The computational behaviour of the $\mathcal{S}$CIFF abductive proof procedure and the *SOCS-SI* system

Marco Alberti
ENDIF, Università di Ferrara

Federico Chesani
DEIS, Università di Bologna

SOMMARIO/*ABSTRACT*

The high computational cost of abduction has limited the application of this powerful and expressive formalism to practical cases.

$\mathcal{S}$CIFF is an abductive proof procedure used for verifying the compliance of agent behaviour to interaction protocols in multi-agent systems; $\mathcal{S}$CIFF has been integrated in *SOCS-SI*, a system able to observe the agent interaction, pass it to $\mathcal{S}$CIFF for the reasoning process and to display in a GUI the results of the $\mathcal{S}$CIFF computation.

In order to assess the applicability of $\mathcal{S}$CIFF and *SOCS-SI* to practical cases, we have evaluated qualitatively and experimentally (not yet formally) their computational behaviour, as far as limitations and scalability. In this paper we show the results of the analysis.

Keywords: Abduction, Proof Procedure, Experimentation, Agent Interaction Verification

1 Introduction

Abductive Logic Programming [KKT98] has often been proposed, in the last two decades, as a powerful and expressive formalism for hypothetical reasoning. However, its application to concrete cases has always had to face the high computational cost of abductive proof procedures.

$\mathcal{S}$CIFF is an abductive proof procedure developed and implemented in the context of the SOCS [SOC] project in order to verify the compliance to interaction protocols of the agent behaviour in multi-agent systems. $\mathcal{S}$CIFF has been integrated in *SOCS-SI*, a system which can observe the agent interaction, pass it to $\mathcal{S}$CIFF for the reasoning process and display the results in a GUI.

While no formal results have yet been proved about the computational complexity of $\mathcal{S}$CIFF, it has seemed apparent that the computational cost can greatly vary depending on the abductive programs used for the specification of the interaction protocols. *SOCS-SI* introduces a further issue, since it keeps track of all the intermediate nodes explored by the $\mathcal{S}$CIFF.

Therefore, the viability of $\mathcal{S}$CIFF and *SOCS-SI* to verification of practical multi-agent systems has required, as a condition, a qualitative and experimental analysis of their computational behaviour. This paper presents the results of such analysis.

First of all, we have generated particular test instances with the purposes of stressing the proof procedure by varying the parameters in the following way:

- by increasing the depth of the search tree;
- by increasing the breadth of the search tree;

The test instances created did not have any particular meaning or significance, and were created for the specific purpose of achieving the worst scenario for the $\mathcal{S}$CIFF. Each test has been repeated in 2 different settings, i.e., by having the $\mathcal{S}$CIFF executing either alone or in conjunction with the *SOCS-SI* tool.

Once determined the computational limits of $\mathcal{S}$CIFF and *SOCS-SI*, we have studied the computational behavior with respect, in particular, to scalability. In this further testing phase, we referred to a real scenario, namely a Combinatorial Auction. Our main motivation is to confront our work with a concrete case of agent interaction, and hopefully to prove the feasibility of using an abductive proof procedure for compliance verification of agent interaction.

The paper is organized as follow: in Section 2 we introduce the SOCS project, with particular attention to the $\mathcal{S}$CIFF proof procedure and *SOCS-SI* tool developed within the project. In Section 3 we present some naive tests and their results: these tests were aimed to stress the $\mathcal{S}$CIFF proof procedure by varying the *depth* and the *breadth* of the searching tree. In Section 4 instead we present a test placed in a more real scenario, and aimed to get some qualitative information about a real-life application, combinatorial auctions. Finally, in Section 5, we summarize the results obtained during the tests.

2 The SOCS Project

The IST-2001-32530 (SOCS) project [SOC] investigated the application of Computational Logic techniques to multi-agent systems. In particular, a part of the project was about the specification and verification of agent interaction protocols in an abductive framework [AGL$^+$03], which defines declarative notions of *fulfillment* and *violation*, mapping, respectively, an agent behaviour that is compliant or non compliant to the interaction protocols. In this section, we briefly recall the operational aspect of the framework: an abductive proof procedure, implemented with CL-based tools and integrated in a system equipped with a GUI and able to observe the agent interaction to be checked for compliance.

