# ENGENHARIAS ELÉTRICA E DE COMPUTAÇÃO:

## O TERCEIRO PILAR

LILIAN COELHO DE FREITAS
(ORGANIZADORA)

Atena
Editora
Ano 2021

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Engenharias elétrica e de computação: o terceiro pilar


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**Dados Internacionais de Catalogação na Publicação (CIP)**

E57 Engenharias elétrica e de computação: o terceiro pilar / Organizadora Lilian Coelho de Freitas. – Ponta Grossa - PR: Atena, 2021.

Formato: PDF
Requisitos de sistema: Adobe Acrobat Reader
Modo de acesso: World Wide Web
Inclui bibliografia
ISBN 978-65-5983-543-0
DOI: https://doi.org/10.22533/at.ed.430213009

1. Engenharia elétrica. 2. Computação. I. Freitas, Lilian Coelho de (Organizadora). II. Título.

CDD 621.3

**Elaborado por Bibliotecária Janaina Ramos – CRB-8/9166**

**Atena Editora**
Ponta Grossa – Paraná – Brasil
Telefone: +55 (42) 3323-5493
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# APRESENTAÇÃO

Os avanços na pesquisa científica em Engenharias Elétrica e de Computação tem revolucionado nossa vida em sociedade. Conexões cada vez mais rápidas, processadores super velozes e a autonomia dos sistemas decorrentes do progresso em Inteligência Artificial são alguns exemplos de aplicações em nosso dia-a-dia.

Este e-book torna acessível os resultados da pesquisa científica realizada por diversos pesquisadores do país. Ao decorrer dos capítulos, apresenta-se aplicações práticas de inteligência artificial, gerência de redes e técnicas de otimização. Aproveite esse momento para aprimorar seus conhecimentos.

Desejo aos autores, meu mais sincero agradecimento pelas significativas contribuições, e aos nossos leitores, desejo uma proveitosa leitura, repleta de boas reflexões.

Lilian Coelho de Freitas

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**https://doi.org/10.22533/at.ed.4302130093**

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# CAPÍTULO 1

## PLANNING AS MIXED-HORN FORMULAS SATISFIABILITY

*Data de aceite: 01/09/2021*
*Data de submissão: 05/07/2021*

**Razer Anthom Nizer Rojas Montaño**
Setor de Educação Profissional e Tecnológica - Universidade Federal do Paraná
Curitiba - Paraná
http://lattes.cnpq.br/8472117901680275

**Bruno César Ribas**
Faculdade do Gama - Universidade de Brasília
Brasília - Distrito Federal
http://lattes.cnpq.br/6871745921667698

**ABSTRACT**: Over the course of the last decade, there have been several improvements in the performance of Boolean Satisfiability (SAT) but just a few works focused on Planning as Satisfiability recently. This paper explores a new way to model a planning instance from BLACKBOX and SATPLAN06. This new approach is a mixed-horn formula (MHF) where it can be seen as a conjunction of a Horn formula and a 2-CNF formula. The theoretical complexity to solve an MHF is $O(2^{0.5284n})$. With the theoretical complexity combined with improvements of SAT solvers, it is a promising approach to model Planning as Mixed-Horn Formulas Satisfiability. It is observed that this formulation has some improvements with current state-of-the-art SAT solvers.
**KEYWORDS**: Planning, Satisfiability, Mixed-horn formula, Satplan.

### PLANEJAMENTO COMO SATISFATIBILIDADE DE FÓRMULAS HORN-MISTAS

**RESUMO**: Ao longo da última década, houveram diversas melhorias no desempenho dos resolvedores de Satisfabilidade Booleana (SAT), mas poucos trabalhos em Planejamento como Satisfabilidade exploraram essas novas estratégias. Este artigo explora uma nova maneira de modelar uma instância de planejamento do BLACKBOX e SATPLAN06. Esta nova abordagem é transformar a codificação padrão em uma fórmula Horn-Mista (MHF), que pode ser separada como uma conjunção de uma fórmula de Horn e uma fórmula 2-CNF. A complexidade teórica para resolver uma MHF é $O(2^{0.5284n})$. A complexidade teórica da MHF combinada com as melhorias dos resolvedores SAT leva a uma abordagem promissora, conforme observamos nos benchmarks, quando comparada com a formulação padrão utilizando os mesmos resolvedores SAT.
**PALAVRAS-CHAVE**: Planejamento, Satisfatibilidade, Fórmula Horn-Mista, Satplan.

## 1 I INTRODUCTION

Planning in Artificial Intelligence is an important field of study and an interesting application of Satisfiability to solve generic search problems. The planning problem has the objective to find a sequence of actions from an initial state to reach a given goal. These actions sequences and state sequences attained from actions taken corresponds to assignments of a propositional formula which can be easily generated from the problem description.

