X, \phi) \ \mid max\,(X, \phi) \tag{6}$$

where X is a formula variable and $min\,(X, \phi)$ (respectively $max\,(X, \phi)$) stands for the least (respectively largest) solution of the recursion equation $X = \phi$.

5.1 HML parsing

Our implementation of the Hennessy-Milner logic works as follows: For a given HML expression and a labeled transition system, we should get an output whether that expression is valid for the corresponding labeled graph. One HML expression can be made of these set of tokens {"AND", "OR", "UW", "US", "NOT", "[", "]", "⟨", "⟩", "TT", "FF", "(", ")", "{", "}", ","}

The first part of this process is called tokenization. Tokenization is the process of demarcating and possibly classifying sections of a string of input characters. The resulting tokens are then passed on to some other form of processing.

The process can be considered as a sub-task of parsing input. As the tokens are being read they are proceeded to the parser. The parser is a LR top-down parser. This parser is able to recognize a non-deterministic grammar which is essential for the evaluation of the Hennessy-Milner expression. As the parser is reading the tokens, thus in a way we move through the graph and determine if some of the following steps are possible. Every condition is in a way kept on stack and that enables later return to any of the previous conditions. The process is finished when the expression is processed or when it is in a condition from which none of the following actions can be taken over.

5.2 U^w and U^s implementation

The implementation of the U^w and U^s operators was done as follows. First we get the current state which is the state that contains all the nodes that satisfied the previous actions. For example if we have expression

$$\langle a \rangle \langle a \rangle TT \; U^s \; \langle b \rangle TT,$$

then we get all the nodes that we can reach, starting from the start node, with two actions a. When we get to the Until operation, in this case U^s, we take the start state and check if we can make an action b from some node. If we cannot do the action b, then we repeat the process, do action a again and check if can we do action b. This process is being repeated until we come to a state in which we can't do action a from all nodes in that state.

In the end we check the operator's type (strong or weak). If the operator is strong, then only one node in its state is enough. If it is weak, we check if there are no nodes in its new state or if we can get from the starting node to some of its neighbors through the action b.

6 Application

TMACS is still in early development phase and it has the functionality needed to perform modeling, formal specification, and verification of concurrent systems. Here we demonstrate that process of formal specification and verification for two classical problems in the concurrency theory: the Alternating Bit Protocol and the mutual exclusion algorithm of Peterson.

6.1 Alternating Bit Protocol - Modelling, Specification and Verification

The alternating bit protocol is a simple yet effective protocol (usually used as a test case), designed to ensure reliable communication through unreliable transmission mediums, and it is used for managing the retransmission of lost messages [5][29].

Modelling and Specification. The representation of the Alternating Bit Protocol (abbreviated as ABP in the rest of the section) consists of a *sender* S, a *receiver* R and two channels *transport* T and *acknowledge* A as shown below.

The only visible transitions in the ABP are *deliver* and *accept*, which can occur only sequentially, whereas all others are internal synchronizations. Sender S sends a message to a receiver R. Each message sent by S contains the protocol bit, 0 or 1. Channel from S to R is initialized and there are no messages in transit. There is no direct communication between the sender S and the receiver R, and all messages must travel trough the medium (*transport* and *acknowledge* channel).

The functioning of ABP can be described as follows [5]:

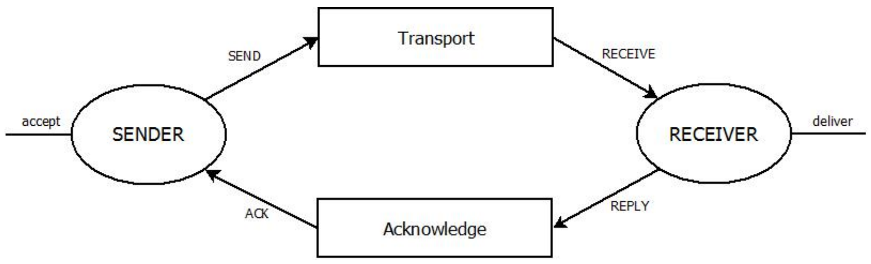

Fig. 6. Alternating Bit Protocol

1. When a sender S sends a message, it sends it repeatedly (with its corresponding bit) until it receives an acknowledgment ($ack0$ or $ack1$) from the receiver R that contains the same protocol bit as the message being sent. Therefore, the behaviour of the process representing the sender can be described as:

$$\begin{aligned} S &= \overline{send0}.S + ack0.accept.S_1 + ack1.S \\ S_1 &= \overline{send1}.S_1 + ack1.accept.S + ack0.S_1 \end{aligned}$$

   The transport channel transmits the message to the receiver, but it may lose the message (lossy channel) or transmit it several times (chatty channel). Therefore, the description of the behaviour of the process representing the transport channel is given with the CCS expression:

$$\begin{aligned} T &= send0.\,(T + T_1) + send1.\,(T + T_2) \\ T_1 &= \overline{receive0}.\,(T + T_1) \\ T_2 &= \overline{receive1}.\,(T + T_2) \end{aligned}$$

2. When R receives a message, it sends a reply to S that includes the protocol bit of the message received. When then receiver will receive the message for the first time, it will deliver it for processing, while subsequent messages with the same bit will be simply acknowledged. That yields the following CCS expression for the receiver:

$$\begin{aligned} R &= receive0.\overline{deliver}.R_1 + \overline{reply1}.R + receive1.R \\ R_1 &= receive1.\overline{deliver}.R + \overline{reply0}.R_1 + receive0.R_1 \end{aligned}$$

   Again, the acknowledgement channel sends the ack to sender, and it can also acknowledge it several times or lose it on the way to the sender. Therefore the CCS expression describing the ackowledgement channel and its behaviour is given as follows:

$$\begin{aligned} A &= reply0.\,(A + A_1) + reply1.\,(A + A_2) \\ A_1 &= \overline{ack0}.\,(A + A_1) \\ A_2 &= \overline{ack1}.\,(A + A_2) \end{aligned}$$

3. When S receives an acknowledgment containing the same bit as the message it is currently transmitting, it stops transmitting that message, flips the protocol bit, and repeats the protocol for the next message.[29][30]