2.1 The SCIFF Proof Procedure

$\mathcal{S}$CIFF [AGL$^+$04] is an abductive proof procedure which extends the IFF proof procedure by Fung and Kowalski [FK97]. A $\mathcal{S}$CIFF program is composed of KB_S, a logic program whose clauses can have abducibles in their body, and $\mathcal{IC}_S$, a set of integrity constraints in the form of implications whose heads are disjunctions.

The extensions to the IFF proof procedure stem from the application domain for which $\mathcal{S}$CIFF has been designed (verification of compliance of agent interaction to interaction protocols), which requires the following features:

- universal variables in abducibles;
- dynamic enlargement of the knowledge base with facts;
- constraints (à la Constraint Logic Programming) applied to variables.

Operationally, $\mathcal{S}$CIFF is a rewriting proof procedure which, to each state of the computation (or *node*), applies one or more *transitions* to generate children nodes. In this way, starting from an initial node, a tree is generated. In general, some of the leaf nodes will be of success, and others of violation. Success nodes represent the *fulfillment* of the interaction protocols by the agents; failure nodes represent *violation.*

$\mathcal{S}$CIFF has been implemented in SICStus Prolog, exploiting, in particular, its Constraint Handling Rules [Frü98] library. While no formal results have yet been proven about the $\mathcal{S}$CIFF computational complexity, qualitative and experimental analysis suggest that the required time to compute an answer can vary dramatically, depending on several input factors.

Qualitatively, the computational complexity of $\mathcal{S}$CIFF can be evaluated as follows. Each $\mathcal{S}$CIFF computation produces a search tree whose *depth* and *breadth* determine the total number of nodes, and thus the time needed to explore the (whole) tree. As the proof tree is explored by $\mathcal{S}$CIFF in a depth-first fashion, the depth of the tree, together with the *size* of a single node, also impacts on space requirements. For both time and space, the worst case is when each branch leads to failure, because in this case the whole tree is explored in search of a success node.

Intuitively, the *depth* of the search tree depends on the total number of *events* (the facts added dynamically to the knowledge base).

The *breadth* of the search tree, instead, is influenced by both the number of disjuncts in the head of the $\mathcal{S}$CIFF integrity constraints, and the alternative branches arising in several of the $\mathcal{S}$CIFF transitions. For example, one of the branches generated by the $\mathcal{S}$CIFF transition *fulfillment* (see [AGL$^+$04]) can be safely pruned, provided that the set $\mathcal{IC}_S$ respects some syntactic conditions, whose discussion is beyond the scope of this paper. In such cases, it is possible to optimize the performance of $\mathcal{S}$CIFF by reducing the number of generated branches. In this paper, we call this optimized $\mathcal{S}$CIFF behaviour *f-deterministic*, as opposed to the *f-non-deterministic*, which does not perform the pruning.

2.2 The *SOCS-SI* Tool

The $\mathcal{S}$CIFF implementation has been integrated into *SOCS-SI* [ACG$^+$04], a Java-based system equipped with a Graphical User Interface, which has been interfaced to platforms for multi-agent systems (PROSOCS [SKL$^+$04], Jade [JAD]), the TuCSoN coordination platform [OZ99], and an email exchange system.

The core of *SOCS-SI* is composed of three main modules (see Fig. 1), namely:

- *Event Recorder*: fetches events from different sources and stores them inside the *History Manager.*
- *History Manager*: receives events from the *Event Recorder* and composes them into an "event history".
- *Social Compliance Verifier*: fetches events from the *History Manager* and passes them on to the proof-procedure in order to check the compliance of the history to the specification. It receives the

