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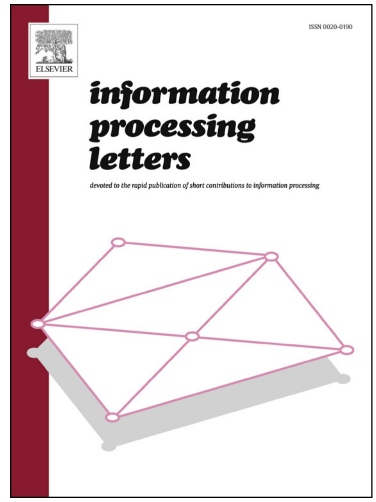

Compositional and Local Livelock Analysis for CSP

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Highlights

- Livelock freedom analysis for CSP can scale using local and compositional techniques.
- The approach avoids the traditional explicit state-space exploration of the system.
- The strategy is based on a local analysis of the shortest event sequences (traces) that represent a recursive behaviour in the CSP model.
- We provide evidence of the efficiency of the proposed approach.

Compositional and Local Livelock Analysis for CSP

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Abstract

The success of component-based techniques for software construction relies on trust in the emergent behaviour of the compositions. Here, we propose an efficient correct-by-construction technique for building livelock-free CSP models. Its verification conditions are based on a local analysis of the shortest event sequences (traces) that represent a recursive behaviour in the CSP model. This affords significant gains in performance in model checking. We evaluate our strategy based on models of the Milner's scheduler and the dining philosophers.

Keywords: Process Algebra, Divergence, Model Checking, Components

1. Introduction

Compositional modelling and verification approaches are popular [4], but rely on trust in the emergent behaviour of the compositions. Process algebras are among the adopted formalisms. CSP [6, 10] is a well established process algebra to model and verify concurrent systems. CSP offers consolidated semantic models that support a wide range of verifications, including livelock freedom. A system is livelock free (divergence free) if there exists no state from which it internally computes through an infinite sequence of internal actions [10].

The main approach to prove divergence freedom requires a global analysis of the system. This strategy is automated for CSP, for instance, by FDR4 [5]. One alternative is a static analysis of the syntactic structure of a process [9]. For that, syntactic rules are proposed either to classify CSP systems as livelock-free or to report an inconclusive result. This approach is implemented in SLAP [9].

We present a technique based on a local analysis, in which we can identify livelock situations when compositions are being performed, predicting, by construction, global property based on known local properties of the components [1]. Our strategy aims at reducing complexity for verifying the absence of divergence, especially comparing with the approach in [9]. We illustrate our technique based on models of the Milner's scheduler and the dining philosophers, and show that it outperforms both FDR4 and SLAP. In cases in which livelock

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freedom is not ensured, we either identify the possibility of divergence or report an inconclusive result. This incompleteness is the trade-off for scalability.

The next section briefly describes our evaluation strategy. Section 3 describes our technique, whose performance is evaluated in Section 4.

2. Material and methods

The demonstration of the usefulness and efficiency of our technique consists of a comparative analysis of three different scenarios: (i) the traditional global analysis of FDR4, (ii) the static livelock-analysis of SLAP, and (iii) our local livelock analysis, which is presented in the next section. We have developed two case studies: the Milner's task scheduler [7], which can be modelled as a ring of cells with pairwise synchronisation, and the dining philosophers [10]. All CSP scripts used in the case studies can be found at goo.gl/mAZWXq. We have used a server with 4 core AMD Phenom II, and 8 GB of RAM in a Ubuntu system.

3. Theory

In CSP, when composing divergence-free processes, divergent behaviour can arise from the use of hiding [10]. For a given CSP process P and a set of events X, the process $P \setminus X$ converts visible occurrences of events of P in X into internal events. This transformation may yield an infinite loop of internal events. For instance, $P = (a \rightarrow P) \setminus \{a\}$ is defined in terms of the prefix operator ($\rightarrow$): it engages in event a and then recurses, but it diverges because the event a is hidden, hence, P indefinitely performs internal events without communicating with its environment. If a process can engage in an unbroken sequence of events from a set X, we must ensure that X cannot be hidden.