Having described the behaviour of the ABP components, the CCS process term describing the behaviour of the protocol as a whole can be obtained as a parallel composition of the processes describing the sender, the transport channel, the receiver and the acknowledgement channel, restricted on the set of actions:

$$L = (send0, send1, receive0, receive1, reply0, reply1, ack0, ack1)$$

Therefore, the CCS implementation of the Alternating Bit Protocol is given as:

$$ABP \overset{def}{=} (S|T|R|A)\setminus L \tag{7}$$

On the other hand, ABP should act as a simple buffer, therefore its CCS specification is defined as follows:

$$\begin{aligned} Buf &= accept.Buf' \\ Buf' &= \overline{deliver}.Buf \end{aligned} \tag{8}$$

Verification. In order to verify the Alternating Bit Protocol, we need to prove that the implementation meets the specification with respect to some behavioural equivalence. We will show that an observational equivalence between *Buf* and *ABP* can be found, i.e. that $ABP \approx Imp$. For that purpose, first we use our tool to obtain the labelled graphs corresponding to the CCS representations of *Buf* and *ABP*, and afterwards we perform a comparison of the labeled transition systems modulo weak bisimilarity which yields a positive answer about the existance of weak bisimulation equivalence between *Buf* and *ABP*.

The weak bisimulation equivalence obtained by running any of the two bisimulation algorithms implemented in our tool over the saturated labeled transition systems is given in Table 2:

6.2 Peterson's algorithm - Modeling, Specification and Testing

Peterson's algorithm [22] is a simple algorithm designed to ensure mutual exclusion between two processes without any special hardware support. It represents a simple refinement of ideas from earlier mutex algorithms such as Dekker's algorithm [32]. Mutual exclusion (often abbreviated as mutex) algorithms are used in concurrent programming to avoid the simultaneous use of a common resource by critical sections. A critical section is a piece of code in which a process or thread accesses a shared resource.

Modeling and Specification. In Peterson's algorithm for mutual exclusion, there are [5]:

- Two processes P_1 and P_2 that want to access the same resource, i.e. enter the critical section;
- Two shared variables b_1 and b_2 which indicate whether process P_1 and process P_2 are trying to enter the critical section;

ABP implementation states	ABP specification states
$(S\|T\|R\|A)\setminus L$	
$(S\|(T+T1)\|R\|A)\setminus L$	
$(S\|(T+T1)\|R\|(A+A2))\setminus L$	
$(S\|T\|R\|(A+A2))\setminus L$	
$\left(S\|(T+T1)\|\overline{deliver}.R1\|A\right)\setminus L$	
$\left(S\|(T+T1)\|\overline{deliver}.R1\|(A+A2)\right)\setminus L$	
$(S1\|(T+T1)\|R1\|(A+A1))\setminus L$	
$\left(S1\|(T+T2)\|\overline{deliver}.R\|(A+A1)\right)\setminus L$	
$(S1\|(T+T2)\|R1\|(A+A1))\setminus L$	
$(S\|(T+T2)\|R\|(A+A2))\setminus L$	Buf
$(accept.S1\|(T+T1)\|R1\|(A+A1))\setminus L$	
$(S\|(T+T1)\|R1\|(A+A1))\setminus L$	
$(S\|(T+T1)\|R1\|(A+A2))\setminus L$	
$(S\|(T+T1)\|R1\|A)\setminus L$	
$(S1\|(T+T2)\|R\|(A+A2))\setminus L$	
$(accept.S\|(T+T2)\|R\|(A+A2))\setminus L$	
$(S1\|(T+T2)\|R\|(A+A1))\setminus L$	Buf'

Table 2. Verification of Alternating Bit Protocol using weak bisimilarity (observational equivalence)

– A shared integer variable k that can take one of the values 1 or 2 and indicates which process is next to enter the critical section;

The boolean variables b_1 and b_2 are initialized to values $false$ because neither of the processes is interested yet to enter the critical section, whereas the initial value of k is arbitrary.

In order to ensure mutual exclusion, each process P_i, $i \in \{1,2\}$, executes the following algorithm presented in pseudocode, where j denotes the index of the other process.

Algorithm 1 Peterson's algorithm pseudocode

```
while $true$ do
  ⟨noncritical section⟩;
  $b_i \leftarrow true$;
  $k \leftarrow j$;
  while ($b_j$ and $k = j$) do
    skip;
  end while
  ⟨criticalsection⟩;
  $b_i \leftarrow false$;
end while
```

Modeling the algorithm of Peterson includes, among other tasks, translation of the algorithm's pseudocode description of the behaviour of the processes P_1 and P_2 into the model of CCS or labeled transition systems.

Following the message-passing paradigm on which CCS is based, the variables manipulated by the processes P_1 and P_2 are viewed as passive agents that react to actions performed by the processes. The description of the variables used in Peterson's algorithm as processes can be done as follows [5]:

1. The process representing the shared boolean variable b_1 has two states and its behaviour can be represented by the following CCS expressions:

$$\begin{gathered} B1f = \overline{b1rf}.B1f + b1wf.B1f + b1wt.B1t \\ B1t = \overline{b1rt}.B1t + b1wf.B1f + b1wt.B1t \end{gathered}$$

   Similarly for the process describing the behaviour of the variable b_2:

$$\begin{gathered} B2f = \overline{b2rf}.B2f + b2wf.B2f + b2wt.B2t \\ B2t = \overline{b2rt}.B2t + b2wf.B2f + b2wt.B2t, \end{gathered}$$

   where the pattern for the channel name is $b < i >< x >< y >$, with
   – $i \in \{1, 2\}$ for the process ID
   – $x \in \{r, w\}$ for the type of operation (read or write)
   – $y \in \{f, t\}$ for the variable value to be written or read (false or true)
2. The process representing the variable k has two states, denoted by the constants K_1 and K_2, because the variable k can only take one of the two values 1 and 2, and its CCS representation is as follows

$$\begin{gathered} K1 = \overline{kr1}.K1 + kw1.K1 + kw2.K2 \\ K2 = \overline{kr2}.K2 + kw2.K2 + kw2.K2, \end{gathered}$$

   where the pattern for the channel name is $k < x >< n >$, with
   – $x \in \{r, w\}$ for the type of operation (read or write)
   – $n \in \{1, 2\}$ for the value to be written or read