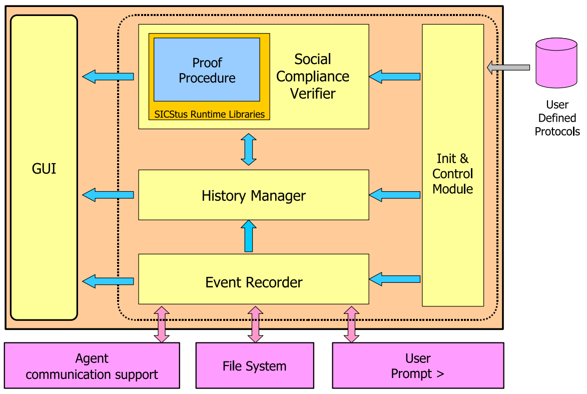
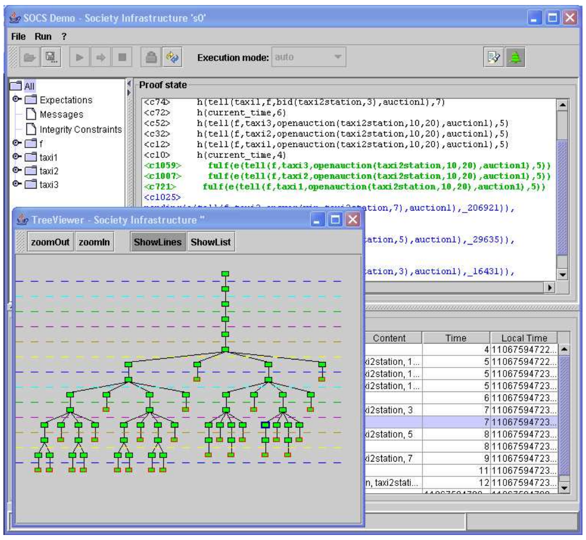


Figure 1: Overview of the *SOCS-SI* architecture



```
<c74>     h(tell(taxi1,f,bid(taxi2station,3),auction1),7)
<c72>     h(current_time,6)
<c52>     h(tell(f,taxi3,openauction(taxi2station,10,20),auction1),5)
<c32>     h(tell(f,taxi2,openauction(taxi2station,10,20),auction1),5)
<c12>     h(tell(f,taxi1,openauction(taxi2station,10,20),auction1),5)
<c10>     h(current_time,4)
<c1059>     fulf(e(tell(f,taxi3,openauction(taxi2station,10,20),auction1),5))
<c1007>     fulf(e(tell(f,taxi2,openauction(taxi2station,10,20),auction1),5))
<c721>     fulf(e(tell(f,taxi1,openauction(taxi2station,10,20),auction1),5))
<c1025>
ation,7),auction1),_206921)),
ation,5),auction1),_29635)),
ation,3),auction1),_16431)),
```

Content	Time	Local Time
	4	11067594722...
xi2station, 1...	5	11067594722...
xi2station, 1...	5	11067594723...
xi2station, 1...	5	11067594723...
	6	11067594723...
xi2station, 3	7	11067594723...
	7	11067594723...
xi2station, 5	8	11067594723...
	8	11067594723...
xi2station, 7	9	11067594723...
	11	11067594723...
n, taxi2stati...	12	11067594723...

Figure 2: The GUI with the OR–Tree

expectations from the proof-procedure and visualises them in the GUI.

The first important assumption we made in our model is that agents communicates by exchanging messages; these messages are the “events” that the $\mathcal{S}$CIFF will check for verification. A second important assumption we made is that the communication layer provides means for accessing all the messages exchanged between agents. Hence, the *SOCS-SI* tool can be aware of the messages exchanged. This is quite a strong assumption, considering the highly distribution characteristic of MAS. However, as already showed in agents platform like JADE [JAD] and PROSOCS [SKL$^+$04], this assumption can be translated in a feasible implementation.

The *Event Recorder* fetches events and records them into the *History Manager*, where they become available to the $\mathcal{S}$CIFF proof-procedure. As soon as the proof-procedure is ready to process a new event, it fetches one from the *History Manager*. The event is processed and the results of the computation are returned to the GUI. The proof-procedure then continues its computation by fetching another event if there is any available, otherwise it suspends, waiting for new events.