In (KAUTZ; SELMAN, 1992) it is proposed a way to solve planning problems using propositional Satisfiability (SAT), but only after 1996, they demonstrated that modern SAT solvers and better translations provided a competitive approach to planning (KAUTZ; SELMAN, 1996).

SATPLAN is the planner based on SAT and one of the most successful approaches to STRIPS planning. This approach translates a planning problem to SAT problems, one formula to each horizon of actions applied. The first satisfiable formula means that a plan was found.

The efficiency of SAT solver is one of the most important characteristics to the success of this logical approach to the planning problem. Consequently, encoding the problem is also important, because the information represented can make the solver work better.

SATPLAN06 constructs a planning graph in a GRAPHPLAN fashion then translates this graph to a set of clauses (CNF) to be solved by a SAT Solver (BLUM; FURST 1995). While the generated formula is UNSAT, the graph is expanded. When the formula is SAT, the valuation found is translated to the solution of the original planning problem.

The classical translation of planning to satisfiability is using axioms generated from the planning graph. The choice of axioms leaves different encodings with different characteristics, as presented by Sideris and Dimopoulos (2010).

While solving time is highly dependent of the SAT solvers, due to better implementation and better solver choices such as: branching heuristics, learning and restart strategies, among others; the way of generating the formula is very important to achieve better solving time, while it is common sense that a minimal formula is better, this is not always the case for current solvers as briefly discussed in (PRESTWICH, 2009). Also, Hooker (2007) suggests that Constraint Programming and Operational Research, in which SAT exchanges ideas and techniques, are Empirical Science and encoding of the problem have to be considered when solving a problem.

In this paper, we show that a planning problem can be translated to a Mixed-Horn Formula (MHF) instance, to be solved by a specific SAT solver. MHFs are formulas composed of 2-CNF positive formulas and Horn formulas. It was demonstrated by Porschen and Speckenmeyer (2007) that SAT in MHF is $O(2^{0.5284n})$, still NP-Complete, but theoretically better than general CNF SAT.

This paper is organized as follows. In section 2 we present theoretical foundations and background information of SAT, planning, and MHF. In section 3 we show the proposed translation of a planning problem in MHF SAT, based on available SATPLAN encodings followed by section 4 where we show preliminary results encoding planning problems in MHF. Finally, in section 5 we present the conclusion and future work.

## 2 | THEORETICAL FOUNDATIONS AND BACKGROUND

### 2.1 Boolean Satisfiability

In Boolean Logic, a formula is said to be in the *Conjunctive Normal Form* (CNF) if it is formed by a sequence of conjunctions, represented by "Λ" consisting of one or more clauses. Each of these clauses should be a disjunction, represented by "v" of one or more literals. A literal is a symbol or the negation of it, used to represent a Boolean statement in logic that can take the value either *True* or *False*. All conjunctions of literals and all disjunctions of literals are in *CNF*, as they can be seen as conjunctions of one-literal clauses and conjunctions of a single clause, respectively. As mentioned, the only propositional connectives in a *CNF* formula are "Λ" "v" and "¬."

Given an assignment to the literals in a CNF formula, the formula is satisfied *iff* all of its clauses are satisfied and a clause is satisfied *iff* at least one of its literals is satisfied. A positive literal is satisfied *iff* the corresponding variable is assigned value *True* and a negative literal is satisfied *iff* the corresponding is assigned to *False*.

The problem of deciding whether a CNF (Boolean) formula is satisfiable, i.e if there exists an assignment to the variables such that the formula is satisfied, is called Boolean *Satisfiability* (SAT). SAT was the first problem that was proved to be NP-complete (COOK, 1971).

A detailed description of modern SAT solvers, techniques, and CNF encodings can be found, respectively in (DARWICHE; PIPATSRISAWAT, 2009), (MARQUES-SILVA; LYNCE; MALIK, 2009) and (PRESTWICH, 2009).

### 2.2 Planning

A *planning problem*, in the reasoning about actions area, is defined as the problem to discover a sequence of actions that goes from an initial situation to reach a goal state. According to Weld (1999), an algorithm that solves these kinds of problems must receive as input:

- A description of world entities and actual situation;
- A description of goals;
- A description of allowed actions.

These algorithms return a sequence of actions that reach a goal state from a starting state.

Planning problems were computationally modeled by Fikes and Nilsson (1971), where they proposed a formal representation that could solve the problem, in conjunction with a search algorithm. This approach is known as STRIPS. Despite the simplicity of STRIPS, planning was proved PSPACE-Complete in (BYLANDER, 1994).