The final step is the CCS formalisation of the behaviour of the processes P_1 and P_2. The process behaviour outside of the critical region can be ignored and the focus can be put on the process entering and exiting the critical section. For simplicity, an assumption is made that the processes cannot fail or terminate within the critical section. Under these assumptions, the initial behaviour of the process P_1 can be described by the following CCS expression:

$$P1 = \overline{b1wt}.\overline{kw2}.P11,$$

where $P11$ models the while loop (with short-circuit evaluation):

$$P11 = b2rf.P12 + b2rt.\,(kr2.P11 + kr1.P12)$$

and $P12$ models the critical section:

$$P12 = enter1.exit1.\overline{b1wf}.P1$$

The behaviour of the process P_2 can be described with CCS expressions in the similar manner:

$$\begin{aligned}
&P2 = \overline{b2wt}.\overline{kw1}.P21\\
&P21 = b1rf.P22 + b1rt.\,(kr1.P21 + kr2.P22)\\
&P22 = enter2.exit2.\overline{b2wf}.P2
\end{aligned}$$

Finally, the CCS process term representing the whole Peterson's algorithm consists of the parallel composition of the terms describing the two processing running the algorithm and of those describing the variables. Since we are only interested in the behaviour of the algorithm pertaining to the access to, and exit from, their critical sections, we shall restrict all the communication channels that are used to read from, and write to, the variables. That set of restricted channel names is

$$L = \{b1rf, b1rt, b1wf, b1wt, b2rf, b2rt, b2wf, b2wt, kr1, kw1, kr2, kw2\}$$

Assuming that the initial value of the variable k is 1, our CCS description of Petersons algorithm is therefore given by the term:

$$PETERSON \overset{def}{=} (B1f|B2f|K1|P1|P2)\setminus L \tag{9}$$

On the other hand, the desired behaviour of the Peterson's algorithm is as the one of any simple mutex algorithm. Initially, both processes enter their critical sections, however once one of the processes has entered its critical section, the other process cannot enter its own critical section until the first process has exited its critical section. Therefore, a suitable CCS specification of the behaviour of a mutual exclusion algorithm like Peterson's is given as follows:

$$MutexSpec = enter1.exit1.MutexSpec + enter2.exit2.MutexSpec \tag{10}$$

Testing. Testing the preservation of the mutual exclusion property is one of the approaches that can be used to establish the correctness of the Peterson's algorithm. A test is a finite rooted labeled transition system over the set of actions $Act \cup \left\{\overline{bad}\right\}$, where bad is a distinguished channel name not occurring in Act. The idea is that the test would act as a monitor process that 'observes' the behaviour of a process and reports an error in case of an occurrence of an undesirable situation by performing a *bad*-labelled transition. Assuming that the monitor process outputs 'bad' when it discovers that two enter actions have occurred without intervening exit, a CCS process describing this behaviour is [5]:

$$\begin{aligned}
&MutexTest = \overline{enter1}.MutexTest1 + \overline{enter2}.MutexTest2\\
&MutexTest1 = \overline{exit1}.MutexTest + \overline{enter2}.\overline{bad}.0\\
&MutexTest2 = \overline{exit2}.MutexTest + \overline{exit1}.\overline{bad}.0
\end{aligned}$$

Now, in order to check whether process $PETERSON$ ensures mutual exclusion, it is now sufficient to let it interact with $MutexTest$ and see if the resulting system

$$(PETERSON|MutexTest)\setminus M, \tag{11}$$

where

$$\{enter1, enter2, exit1, exit2\},$$

can initially perform the action $\overline{bad}$.

Indeed, the labeled transition system of the above CCS expression generated by our tool does not have states which afford *bad* transitions. This proves that Peterson's algorithm ensures mutual exclusion.

7 Conclusions and Future Work

In this paper we presented a tool for modeling, manipulation and analysis of concurrent systems. It includes recognizing CCS expressions, building labeled transition system graphs and checking equivalence between two labeled graphs with respect to strong and weak bisimilarity. The tool is very simple, but yet functional enough to perform specification and verification of concurrent systems described as CCS expressions and/or labeled transition systems graphs. We have successfully tested the tool with large number of examples comparing the results obtained with mCRL2 and CWB, and we also presented few examples showing the tool usage.

Future work can include optimization of the tool response times for very large labeled transition system graphs, as well as implementation of prunung strategy for infinite labeled transition system graphs. It would be also usefull if the labeled graph is better visualized where every SOS rule is shown, with its source and sink nodes showing the CCS expression for each of the nodes. Such a visualization can be very helpfull for understanding the semantics of the CCS language for students that are starting to study it. Furthermore, the minimization and comparison functionality for labeled transition systems which at the moment includes only strong and weak bisimilarity can be extended to include other behavioural equivalences as well. Another direction for future development can be to extend the tool to support not only CCS expressions, but variety of other process semantics as well.

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References

1. R. Milner, *A Calculus of Communicating Systems*, Lecture Notes in Computer Science, vol. 92, Springer-Verlag, 1980
2. R. Milner, *Communication and Concurrency*, Prentice-Hall, 1989
3. J.A. Bergstra, A. Ponse, S.A. Smolka, *Handbook of Process Algebra*, Elsevier Science B.V., 2001