In order to support different agent platforms (and more general communciation layers), a “plug-in–like” mechanism has been implemented in the *Event Recorder*. Beside the integration with the communication layer developed within the SOCS project, we have developed plug-ins to support JADE [JAD], TuCSoN [ROD02], and the standard e-mail system (human agents communicating by exchanging properly formatted e-mails). For testing and debugging purposes, we also developed modules to interact with the user prompt, as well as with the file system: i. e., it is possible to log to a file agent interactions and analyze it a-posteriori. We will take advantage in particular of this last feature in order to simulate interactions that worse the performances of the $\mathcal{S}$CIFF and *SOCS-SI* tool.

The Graphical User Interface (Figure 2) provides access to the proof state, i.e., the results of the computation, returned by the proof-procedure. These results are expressed in terms of society expectations about the future behavior of agents, and also in terms of fulfilled expectations and violations of social rules. A graphical tree-view of the whole computation is provided: interestingly, the shown tree bears both an operational and a logical interpretation. The operational interpretation is an intuitive graphical form of a log-file, showing the most significant computational steps, useful for debugging purposes. The logical meaning is an or-tree of the possible $\mathcal{S}$CIFF derivations timed by the incoming events. For each incoming event that enriches the knowledge base, the frontier of the explored proof-tree (which is a logical disjunction, as in various proof-procedures [FK97]) is shown. The user can inspect each of the nodes, and see in the main window the state of the computation, i.e., the conjunction of logical formulae of the types in the $\mathcal{S}$CIFF language: abducibles, constraints, literals, implications. As it is quite easy to guess, the possibility of inspecting the proof state for each node of the exploration tree is quite expansive in term of memory requirements, and it is one of the main reasons for the degradation of performances when $\mathcal{S}$CIFF is used on conjunction with *SOCS-SI*.

3 Tests in simple scenarios

In this section we test the computational time required by $\mathcal{S}$CIFF/*SOCS-SI* to process some simple protocols and histories. In particular, the aim of this group of tests is not to establish absolute values about performances, but rather to understand how the computation time required to provide an answer is affected by changes in the length of the history processed (Section 3.1), and by changes in the alternatives dialogues allowed by the protocol (Section 3.2). The last experiment in particular roughly correspond to increasing the breadth of the search tree explored by $\mathcal{S}$CIFF, whether the former corresponds to increasing the depth of the tree.

The output considered is only the computational time required to elaborate an answer. For test instances of certain dimension (see Tables 1 and 2), it was not possible to achieve the completion of the test, mainly for limitations of the hardware. This condition is expressed by placing a question mark in the results tables, instead of a value.

All the tests were designed to provide a positive answer by $\mathcal{S}$CIFF, and were executed on a PC with a 2 GHz Pentium IV CPU, 512 MB of RAM, Windows XP Professional Edition and SICStus Prolog 3.10.1.

3.1 Increasing the depth of the exploring tree

The aim of this test is to evaluate the impact of histories of various length on $\mathcal{S}$CIFF and *SOCS-SI*. In order to do so, we have considered a very naive protocol, presented in the Specification 3.1, along with the history used to test it. The considered results, presented in the Table 1, are the time required to $\mathcal{S}$CIFF and *SOCS-SI* respectively to elaborate the histories of various length, and to provide the expected positive answer. The used protocol does not contain any alternative (disjunction) in the head of the rule: each time an appropriate event is processed, a new expectation is generated and, if possible, fulfilled. The parameter varied was the number of messages (events) composing each history, and results are shown in Table 1.

Specification 3.1 The naive protocol and an example history used for testing $\mathcal{S}$CIFF and *SOCS-SI* performances with the increasing of the *depth* of the search tree.

$$\begin{aligned} & \mathbf{H}(tell(A, B, aQuestion(aParameter), D), T) \\ \rightarrow\ & \mathbf{E}(tell(B, A, anAnswer(aParameter), D), T_1)\ \wedge \\ & T_1\ \geq\ T \end{aligned}$$

$tell(a, b, aQuestion(aParameter), d_1, 1)$
$tell(b, a, anAnswer(aParameter), d_1, 1)$
$tell(a, b, aQuestion(aParameter), d_2, 2)$
$tell(b, a, anAnswer(aParameter), d_2, 2)$
$\ldots$
$tell(a, b, aQuestion(aParameter), d_x, x)$
$tell(b, a, anAnswer(aParameter), d_x, x)$