The hiding operator is also implicitly used in a particular kind of parallel composition: the *linked parallel composition* $P[a \leftrightarrow b]Q$, in which P and Q proceed in parallel with communications on a in P becoming hidden synchronisations with communications on b in Q. Communications on other channels are interleaved: they do not require synchronisation. In general, multiple channels may be linked as, for example, in $P[a \leftrightarrow b, c \leftrightarrow d]Q$.

We propose a constructive approach which guarantees that, for livelock-free processes that obey certain conditions and are composed pairwise using linked parallel, the resulting composition is livelock-free. To achieve scalability, we perform an optimisation (which we refer in Figure 1 as OP) that prunes the alternative behaviours of the resulting composition with interleaved events, choosing only one of the alternatives.

Our approach is based on three main verifications, which are systematically applied (see Figure 1): the Simple Verification (SV) ensures livelock freedom based on an individual analysis of the processes involved in the composition. The absence of livelock is guaranteed if one of the processes is livelock-free after hiding its linking events locally. If that fails, the Complex Verification (CV) checks if the linked processes are able to communicate in an infinite loop via

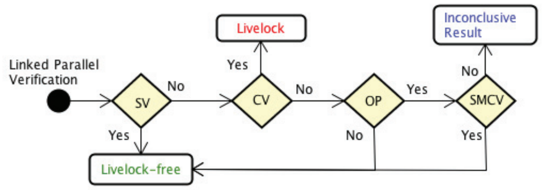

Figure 1: BPM Model of the Livelock Analysis for Linked Parallel Composition

the linked (internal) events. If they are, we have a livelock. Otherwise, if the optimisation (OP) has not been applied, the composition is livelock-free. If, however, the optimisation has been applied, our strategy guarantees livelock freedom only if we have a Safe Multiple Composition ($SMCV$), which does not link events on a many-to-many fashion. Otherwise, the interleaved events pruned by our optimisation may lead the system to divergence. Our strategy is, therefore, inconclusive in such cases. In what follows, we present the basic definitions used in our technique and formally describe these local verifications.

3.1. Basic Definitions

Our method considers developments that use livelock-free basic processes, which can be described using most of the CSP main operators, including conditionals, tail and mutual recursions. We also consider parameters. Further information on basic processes can be found in [3]. Parallelism (and hiding) is achieved by composing processes (either basic or resulting from previous compositions) using the linked parallel composition.

The first step of our technique is to identify the infinite behaviours of a given process. For that, we use a pair (tr, mip) of sequences (traces). Its first element is a trace that leads a given process to a recursive behaviour. The second one is a minimal interaction pattern of a given process, that is, the shortest finite sequence of events that represents the recursion itself. The set $XIP(P)$ contains all possible pairs (tr, mip) of the process P.

To exemplify our method, we introduce a classical concurrent system, the dining philosophers [10]. It consists of philosophers sitting at a round table that need to acquire a pair of shared forks before eating. The behaviour of each philosopher and each fork is modelled as a process P_i or F_i for values i from a set ID of philosopher and fork identifiers. We consider two philosophers and two forks and use $ID = \{1, 2\}$. A channel $fk : ID.ID.EV$, where $EV = \{U, D\}$ defines events $fk.i.j.e$ that indicate that the fork i is put up or down, depending on whether e is U or D, by the philosopher j. The fork processes are as follows.

$$F_1 = fk.1.1.U \rightarrow fk.1.1.D \rightarrow F_1 \;\square\; fk.1.2.U \rightarrow fk.1.2.D \rightarrow F_1$$
$$F_2 = fk.2.2.U \rightarrow fk.2.2.D \rightarrow F_2 \;\square\; fk.2.1.U \rightarrow fk.2.1.D \rightarrow F_2$$