4. R.M. Keller, *Formal Verification of Parallel Programs*, Communications of the ACM, 19(7), pp. 371-384, 1976
5. L. Aceto, A. Ingolfsdottir, K. G. Larsen, J. Srba, *Reactive Systems - Modeling, Specification and Verification*, Cambridge University Press, 2007
6. D.M.R. Park, *Concurrency and Automata on Infinite Sequences*, In: Proceedings of the 5th G.I.Conference in Theoretical Computer Science, Lecture Notes in Computer Science, vol. 104, Springer-Verlag, pp. 167-183, 1981
7. A.W. Roscoe, *Understanding Concurrent Systems*, Texts in Computer Science, Springer-Verlag, 2010
8. R. Milner, *Operational and Algebraic Semantics of Concurrency Processes*, In: J. van Leeuwen (ed.) Handbook of Theoretical Computer Science, pp. 1201-1242, Elsevier and MIT Press, 1990
9. C. Baier, J.-P. Katoen, *Principles of Model Checking*, The MIT Press, 2008
10. M.C.B. Hennessy, R. Milner, *Algebraic Laws for Nondeterminism and Concurrency*, Journal of the ACM, 32(1), pp. 137-161, 1985
11. K.G. Larsen, *Proof Systems for satisfiability in HennessyMilner logic with recursion*, Theoretical Computer Sciece, 72(2-3), Special Issue, pp. 265288, 1990
12. The Java tutorials, *Packaging Programs in JAR Files*, `http://download.oracle.com/javase/tutorial/deployment/jar/index.html`
13. CADP manual, *Aldebaran format for Labeled Transition Systems*, `http://www.inrialpes.fr/vasy/cadp/man/aldebaran.html#sect6`
14. *The Edinburgh Concurrency Workbench (CWB)*, `http://homepages.inf.ed.ac.uk/perdita/cwb/summary.html`
15. *micro Common Representation Language 2 (mCRL2)*, `http://www.mcrl2.org`
16. *The Mobility Workbench (MWB)*, `http://www.it.uu.se/research/group/mobility/mwb`
17. *Construction and Analysis of Distributed Processes (CADP)*, `http://www.inrialpes.fr/vasy/cadp.html`
18. *Labelled Transition System Analyser (LTSA)*, `http://www.doc.ic.ac.uk/ltsa/`
19. J.-C. Fernandez, *An Implementation of an Efficient Algorithm for Bisimulation Equivalence*, Science of Computer Programming, vol. 13, pages 219-236, 1989/1990
20. W.C. Lynch, *Computer systems: Reliable full-duplex file transmission over half-duplex telephone line*, Communications of the ACM, vol. 11, no. 6, pp. 407410, 1968
21. K.A. Bartlett, R.A. Scantlebury, P.T. Wilkinson, *A note on Reliable Full-duplex Transmission over Half-duplex Links*, Communications of the ACM, vol. 12, pp. 260261, 1969
22. G.L. Peterson, *Myths about the Mutual Exclusion Problem*, Information Processing Letters, 12(3), pages 115-116, 1981
23. J.F. Groote, M. Reniers, *Modelling and Analysis of Communicating Systems,* Technical University of Eindhoven, rev. 1478, 2009
24. N. Chomsky, *Three Models for the Description of Language*, IEEE Transactions on Information Theory, 1956
25. A.V. Aho, R. Sethi, J.D. Ullman, *Compilers: Principles, Techniques, and Tools* Addison Wesley, 2006
26. T. Parr, *The Definitive ANTLR Reference - Building Domain-Specific Languages*, The Pragmatic Bookshelf, 2007
27. R. Paige, R. Tarjan, *Three Partition Refinement Algorithms,* SIAM J. Comput. 16 (6), 1987
28. A. Dovier, C. Piazza, A. Policriti, *An Efficient Algorithm for Computing Bisimulation Equivalence,* Theoretical Computer Science 311, pages 221-256, 2004

29. Seth Kulick, *Process Algebra, CCS, and Bisimulation Decidability*, University of Pennsylvania, pages 8-10, 1994
30. M.Alexander, W.Gardner, *Process Algebra for Parallel and Distributed Processing*, Chapman&Hall/CRC Press, Computational Science Series, pages 114-118, 2009
31. L. Aceto, A. Ingolfsdottir, *Testing Henessy-Milner logic with Recursion*, BRICS Report Series, pages 3-5, 1998
32. E. W. Dijkstra, *Co-operating Sequential Processes*, In F. Genuys, editor, Programming Languages, pages 43112. Academic Press, New York, 1968 Reprinted from: Technical Report EWD-123, Technological University, Eindhoven, the Netherlands, 1965

Appendix A: Comparison and Analysis of the bisimulation equivalence algorithms

There is no official set of benchmarks for testing algorithms for computing bisimulation equivalence [28]. And it is also very difficult to randomly generate labeled transition systems suitable for proper testing of bisimulation equivalence. Therefore, we used the academical examples from mCRL2 as experimental test models.

The experiments were conducted on a portable computer with the following specifications:

1. CPU: Intel Pentium P6100 2.0 GHz
2. Memory: 3 GB
3. OS: Windows 2007 Premium

Each of the experiments carried out on our Java implementations of the two algorithms for computing bisimulation equivalence consisted of 10 repeated runs of each of the algorithms on each of the aldebaran test files and measuring the average running time in miliseconds. The results from these experiments are presented in Table 3. The table includes the running times in miliseconds and the absolute error in miliseconds for both of the algorithms, the number of pairs of bisimilar states obtained with the naive algorithm (excluding the reflexive and symmetric pairs) and the number of classes of bisimulation equivalence obtained with the algorithm due to Fernandez (excluding the one-element classes), as well as the ratio of the running time of the naive algorithm with respect to the running time of Fernandez's algorithm.

The results from the experiments carried out are presented graphically in Fig. 7 and Fig. 8 for the naive algorithm and the algorithm of Fernandez, respectively.

It can be seen that for all test models, with the exception of the first one, the running time of the naive algorithm is proportional to the number of states, the number of transitions and the number of resulting bisimilar pairs. However, we need to note that this is not a general conclusion and that in general the running time of the naive algorithm for computing bisimulation equivalence depends on the nature of the monotonic function used by this algorithm, which is strongly

			Naive		Fernandez				Ratio
aut	states	transitions	$t(ms)$	$\Delta t(ms)$	$t(ms)$	$\Delta t(ms)$	bisimilar pairs	bisimilar classes	t_n/t_f
dining3	93	431	16.8	0.8	250	2	1	2	0.067
abpbw	97	122	287.9	0.94	173.3	5.22	32	27	1.661
abp	74	92	162.2	1.44	69.6	3.92	6	6	2.33
scheduler	13	19	17.4	1.18	4.4	0.96	1	1	3.95
mpsu	52	150	215.4	1.16	27.5	0.5	4	4	7.83
trains	32	52	64.5	7.3	7.6	1.76	6	6	8.48
par	94	121	5909.4	22.68	28.5	0.7	170	27	207.34
leader	392	1128	/	/	841.5	41.5	/	20	/
tree	1025	1024	/	/	1858.1	55.16	/	8	/
cabp	672	2352	/	/	16184.3	198.94	/	90	/

Table 3. Results of the comperisons

related with the form of the labeled transition system. As an example, dining3 is a labeled transition system that has big number of transitions, however in this test model the algorithm determines that the monotony condition is not fulfilled in the second development of the monotonic function and therefore the algorithm stops there.