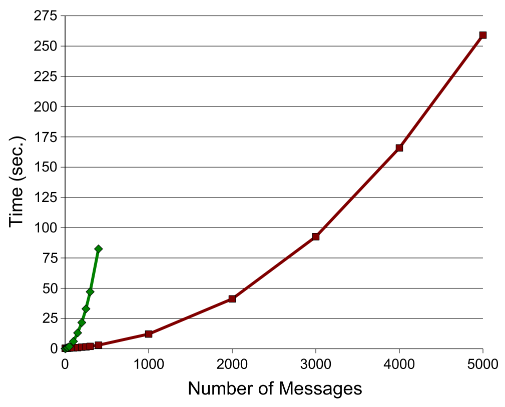


Figure 3: Performances with histories of increasing dimension.

Due to the simplicity of the protocol used in this test, it would not be correct to assume the results as meaningful in their absolute values. In fact, although in this test the $\mathcal{S}$CIFF was able to elaborate up to 5000 messages, this does not mean that in a real scenario it would be able to. The test instead provide two very useful information about the behavior of $\mathcal{S}$CIFF and *SOCS-SI*. First of all, the time required to elaborate longer histories increases in an almost quadratic way, as it is possible to observe in Figure 3. Secondly, the *SOCS-SI* has a big impact on performances, in respect with $\mathcal{S}$CIFF running without a GUI. Not only the *SOCS-SI* lowers the maximum number of processable events before an "Out–of–Memory" error, but also the performances are worsened, with a factor that is not constant, but that tends to increase.

No. of Messages	*SOCS-SI* Time(sec.)	$\mathcal{S}$CIFF Time(sec.)
2	0,13	0,42
4	0,18	0,43
20	0,68	0,51
30	0,98	0,51
50	1,82	0,57
100	6,13	0,76
150	13,13	0,97
200	21,68	1,35
250	33	1,62
300	47,05	1,99
400	82,47	3,00
1000	?	12,16
2000	?	41,21
3000	?	92,56
4000	?	165,89
5000	?	259,02

Table 1: Testing performances of $\mathcal{S}$CIFF and *SOCS-SI* while increasing the depth of the search tree.

3.2 Increasing the breadth of the exploration tree

The purpose of this test is to understand how performances of $\mathcal{S}$CIFF and *SOCS-SI* change if the breadth of the search tree increases. To do so, we have developed a different approach w.r.t. the test presented in Section 3.1. In this test, in fact, we vary the protocol definition by increasing the number of disjunction in the head of an Integrity Constraint; the history used, instead, is of a fixed length. The protocol, presented in the Specification 3.2, is again a naive protocol, where the constraint changes for every setting: a subscript x indicates the total number of disjunction. The history has been thought in order to fulfill the protocol only w.r.t. the expectation presented in the last disjunction. Since the $\mathcal{S}$CIFF explores the search tree by expanding the possible branches following the definition order of the disjunctions in the constraint, this history forces the $\mathcal{S}$CIFF proof procedure to explore all the tree. The results obtained are presented in the Table 2.

Specification 3.2 The naive protocol and an example history used for testing $\mathcal{S}$CIFF and *SOCS-SI* performances with the increasing of the *breadth* of the search tree.

$$
\begin{array}{ll}
 & \mathbf{H}(tell(A, B, aQuestion(aParameter), D), T) \\
\rightarrow & \mathbf{E}(tell(B, A, answer_1(aParameter), D), T_1) \ \wedge \\
 & T_1 \ \geq \ T \\
\vee & \mathbf{E}(tell(B, A, answer_2(aParameter), D), T_2) \ \wedge \\
 & T_2 \ \geq \ T \\
\vee & \mathbf{E}(tell(B, A, answer_3(aParameter), D), T_3) \ \wedge \\
 & T_3 \ \geq \ T \\
\vee & \ldots \\
\vee & \mathbf{E}(tell(B, A, answer_{x-1}(aParameter), D), T_{x-1}) \ \wedge \\
 & T_{x-1} \ \geq \ T \\
\vee & \mathbf{E}(tell(B, A, end(aParameter), D), T_x) \ \wedge \\
 & T_x \ \geq \ T
\end{array}
$$

$tell(a, b, aQuestion(aParameter), d_1, 1)$
$tell(b, a, end(aParameter), d_1, 2)$
$close\_history.$

Also for this test, the absolute values are not really meaningful, due to the to simplicity of the protocol used. However, the results show that the time requirements increase with a almost quadratic coefficient w. r. t. the increasing of the disjunctions in the protocol.