The first algorithm that solves planning with satisfactory performance was SATPLAN

(KAUTZ; SELMAN, 1992) (KAUTZ; SELMAN,1996), which translates the planning problem to satisfiability (SELMAN; LEVESQUE; MITCHELL,1992) (SAT).

In (BLUM; FURST,1995) a new approach is presented, resulting in a new planner called *GRAPHPLAN*. This approach represents the planning problem as a planning graph and the resolution is using a backward search. In (KAUTZ; SELMAN, 1999) SAT-based and graph-based approaches were united, resulting in a smaller instance compared to the generated from *GRAPHPLAN*, it was called BLACKBOX.

In 2004, Kautz and Selman submitted to the 2004 International Planning Competition (IPC) a new version of SATPLAN (called SATPLAN04) with some improvements. But in 2006, the SATPLAN06 (KAUTZ; SELMAN; HOFFMANN 2006) was implemented with mutex propagation on the planning graph and encoding with boolean variables for actions and fluents. This allowed harder instances to be solved and avoid some memory problems.

## 2.3 Planning as Satisfiability

A STRIPS planning problem is a triple $P=\langle I,G,A\rangle$, where  is the set of facts true in the initial state, $G$ is the set of facts true in the goal state, and $A$ a set of allowed actions. Each action $a \in A$ has preconditions ($pre(a)$), added effects ($add(a)$) and deleted effects ($del(a)$).

In SAT, propositions are time-stamped to represent actions and facts in different situations. Let $a \in A$ be an action, so $a(t)$ is a decision if the action $a$ is taken or not at time $t$. The same notion is applied to facts, eg, $f(t)$.

According to Sideris and Dimopoulos (2010), the direct translation of *GRAPHPLAN* into propositional logic is made using some subset of the following clauses:

1. Unit clauses for initial and goal state;

2. $a\ (t) \rightarrow f(t)$, for every action $a$ and fact $f \in pre\ (a)$;

3. $a\ (t) \rightarrow f(t+1)$, for every action $a$ and fact ; $f \in add\ (a)$;

4. $a\ (t) \rightarrow \neg f(t+1)$, for every action $a$ and fact $f \in del\ (a)$;

5. $f(t) \rightarrow a_1(t-1) \vee ... \vee\ a_m\ (t-1)$, for every fact $f \in add\ (a_i)$ and all actions $a_i$, $1 \leq i \leq m$ (including the noops);

6. $\neg f\ (t) \rightarrow a_1(t-1) \vee ... \vee\ a_m\ (t-1) \vee \neg f\ (t-1)$, for every fact $f \in del\ (a_i)$ and all actions $a_i$, $1 \leq i \leq m$;

7.1. $\neg a_1(t) \vee \neg\ a_2(t)$, for every pair of action $a_1$, $a_2$, such that the set $del(a_1) \cap pre(a_2)$ is non-empty;

7.2. $\neg a_1(t) \vee \neg\ a_2(t)$, for every pair of action $a_1$, $a_2$, such that the set $del(a_1) \cap add(a_2)$ is non-empty;

7.3. $\neg a_1(t) \vee \neg\ a_2(t)$, if there is a pair of facts $f_1 \in pre(a_1)$, $f_2 \in pre(a_2)$, such that $f_1$, $f_2$ are mutually exclusive at time $t$;

8. $\neg f_1(t) \vee \neg f_2(t)$, for every pair of facts $f_1$, $f_2$ that are mutex at time $t$.

BLACKBOX support different encodings of planning problem, for example:

- BB-7: Clauses 1, 2, 5, 7.1, 7.2, 7.3
- BB-31: Clauses 1, 2, 3, 4, 5, 7.1, 8
- BB-32: Clauses 1, 2, 3, 4, 5, 7.1, 7.2, 7.3, 8

SATPLAN06 also supports different encodings, such as:

- SATPLAN06-3: Clauses 1, 2, 5, 7.1, 7.2, 7.3, 8
- SATPLAN06-4: Clauses 1, 2, 5, 7.1, 7.2, 8

Each encoding has different characteristics and must be chosen carefully to be translated to MHF.

## 2.4 Mixed-Horn Formulas

Mixed-Horn Formulas (MHF) are formulas composed of a 2-CNF part (clauses containing only two literals) and a Horn part (clauses with at most one positive literal). In our case, the 2-CNF part is composed only of positive literals, called positive monotone 2-CNF. The research in MHF is not new, and many problems can be formulated in terms of MHF, like the level-planarity test (Randerath et al. 2001) and graph colorability. Now we are introducing planning as a problem that can be represented directly as MHFs.