Similar conclusions can be drawn for the algorithm due to Fernandez. Its running time is also proportional to the number of transitions, number of states and the number of bisimilar classes.

The comparison of running times of the two algorithms obtained with the experiment is shown in Fig. 9. As it can be clearly seen the algorithm of Fernandez is few times faster than the naive algorithm. The biggest difference can be noticed for the example par.aut where the ratio of the running times is 207.34. An exception is only the example dining3.aut for which the naive algorithm performs faster due to the reasons described earlier. The ration of the running times in this case is 0.0067. Fig. 10 shows the ratios of the running times of the two algorithms for each of the examples.

Appendix B: CCS grammar

One of the few standard ways of showing a grammar is a syntax diagram. On Fig. 11 we show the syntax diagram for the grammar that recognizes CCS expressions and is used in our tool.

Appendix C: HML grammar

The grammar that recognizes HML expressions and is used in our tool is given below.

1. $HML \Rightarrow$ Term Expression

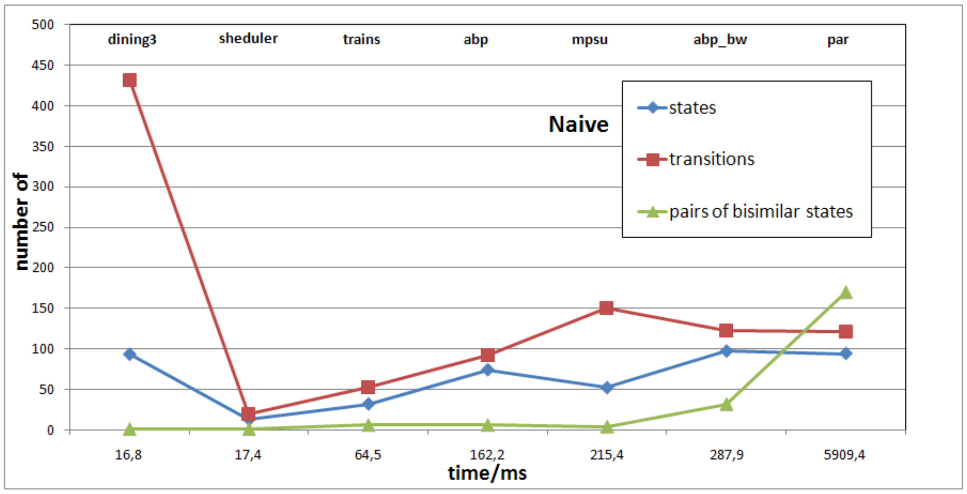


Fig. 7. Analysis of the running time of the naive bisimulation algorithm

2. Expression ⇒ AND Term Expression
3. Expression ⇒ OR Term Expression
4. Expression ⇒ Uw Term Expression
5. Expression ⇒ Us Term Expression
6. Expression ⇒ λ
7. Term ⇒ NOT Term
8. Term ⇒ [Actions] Term
9. Term ⇒ ⟨ Actions ⟩ Term
10. Term ⇒ TT
11. Term ⇒ FF
12. Term ⇒ (HML)
13. Actions ⇒ Action
14. Actions ⇒ Action ActionsList
15. ActionsList ⇒ Action ActionsList
16. ActionsList ⇒ λ
17. Action ⇒ Literal Name
18. Name ⇒ Literal
19. Name ⇒ Number
20. Name ⇒ λ
21. Literal ⇒ $a \mid b \mid c \mid d \mid e \mid f \mid g \mid h \mid i \mid j \mid k \mid l \mid m \mid n \mid o \mid p \mid q \mid r \mid s \mid t \mid u \mid v \mid w \mid x \mid y \mid z$
22. Number ⇒ 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9

Appendix D: Tool Usage

In this section we present how to use the tool to show that the specification and implementation of the ABP are weakly bisimiliar. As a first step we always

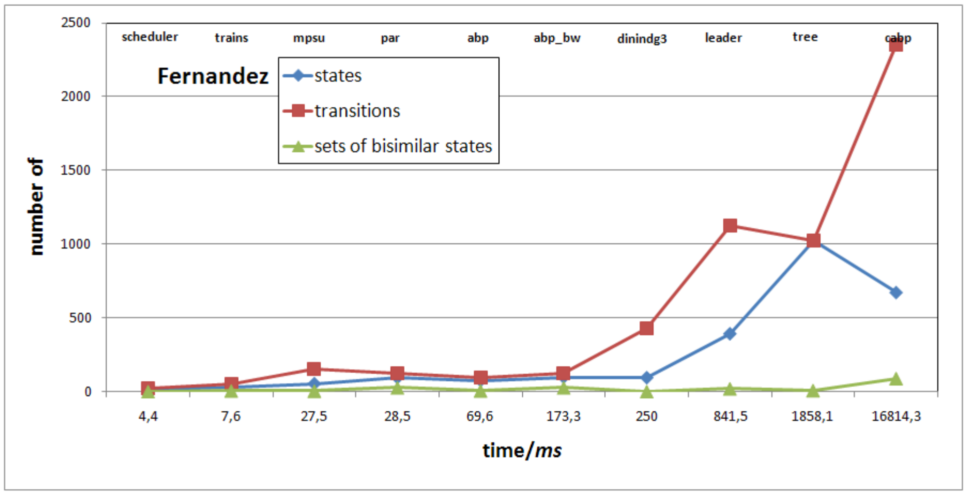


Fig. 8. Analysis of the running time of the bisimulation algorithm due to Fernandez

need to generate the labeled transition systems from both the specification and implementation of the system that we are trying to model. That can be done in the tab ”CCS to LTS” in the tool. As shown in Fig. 12 in the upper text area we need to write down the CCS expressions that describe the system or load them from a file. One constraint here is that a general CCS expression that describes the whole system has to be put on the first line. The algorithm for generating the labeled graph starts evaulation and construction of the graph starting from the first line. When we have our CCS expressions put in place we have to click ”Generate LTS”. This action will make the application parse the expression and if no errors are found will start generating the labeled graph The results from the generated graph will be presented in the lower text area in Aldebaran format. The users can save the results in a file or can click ”View LTS Graph” which causes the tool to display a computer generated image of the labeled graph.