Then, in Figure 4 it is possible to appreciate the overhead introduced by the *SOCS-SI*, suggesting how much the GUI impacts on the overall performances.

We did not test how performances could have changed using the *f-deterministic* version of $\mathcal{S}$CIFF. In fact, in this dummy scenario, it has no sense to introduce knowledge about the domain, and thus it is not possible to take advantage of the *f-deterministic* $\mathcal{S}$CIFF.

No. of Messages	*SOCS-SI* Time(sec.)	$\mathcal{S}$CIFF Time(sec.)
2	0,032	0,015
5	0,047	0,016
10	0,093	0,031
20	0,219	0,063
30	0,375	0,109
40	0,578	0,188
50	0,859	0,282
100	2,813	0,921
200	10,968	3,360
300	25,423	7,516
400	46,390	12,937
500	71,496	19,875
1000	?	111,750

Table 2: Testing performances of $\mathcal{S}$CIFF and *SOCS-SI* while increasing the depth of the search tree.

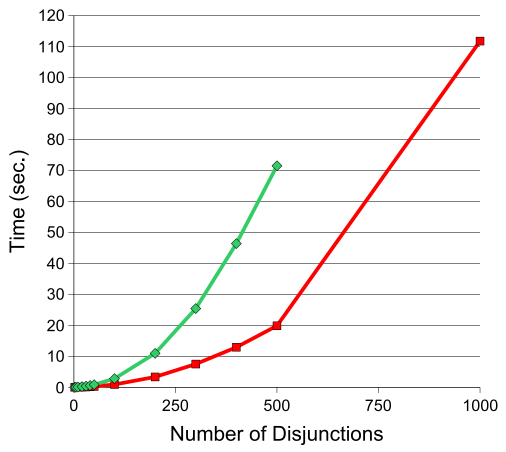


Figure 4: Performances with protocols that allow increasing alternatives.

4 Tests in a real scenario

In this section, we show some experimental results obtained applying $\mathcal{S}$CIFF to the verification of compliance to the combinatorial auction protocols described in [ACG$^+$05]. While not being an exhaustive experimentation, the results show the effect on the time costs of $\mathcal{S}$CIFF of the breadth and depth of the search tree.

The branching factor of the proof tree obviously impacts heavily on the computational costs of $\mathcal{S}$CIFF. In order to show its effect, we have performed some experiments on a combinatorial auction scenario [ACG$^+$05] varying two parameters which contribute to determine the breadth of the proof tree:

1. $\mathcal{S}$CIFF version (*f-non-deterministic* vs. *f-deterministic*, see Sect. 2.1);

Specification 4.1 Two versions of a Social Integrity Constraint.

$$\begin{array}{ll}
 & \mathbf{H}(\mathit{tell}(B, A, \mathit{bid}(\mathit{ItemList}, P), D), \mathit{Tbid}) \ \wedge \\
 & \mathbf{H}(\mathit{tell}(A, B, \mathit{openauction}(\mathit{Items}, \mathit{Tend}, \mathit{Tdeadline}), D), \mathit{Topen}) \\
\rightarrow & \mathbf{E}(\mathit{tell}(A, B, \mathit{answer}(\mathit{win}, B, \mathit{Itemlist}, P), D), \mathit{Tanswer}) \ \wedge \\
 & \mathit{Tanswer} \ > \ \mathit{Tend} \ \wedge \ \mathit{Tanswer} \ < \ \mathit{Tdeadline} \\
\vee & \mathbf{E}(\mathit{tell}(A, B, \mathit{answer}(\mathit{lose}, B, \mathit{Itemlist}, P), D), \mathit{Tanswer}) \ \wedge \\
 & \mathit{Tanswer} \ > \ \mathit{Tend} \ \wedge \ \mathit{Tanswer} \ < \ \mathit{Tdeadline}
\end{array}$$