Initially, a fork can be picked up by either philosopher. Once it is picked up, it can only be put down by the same philosopher. Accordingly, the process

F_1 offers a deterministic choice ($\Box$): it engages either on the events $fk.1.1.U$ or $fk.1.2.U$. The prefix operator ($\rightarrow$) states that the corresponding down event (D) is offered afterwards. The process recurses after the down event. Hence, $XIP(F_1) = \{(\langle\rangle, \langle fk.1.1.U, fk.1.1.D\rangle), (\langle\rangle, \langle fk.1.2.U, fk.1.2.D\rangle)\}$. In this example, as F_1 returns to its initial state, tr is the empty trace ($\langle\rangle$).

Similarly, $pfk.j.i.e$ records the action e on fork j by philosopher i. The channel $wk : ID$ defines events $wk.i$, indicating that the philosopher i has just woken up. Finally, the channel $lf : ID.LF$, where $LF = \{T, E\}$ defines events $lf.i.l$, indicating that the philosopher i is either thinking (T) or eating (E).

$$
\begin{aligned}
&P_1 = wk.1 \rightarrow PS_1\\
&PS_1 = lf.1.T \rightarrow pfk.1.1.U \rightarrow pfk.2.1.U \rightarrow lf.1.E \rightarrow pfk.1.1.D \rightarrow\\
&\qquad pfk.2.1.D \rightarrow PS_1\\
&P_2 = wk.2 \rightarrow PS_2\\
&PS_2 = lf.2.T \rightarrow pfk.1.2.U \rightarrow pfk.2.2.U \rightarrow lf.2.E \rightarrow pfk.1.2.D \rightarrow\\
&\qquad pfk.2.2.D \rightarrow PS_2
\end{aligned}
$$

The process P_1 initially performs the event $wk.1$ and then behaves as PS_1, which represents the recursive behaviour of the philosopher: before eating, he thinks and picks the forks up; after eating, he puts the forks down. In this case, $XIP(P_1) = \{(\langle wk.1\rangle, \langle lf.1.T, pfk.1.1.U, pfk.2.1.U, lf.1.E, pfk.1.1.D, pfk.2.1.D\rangle)\}$.

We are now able to calculate which events of a given process can be hidden without introducing livelock. The function $Allowed(P)$ identifies all sets of events that can be individually hidden from P. Here, Σ is the set of all possible events, $MIP(P)$ is the set that contains only the second element of the pairs $(tr,\ mip)$ in $XIP(P)$, and $\operatorname{ran}(s)$ is the set of the elements of the sequence s.

Definition 3.1 (*Allowed*). *Let P be a livelock-free CSP process. The set of sets of events of P that can be hidden with no introduction of divergence is given by $Allowed(P)$, which is defined as follows:*

$$Allowed(P) = \{cs : \mathbb{P}\,\Sigma \mid \neg\ \exists\, s : MIP(P) \bullet \operatorname{ran}(s) \subseteq cs\}$$

In our example, hiding either $\{fk.1.1.U, fk.1.1.D\}$ or $\{fk.1.2.U, fk.1.2.D\}$ from F_1 introduces divergence because there exists an element in $MIP(F_1)$ that only has events in such sets; they are not in $Allowed(F_1)$. Our concern here is only with the sequences in $MIP(P)$, since livelock may be introduced if we hide all elements of a sequence that is recursively offered by P. The first element of the pair (tr, mip) is not relevant in this context because livelock is never introduced if we hide all elements of a sequence that is offered a finite number of times. We are now able to formally define our local verifications, as illustrated in Figure 1.