Reduction of the state space of a labeled transition system can be done in the ”LTS minimization” tab. The minimization is pretty straigthforward process. As shown in Fig. 13 and Fig. 14 the labeled transtion system is loaded from an Aldebaran file, a method of calculation has to be chosen and in order to perform calculation the user has to click the button ”Calculate”.

Checking for labeled transition system bisimilarity is performed in the ”LTS comparison” tab. This tab is similar to the one for the minimization. As shown in Fig. 15 and Fig. 16 two labeled transition systems have to be loaded from Aldebaran files. In order to perform comparison of the two labeled transition systems with respect to strong or weak bisimulation equivalence, the user has to choose a method for calculation and click on the button ”Calculate”. The results will be displayed on the right side of the button and they give information

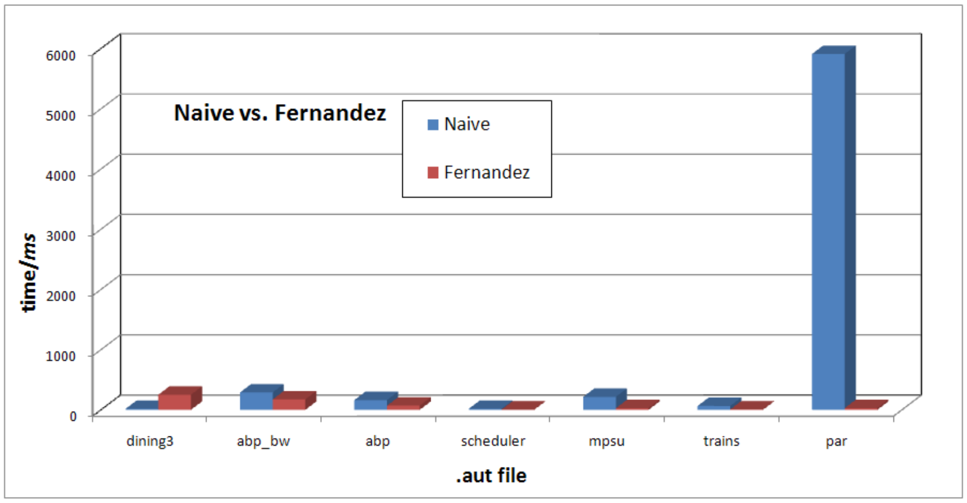


Fig. 9. Comparison of the running time of the two bisimulation algorithms

whether the labeled transition systems are bisimilar and how long the calculation lasted.