$$\begin{array}{ll}
 & \mathbf{H}(\mathit{tell}(B, A, \mathit{bid}(\mathit{ItemList}, P), D), \mathit{Tbid}) \ \wedge \\
 & \mathbf{H}(\mathit{tell}(A, B, \mathit{openauction}(\mathit{Items}, \mathit{Tend}, \mathit{Tdeadline}), D), \mathit{Topen}) \\
\rightarrow & \mathbf{E}(\mathit{tell}(A, B, \mathit{answer}(\mathit{Answer}, B, \mathit{Itemlist}, P), D), \mathit{Tanswer}) \ \wedge \\
 & \mathit{Tanswer} \ \geq \ \mathit{Tend} \ \wedge \ \mathit{Tanswer} \ \leq \ \mathit{Tdeadline} \ \wedge \\
 & \mathit{Answer} :: [\mathit{win}, \mathit{lose}]
\end{array}$$

2. social specification. Spec. 4.1) shows two versions of a social integrity constraint used in the protocol, which are semantically equivalent (i.e., an agent behaviour that respects one will respect the other, and vice-versa), but are verified by $\mathcal{S}$CIFF in a computationally different way. The first version expresses with a disjunction in the head that the auctioneer can either declare a bid winning (first disjunct) or declare it losing (second disjunct). In the second version, this alternative is expressed by means of a domain variable: intuitively, tha auctioneer must declare each bid *Answer*, where *Answer* can be either *win* or *lose*. Operationally, in the first case, two branches are generated by $\mathcal{S}$CIFF; in the second case, only one branch is generated and the binding of the domain variable is delayed.

In particular, we measure the computation time for sequences of auctions with different numbers of bidders in the two following implementations of the protocol:

1. *f-non-deterministic* $\mathcal{S}$CIFF, protocol with disjunction (which we call the *first setup* of $\mathcal{S}$CIFF and protocol);

2. *f-deterministic* $\mathcal{S}$CIFF, protocol with no disjunction (which we call the *second setup* of $\mathcal{S}$CIFF and protocol).

The protocol is in both cases the one reported in [ACG$^+$05], apart from the fourth Social Integrity Constraint which, in each setup, is one of those the one in Spec. 4.1: in the first case, the alternative is expressed by means of a disjunction, in the second by means of a variable with domain.

The protocols have been run by varying the number N of bidders, in two different cases.

- In each run of the first case:

  1. the auctioneer sends an *openauction* message to each of the N bidders;
  2. each of the N bidders places a *bid*;
  3. the auctioneer issues a *closeauction* message to each of the N bidders;
  4. the auctioneer notifies each of the N bidders with either a *win* or a *lose* message,

  thus resulting in $4N$ total messages exchanged.

- In each run of the second case, the last notification to one of the bidders is missing, thus resulting in a violation of the protocol and $4N-1$ total messages.

f-non-deterministic, disjunction		*f-deterministic, domain*	
Bidders	Time(sec.)	Bidders	Time(sec.)
5	1	5	1
10	1	10	1
15	2	15	2
20	3	20	6
25	4	25	8
30	6	30	10
35	9	35	15
40	10	40	18
45	12	45	23
50	21	50	30

Table 3: Combinatorial Auction case 1: Fulfillment

The experiments were run on a PC with a 2 GHz Pentium IV CPU, 512 MB of RAM, Linux 2.4.18, glibc 2.2.5 and SICStus Prolog 3.10.1. Reported times are in seconds.