3.2. Simple Verification

As an example, we consider $PComp_1 = P_1[pfk.1.1 \leftrightarrow fk.1.1]F_1$, which is equivalent to $P_1[pfk.1.1.U \leftrightarrow fk.1.1.U, pfk.1.1.D \leftrightarrow fk.1.1.D]F_1$. We observe that $\{pfk.1.1.U, pfk.1.1.D\}$ is in $Allowed(P_1)$ and $\{fk.1.1.U, fk.1.1.D\}$ is not in $Allowed(F_1)$. Nevertheless, the composition is livelock-free because, after synchronisation on *pfk* events, P_1 necessarily has to engage on an independent visible event, such as $lf.1.E$. We present below our first result, which justifies our claim in this example. Here, $\alpha(P)$ is the set of events that P can communicate.

Proposition 3.1 (*SV*). *Let P and Q be two livelock-free CSP processes with $\alpha(P) \cap \alpha(Q) = \emptyset$, and $I = \{i_1, ..., i_n\}$ and $O = \{o_1, ..., o_n\}$ two disjoint sets of events ($I \cap O = \emptyset$). If either $I \in Allowed(P)$ or $O \in Allowed(Q)$, then the composition $P[i_1 \leftrightarrow o_1, ..., i_n \leftrightarrow o_n]Q$ is livelock free.*

This proposition states that, if any of the connecting sets of events used in the composition belongs to the set of *Allowed* events of the corresponding process, the linked parallel composition is livelock-free.

3.3. Complex Verification

If the restriction indicated in Proposition 3.1 does not hold, we have local possibilities of livelock. This, however, does not necessarily introduce livelock because the composition diverges only if both processes synchronise indefinitely on the composed events. As an example, we consider the following processes.

$$P_3 = a \rightarrow P_4 \qquad\qquad Q_3 = e \rightarrow Q_4$$
$$P_4 = b \rightarrow c \rightarrow P_4 \qquad\qquad Q_4 = f \rightarrow Q_3$$

Here, we have $XIP(P_3) = \{(\langle a \rangle, \langle b, c \rangle)\}$ and $XIP(Q_3) = \{(\langle\rangle, \langle e, f \rangle)\}$. Neither $\{b, c\}$ is in $Allowed(P_3)$ nor $\{e, f\}$ is in $Allowed(Q_3)$. Therefore, if we hide the set of events $\{b, c\}$ in P_3, livelock is introduced. The same takes place when we hide $\{e, f\}$ in Q_3. However, if we perform the composition $P_3[b \leftrightarrow f, c \leftrightarrow e]Q_3$, livelock is not introduced because we have a deadlock.

To make this verification, we consider $ProjXIP(P, cs)$, which identifies the pairs (tr, mip) in $XIP(P)$ in which mip has only elements in cs. With cs as the set of events hidden in a composition of processes P and Q, we identify the sequences that may cause livelock using $ProjXIP(P, cs)$ and $ProjXIP(Q, cs)$ as described next. Since the elements that are not in cs do not contribute to the synchronisations, they are removed from tr in the pairs defined by $ProjXIP$.

To check for the possibility of (indefinite) synchronisation between parallel processes, we compare their sets of pairs defined by $ProjXIP$ and identify the possibility of matching communications on the linked events. Since these are (potentially) different events, like b and c, and e and f in the example above, we rename the pairs of traces in $ProjXIP(P)$ using the function $RenXIP(P, f)$. Nevertheless, only using $RenXIP$ is not enough to compare the elements of the pairs. As an example, we consider the following CSP processes.

$$P_5 = a.1 \rightarrow P_6 \qquad\qquad Q_5 = b.1 \rightarrow Q_6$$
$$P_6 = a.2 \rightarrow a.1 \rightarrow P_6 \qquad\qquad Q_6 = c.1 \rightarrow c.2 \rightarrow Q_6$$

Here, we have $ProjXIP(P_5, \{a\}) = \{(\langle a.1 \rangle, \langle a.2, a.1 \rangle)\}$ and $ProjXIP(Q_5, \{c\}) = \{(\langle\rangle, \langle c.1, c.2 \rangle)\}$. We use renaming functions $f_1 = \{a.1 \mapsto x1, a.2 \mapsto x2\}$ and $f_2 = \{c.1 \mapsto x1, c.2 \mapsto x2\}$ so that the linked events in $P_5[a \leftrightarrow c]Q_5$ are renamed to the same fresh events $x1$ and $x2$. The choice of names $x1$ and $x2$ is arbitrary. With these renaming functions, we have $RenXIP(P_5, f_1) = \{(\langle x1 \rangle, \langle x2, x1 \rangle)\}$ and $RenXIP(Q_5, f_2) = \{(\langle\rangle, \langle x1, x2 \rangle)\}$.