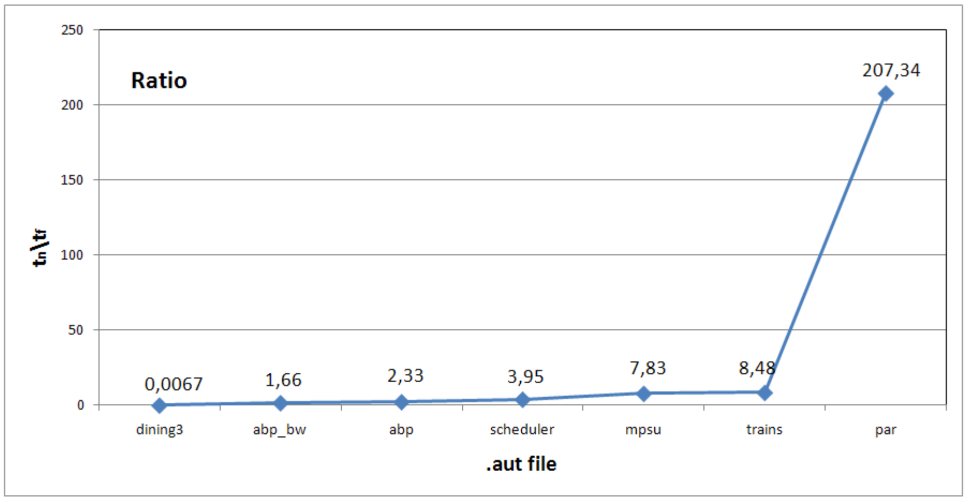


Fig. 10. Ratio of the running times of the two bisimulation algorithms

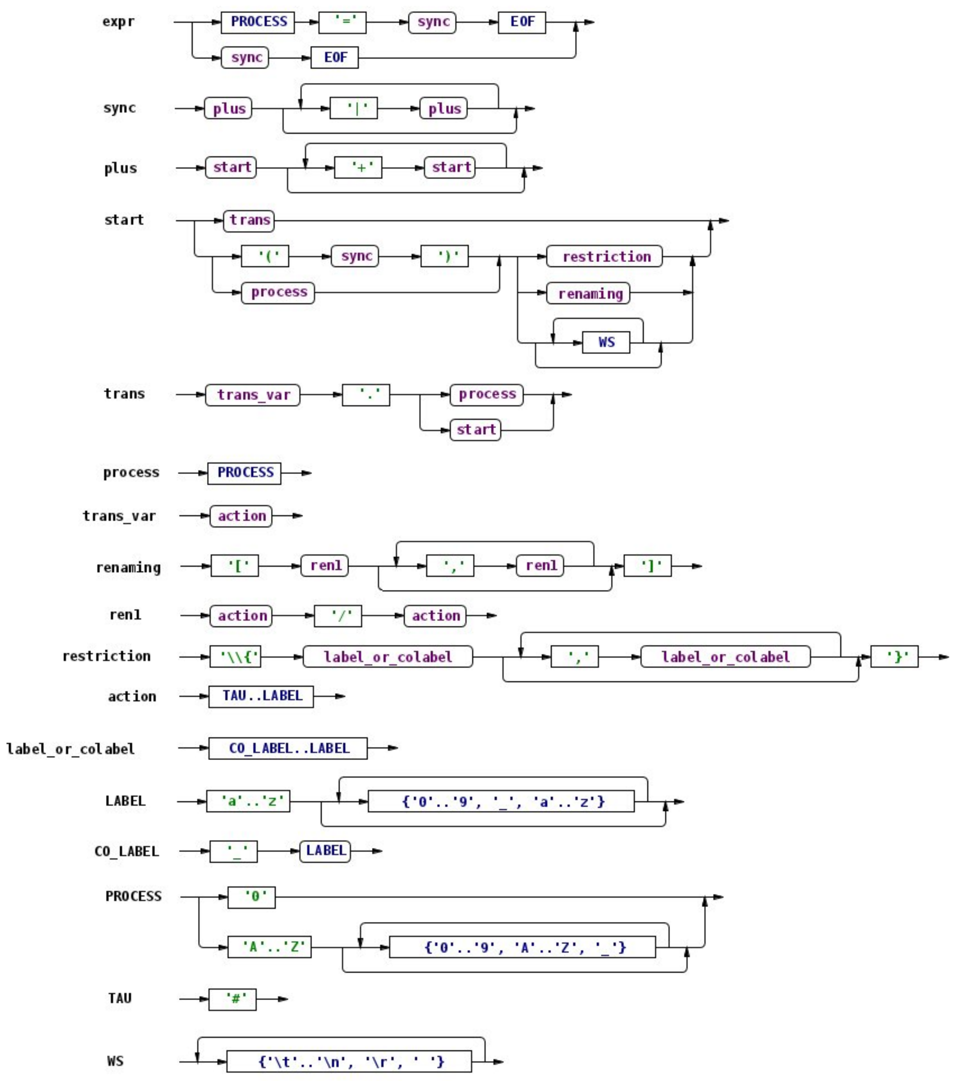
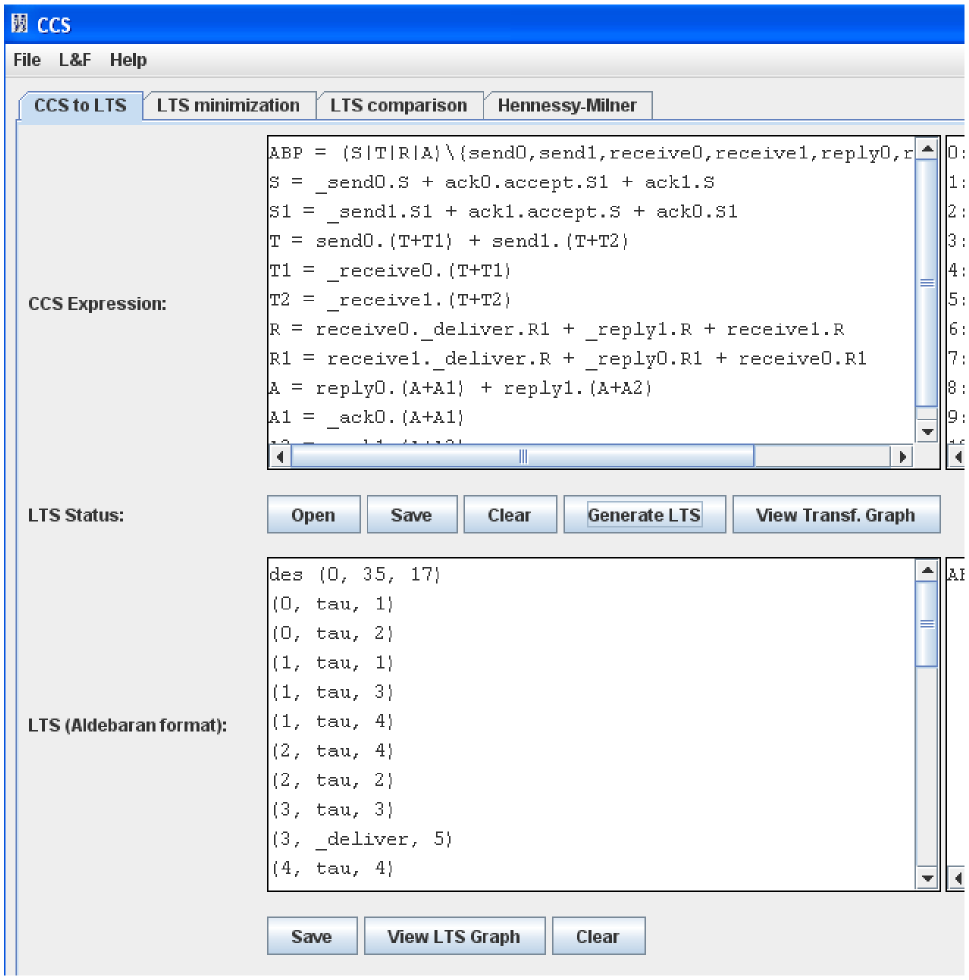


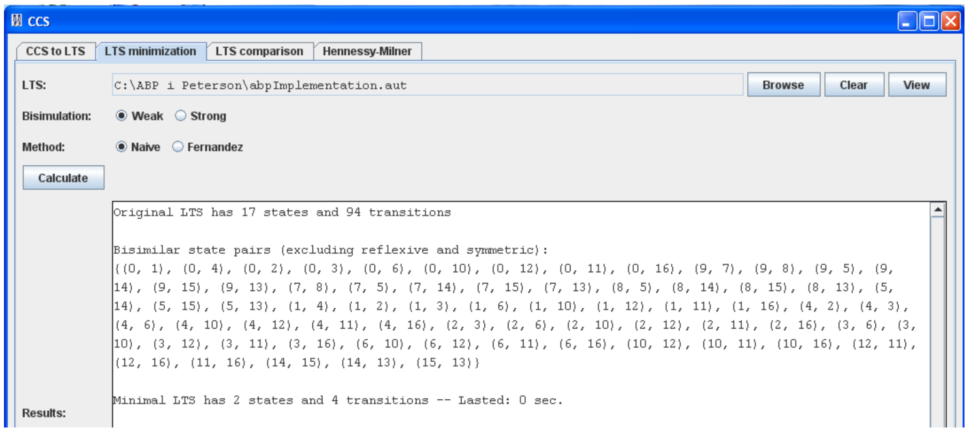
Fig. 11. Syntax diagram for the CCS grammar



```
ABP = (S|T|R|A)\{send0,send1,receive0,receive1,reply0,r
S = _send0.S + ack0.accept.S1 + ack1.S
S1 = _send1.S1 + ack1.accept.S + ack0.S1
T = send0.(T+T1) + send1.(T+T2)
T1 = _receive0.(T+T1)
T2 = _receive1.(T+T2)
R = receive0._deliver.R1 + _reply1.R + receive1.R
R1 = receive1._deliver.R + _reply0.R1 + receive0.R1
A = reply0.(A+A1) + reply1.(A+A2)
A1 = _ack0.(A+A1)
```

```
des (0, 35, 17)
(0, tau, 1)
(0, tau, 2)
(1, tau, 1)
(1, tau, 3)
(1, tau, 4)
(2, tau, 4)
(2, tau, 2)
(3, tau, 3)
(3, _deliver, 5)
(4, tau, 4)
```