In case of fulfillment (see Table 3), the first setup of $\mathcal{S}$CIFF and protocol seems to scale well with the number of bidders and, in fact, it achieves better execution timing than the second (also shown in Fig. 5). This is basically due to the fact that the cho-

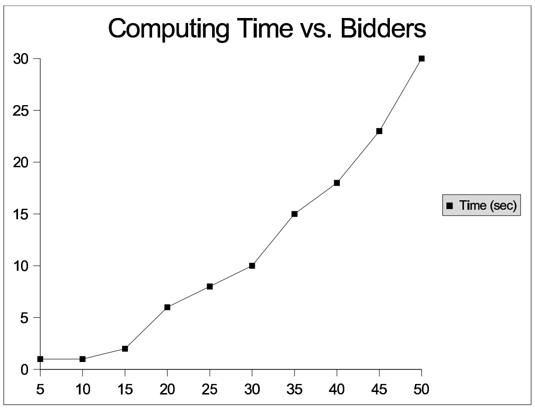


Figure 5: Proof performance on a basic auction (compliant)

sen setup of interactions directly leads to a successful

$\mathcal{S}$CIFF derivation, and only one branch of the tree is explored.

f-non-deterministic, disjunction		*f-deterministic, domain*	
Bidders	Time(sec.)	Bidders	Time(sec.)
3	7	3	0
4	55	4	0
5	?	5	0
10	?	10	1
15	?	15	3
20	?	20	4
25	?	25	7
30	?	30	10
35	?	35	14
40	?	40	17
45	?	45	22
50	?	50	26

Table 4: Combinatorial Auction case 2: Violation

In the case of violation (see Table 4), however, the first setup of $\mathcal{S}$CIFF and protocol explodes for a very small number of bidders. The experiment with 5 bidders was suspended since this did not reach the answer of violation after several minutes of computing time; no experiments were performed with a higher number of computees, which would have made things even worse. The second setup (also shown in Fig. 6), instead, scales very well also in case of violation. In this case, a CLP(FD) solver, written in CHR, directly manages the two alternative values for variable `Answer`.

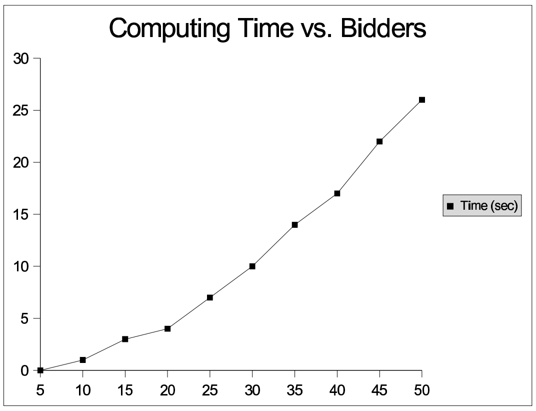


Figure 6: Proof performance on a basic auction (non compliant)

The difference between the two setups of $\mathcal{S}$CIFF and protocol becomes apparent in the worst case (i.e., the case of violation) when the whole tree is explored. With the first setup, the choice points left open in case of fulfillment and the disjunctions in the head of the integrity constraint make the number of nodes in the proof tree explode even for small number of bidders. With the second setup, instead, the tree has only one branch, and is thus explored in a reasonable time when the number of bidders increases.

5 Conclusions

In this paper, we have shown the results of the qualitative and experimental analysis of the computational behaviour of $\mathcal{S}$CIFF (an abductive proof procedure used for verifying the compliance of agent interaction to interaction protocols) and *SOCS-SI* (the GUI-equipped system used to interface $\mathcal{S}$CIFF to multi-agent systems).

The tests on laboratory-sized protocols show that $\mathcal{S}$CIFF and *SOCS-SI*, although being research prototypes, can handle a number of messages which makes them usable in real applications such as electronic commerce.

However, the tests on a real protocol (combinatorial auction) show that the time costs of $\mathcal{S}$CIFF may explode if the branching factor of the proof tree is high. In some cases (such as the combinatorial auction scenario shown in this paper) it is possible to reduce the branching factor by rewriting some of the integrity constraints (namely, by replacing disjunctions with domain variables). If the breadth of the proof tree is small, then the performance of $\mathcal{S}$CIFF scales reasonably well.

One further step in this analysis, which we intend to pursue, is to identify a set of techniques such as the mentioned above to decrease the breadth of the proof tree (possibly automatic, based on syntactic conditions on the original protocol).

Future works will be dedicated also to study complexity formally, possibly building on the work by Eiter, Gottlob and Leone, who have shown [EG95, EGL97] that the complexity of the abduction model for the *consistency* problem is $\sum_2^P$.

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