Renaming the projected pairs is still not enough to identify the matching in these traces directly. In this case, before the recursion, the trace in *tr* of $RenXIP(P_5, f_1)$ synchronises with the first element in *mip* of $RenXIP(Q_5, f_2)$. After that, an infinite loop is reached due to the synchonisation of the *mip* $\langle x2, x1 \rangle$ of $RenXIP(P_5, f_1)$ with $\langle x2, x1 \rangle$, which is other possible behaviour in which the loop can be observed in $RenXIP(Q_5, f_2)$. That is, besides the original pair in $RenXIP(Q_5, f_2)$, we also can observe the recursion through the pair $(\langle x1 \rangle, \langle x2, x1 \rangle)$. For that, we consider $RenXIP^+$, which identifies all pairs obtained from those in *RenXIP* that lead to a loop. They are possibilities in which the original pairs can perform the loops. With this, we identify that P_5 and Q_5 communicate continuously via internal synchronisations on a and c.

Our strategy uses these enriched sets to identify a *Minimum Common Interaction Pattern (MCIP)* because we only need to perform this verification until the first minimum sequence is found; it identifies the first trace that leads the composition to divergence. The function $MCIP(S_1, S_2)$ applies to two enriched sets of projected renamed pairs, S_1 and S_2, and identifies the commom sequences that can be reached by the concatenation of the elements of *tr* with the arbitrary concatenation of the elements of *mip* of both sets. In our example, the minimum commom sequence is $\langle x1, x2, x1 \rangle$.

We now present our second main result for ensuring the absence of divergence for non-trivial linked parallel compositions.

Proposition 3.2 (*CV*). *Let P and Q be two livelock-free CSP processes with $\alpha(P) \cap \alpha(Q) = \emptyset$, $I = \{i_1, ..., i_n\}$ and $O = \{o_1, ..., o_n\}$ two disjoint sets of events, $X = \{x_1, ..., x_n\}$ a set of fresh event names, and $f_1 = \{i_1 \mapsto x_1, ..., i_n \mapsto x_n\}$ and $f_2 = \{o_1 \mapsto x_1, ..., o_n \mapsto x_n\}$ two renaming functions from events to fresh event names. If $MCIP(RenXIP(P, f_1)^+, RenXIP(Q, f_2)^+) = \emptyset$, then the composition $P[i_1 \leftrightarrow o_1, \ldots, i_n \leftrightarrow o_n]Q$ is livelock-free; otherwise, there is a livelock.*

Proposition 3.2 states that livelock is not introduced if there exists no common sequence that can be reached by the concatenation of the elements of any enriched renamed projected pairs of the processes involved in the composition. Otherwise, besides indicating the possibility of identifying livelock compositions, we also capture the traces that lead the composition to divergence.

Although the method so far is complete, it does not scale for complex compositions. We, therefore, consider an optimisation that prunes the alternative behaviours induced by the parallelism. With this, we lose completeness and need to consider a more elaborate strategy, but this is the trade-off for scalability. If the optimisation has been performed, the verification is based on the identification of a specific pattern of composition, as discussed next.