Fig. 12. Tool Usage: ABP Modeling and Generating labeled transition system



LTS: C:\ABP i Peterson\abpImplementation.aut

Bisimulation: [✓ Weak] Strong

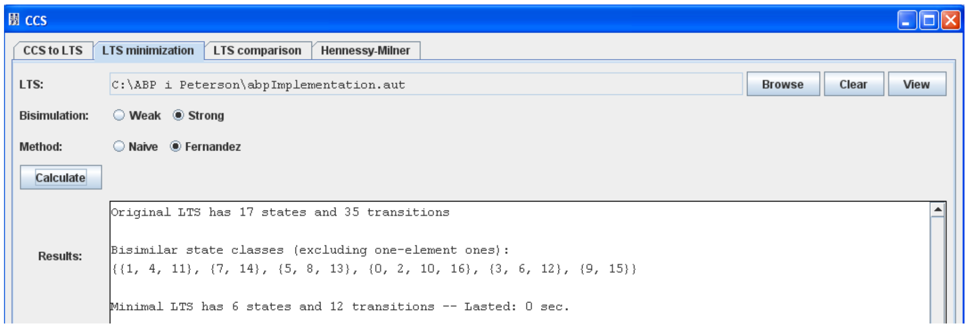
Method: [✓ Naive] Fernandez

```
Original LTS has 17 states and 94 transitions

Bisimilar state pairs (excluding reflexive and symmetric):
{(0, 1), (0, 4), (0, 2), (0, 3), (0, 6), (0, 10), (0, 12), (0, 11), (0, 16), (9, 7), (9, 8), (9, 5), (9,
14), (9, 15), (9, 13), (7, 8), (7, 5), (7, 14), (7, 15), (7, 13), (8, 5), (8, 14), (8, 15), (8, 13), (5,
14), (5, 15), (5, 13), (1, 4), (1, 2), (1, 3), (1, 6), (1, 10), (1, 12), (1, 11), (1, 16), (4, 2), (4, 3),
(4, 6), (4, 10), (4, 12), (4, 11), (4, 16), (2, 3), (2, 6), (2, 10), (2, 12), (2, 11), (2, 16), (3, 6), (3,
10), (3, 12), (3, 11), (3, 16), (6, 10), (6, 12), (6, 11), (6, 16), (10, 12), (10, 11), (10, 16), (12, 11),
(12, 16), (11, 16), (14, 15), (14, 13), (15, 13)}

Minimal LTS has 2 states and 4 transitions -- Lasted: 0 sec.
```

Fig. 13. Tool Usage: ABP Minimization, Weak, Naive



LTS: C:\ABP i Peterson\abpImplementation.aut

Bisimulation: Weak [✓ Strong]

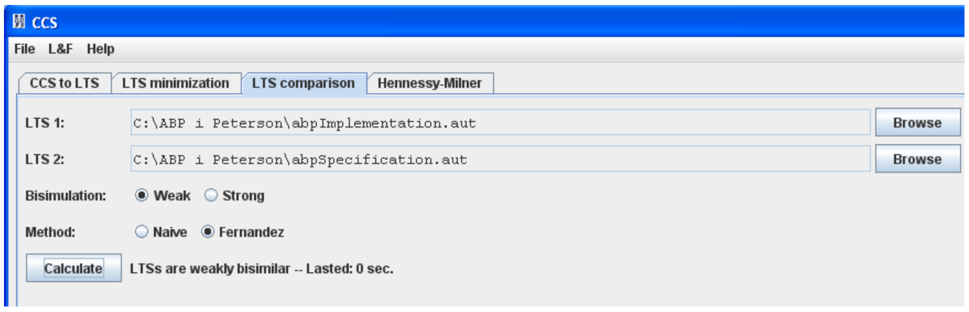
Method: Naive [✓ Fernandez]

```
Original LTS has 17 states and 35 transitions

Bisimilar state classes (excluding one-element ones):
{{1, 4, 11}, {7, 14}, {5, 8, 13}, {0, 2, 10, 16}, {3, 6, 12}, {9, 15}}

Minimal LTS has 6 states and 12 transitions -- Lasted: 0 sec.
```

Fig. 14. Tool Usage: ABP Minimization, Strong, Fernandez



LTS 1: C:\ABP i Peterson\abpImplementation.aut

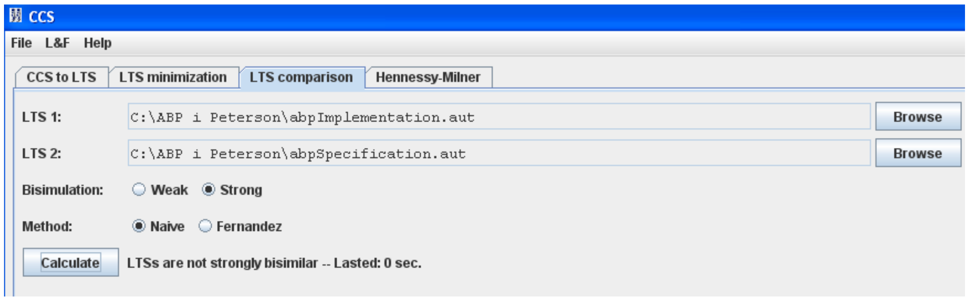
LTS 2: C:\ABP i Peterson\abpSpecification.aut

Bisimulation: [✓ Weak] Strong

Method: Naive [✓ Fernandez]

LTSs are weakly bisimilar -- Lasted: 0 sec.

Fig. 15. Tool Usage: ABP Bisimilarity, Weak, Fernandez



LTS 1: C:\ABP i Peterson\abpImplementation.aut

LTS 2: C:\ABP i Peterson\abpSpecification.aut

Bisimulation: ○ Weak [✓ Strong]

Method: [✓ Naive] ○ Fernandez

LTSs are not strongly bisimilar -- Lasted: 0 sec.

Fig. 16. Tool Usage: ABP Bisimilarity, Strong, Naive