3.4. Safe Multiple Composition Verification

In CV, besides analysing the synchronisation of the processes, we also have to take into account the possible combinations of independent (interleaved) events that can be performed after a parallel composition. As an example, we consider the following livelock-free CSP processes.

$$P_7 = a \to b \to P_7 \ \Box\ c \to P_7 \qquad Q_7 = d \to e \to Q_7 \qquad R_7 = f \to g \to R_7$$

After synchronising on a and d, the composition $PQ_7 = P_7[a \leftrightarrow d]Q_7$ needs to engage both in b and in e before it recurses. This can happen in two different ways: $\langle b, e\rangle$ or $\langle e, b\rangle$. In general, we have an interleaving on events that do not require synchronisation, and, from a practical point of view, the consideration of theses traces can lead to an explosion on the number of possible behaviours. To make our strategy scalable, we consider just one of the traces that can arise from the interleaving. As a result, we have, $XIP(PQ_7) = \{(\langle\rangle, \langle b, e\rangle), (\langle\rangle, \langle c\rangle)\}$. The analysis of a further composition of PQ_7 may be impacted by this. For example, in $PQR_7 = PQ_7[b \leftrightarrow g, e \leftrightarrow f]R_7$, there is no divergence, according to our strategy as presented so far; however, if we had considered the pair $(\langle\rangle, \langle e, b\rangle)$ as part of $XIP(PQ_7)$, then our strategy would identify a divergence that indeed exists. The optimisation may cause the livelock analysis to fail.

This problem can be circumvented by imposing restrictions on the composition. Our strategy requires that, in every composition, each basic process on the left-hand side is linked with just one basic process on the right-hand side, and vice-versa. The verification of this requirement uses the notion of *Basic Process Alphabet* ($BPA(P)$): a set that contains the alphabets of the basic processes of a given process P. Each element of $BPA(P)$ is the alphabet of a distinct basic process of P. In our example, we have:

$$BPA(P_7) = \{\{a, b, c\}\} \qquad BPA(Q_7) = \{\{d, e\}\} \qquad BPA(R_7) = \{\{f, g\}\}$$

The resulting BPA of a composition is the union of the BPAs of the processes involved in the composition with the linked events removed from them. For example, $BPA(PQ_7) = \{\{b, c\}, \{e\}\}$.

The analysis of compositions that only connect basic processes is not affected by our optimisation. This is because in our optimised verification, we still consider all pairs of basic processes. It is the compositions of composed processes that are affected, that is, compositions that originate different traces that always communicate on the same events. As an example, we consider PQR_7 presented above. It does not satisfy our restriction because the left linked events b and e are originated from different basic processes in PQ_7 ($b \in \alpha(P_7)$ and $e \in \alpha(Q_7)$). On the other hand, $PQR_8 = PQ_7[b \leftrightarrow f, c \leftrightarrow g]R_7$ satisfies our restriction because R_7 is a basic process and the composition only connects events from P_7, which is also a basic process in PQ_7. For such compositions, the search for an *MCIP* is correctly performed since all traces that may lead the composition to divergence are verified because the traces of basic processes are not optimised; they do not have parallel composition in their behaviours.

Our restriction, however, also allows connections of an arbitrary number of basic processes as long as they are effectively one-to-one connections. This condition is formally defined below. The expression $R(\!|\ S\ |\!)$ is the relational image of the relation $R : X \leftrightarrow Y$ on the set $S \subseteq X$.

Definition 3.2 (*Multiple Basic Processes Composition*). *Let P and Q be two livelock-free CSP processes with $\alpha(P) \cap \alpha(Q) = \emptyset$, and $I = \{i_1, ..., i_n\}$ and $O = \{o_1, ..., o_n\}$ two disjoint sets of events ($I \cap O = \emptyset$). Then, the composition $P[i_1 \leftrightarrow o_1, ..., i_n \leftrightarrow o_n]Q$ is a Multiple Basic Processes Composition if:*

$$
\begin{array}{l}
MBPC(P, Q) \wedge MBPC(Q, P), \textit{where} \\
MBPC(X, Y) = \\
\quad \forall\, p : BPA(X) \bullet \\
\qquad \neg\, \exists\, q_1, q_2 : BPA(Y) \mid q_1 \neq q_2 \bullet q_1 \cap L(\!|\, p \,|\!) \neq \emptyset \wedge q_2 \cap L(\!|\, p \,|\!) \neq \emptyset \\
\textit{where } L = \{(i_1, o_1), ..., (i_n, o_n)\}.
\end{array}
$$

This condition requires that for every BPA of P, there exists at most one BPA of Q that is being linked to it, and vice-versa.

Finally, we present our result for ensuring livelock-free linked parallel composition for cases in which an optimisation has been performed.

Proposition 3.3 (*SMCV*). *Let P and Q be two livelock-free CSP processes with $\alpha(P) \cap \alpha(Q) = \emptyset$, $I = \{i_1, ..., i_n\}$ and $O = \{o_1, ..., o_n\}$, two disjoint sets of events ($I \cap O = \emptyset$), $X = \{x_1, \ldots, x_n\}$ a set of fresh event names, and $f_1 = \{i_1 \mapsto x_1, ..., i_n \mapsto x_n\}$ and $f_2 = \{o_1 \mapsto x_1, ..., o_n \mapsto x_n\}$ two renaming functions from events to fresh event names. If the linked parallel composition $P[i_1 \leftrightarrow o_1, \ldots, i_n \leftrightarrow o_n]Q$ is a Multiple Basic Processes Composition and $MCIP(RenXIP(P, f_1)^+, RenXIP(Q, f_2)^+) = \emptyset$, then the linked parallel composition $P[i_1 \leftrightarrow o_1, \ldots, i_n \leftrightarrow o_n]Q$ is livelock free.*

Proposition 3.3 states that a linked parallel composition is livelock-free in cases in which we do not have communications of basic processes on a many-to-many fashion and there exists no $MCIP$. Otherwise, our strategy is inconclusive.

We have implemented an algorithm that supports livelock verification using these concepts. Further details can be found elsewhere [3].

4. Results and Discussion

The comparative analysis to evaluate our strategy has been conducted for a livelock-free Milner's scheduler system and for a dining philosopher system. Table 1 and Table 2 summarise our results, where N is the size of the configuration of these systems (for instance, on the first example it is the number of cells and in the second the number of philosophers and forks), and # represents the number of compositions. Furthermore, time is in seconds, * indicates one hour timeout, and ** indicates memory overflow.

N	#	FDR4	SLAP	CLLA
10	9	1,68	0.39	0.72
100	99	**	**	1.98
1,000	999	**	**	7.75
2,000	1,999	**	**	12.72

Table 1: Results for the Milner's Scheduler

N	#	FDR4	SLAP	CLLA
10	19	**	19.72	1.49
100	199	**	*	4.21
1,000	1,999	**	**	53.40
10,000	10,999	**	**	3451.02

Table 2: Results for the Dining Philosopher

The results show that FDR4 and SLAP are unable to deal with large synchronous models. On the other hand, our method (CLLA) verified, for instance, the absence of divergence for 10,000 philosophers and 10,000 forks (20,000 CSP processes and 10,999 linked parallel compositions) in less than 58 minutes. This is a promising result in dealing with large and complex systems.

In [10], a technique called the order rule is proposed to check the absence of livelock. In summary, a network is proved to be livelock-free if there is a specific order on its components such that no component can communicate exclusively and infinitely with components lower than it in this order. This strategy has not been implemented so far, and, consequently, no practical experiment was provided in this work. Our strategy is not restricted to this communication pattern and analyses the components pairwise to improve performance.

Another classical and extremely relevant property in concurrent systems is deadlock freedom. Approaches to local and compositional deadlock analysis have gained significant attention in the literature, including, for instance [2, 8]. As in the case of livelock, the approaches are efficient, but incomplete.

We plan to extend our technique to consider other kinds of parallel composition. Of course, the impact in efficiency of these improvements would need to be analysed. Additional case studies are also in our research agenda.

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