It is well known that 2-CNF satisfiability and Horn satisfiability are solvable in linear time (ASPVALL; PLASS; TARJAN, 1979) (MINOUX, 1988), but SAT for MHF (MHF-SAT) is NP-Complete as showed by Porschen and Speckenmeyer (2007). In (PORSCHEN; SPECKENMEYER, 2005) (PORSCHEN; SPECKENMEYER, 2007), it was studied satisfiability of Mixed-Horn Formulas, proving that the worst case is $O(2^{0.5284n})$, where $n$ is the number of variables in the instance.

**Algorithm**: MHFSAT

**Require**: M: MHF Formula
**Ensure**: $\tau$: Model found

```
Compute P := P(M)
IF P=∅ THEN
   RETURN τ ← HornSat(M)
END IF
Compute Graph G_p
τ ← nil; X ← nil;
REPEAT
    Compute by MinVC(G_p) the next minimal vertex cover X of G_p
    IF X ≠ nil THEN
        τ ← HornSat(M[X])
    END IF
UNTIL τ ≠ nil OR X = nil
RETURN X ∪ τ
```

ALGORITHM 1: MFH-SAT Algorithm using minimal vertex cover.

Porschen and Speckenmeyer also showed there is a polynomial-time transformation of an unrestricted CNF to MHF. In our case, this transformation is not necessary, because each horizon of planning problem can be generated directly as MHF, with only one simple flip of some literals and it will be explained in the next section.

Algorithm 1 defined by Porschen and Speckenmeyer (2007) solves MHF-SAT using minimal vertex cover. The function *P*(*M*) returns all positive monotone 2-clauses in M, *MinVC*(*G*) generate all minimal vertex covers of a graph G with polynomial delay. The function *HornSat*(*H*) returns a minimal model τ of *H* if, and only if, *H* is a satisfiable Horn formula, else returns *nil*.

## 3 I PROPOSED TRANSLATION

This paper proposes a Mixed-Horn formulation to the formulas generated by SATPLAN06 and BLACKBOX hoping we may gain some improvements in solving time with current state-of-the-art SAT solvers. It is important to note that the transformation is cheap to implement, leading to no extra overheads to the planner, as shown below.

Analyzing the axioms used to generate SAT instances from the planning graph, we can generate Mixed-Horn Formulas from, eg, configuration BB-7. In this set of clauses, clauses 1 are unit, clauses 2, 7.1, 7.2, and 7.3 are 2-CNF, and clause 5 can be Horn if we invert interpretation of action taken. If an action $a$ is taken, we represent it as ¬ $a$ and if  is not taken we can represent it as $a$.

The set of axioms (1, 2, 5, 7.1, 7.2 and 7.3), representing actions as described above and converted to clauses, will be:

1. Unit clauses for initial and goal state;

2. $\alpha(t) \vee f(t)$, for every action $a$ and fact $f \in pre(a)$;

5. $\neg f(t) \vee \neg a_1(t-1) \vee \ldots \vee \neg a_m(t-1)$, for every fact $f \in add(a_i)$ and all actions $a_1$, $1 \leq i \leq m$ (including the noops);

7.1. $a_1(t) \vee a_2(t)$, for every pair of action $a_1$, $a_2$, such that the set $del(a_1) \cap pre(a_2)$ is non-empty;

7.2. $a_1(t) \vee a_2(t)$, for every pair of action $a_1$, $a_2$, such that the set $del(a_1) \cap add(a_2)$ is non-empty;

7.3. $a_1(t) \vee a_2(t)$, if there is a pair of facts $f_1 \in pre(a_1)$, $f_2 \in pre(a_2)$, such that $f_1$, $f_2$ are mutually exclusive at time $t$;

Thus, clauses 1 are unit, clauses 2, 7.1, 7.2, and 7.3 are positive monotone 2-CNF, and clauses 5 are Horn. This set of clauses is MHF (2-CNF and Horn) and can be solved or with general SAT solvers or specific MHF solvers.

To modify SATPLAN06, we used configuration 4 (clauses 1, 2, 5, 7.1, 7.2, and 8). The clauses converted are the same as BLACKBOX, except for the exclusion of clause 7.3 and inclusion of clause 8, which is negated 2-CNF (or negated Horn, depending on interpretation). Clause 8 just have facts, so its generation to MHF is the same:

8. $\neg f_1(t) \vee \neg f_2(t)$, for every pair of facts $f_1$, $f_2$ that are mutex at time .

The translation proposed to change some literals (all action literals) by its negations. This change makes the formula generated by SATPLAN06 be in MHF format. This formula is equi-satisfiable to the original formula and, when applied to a SAT Solver, has the same behavior, but the valuation of action literals must be negated in the subjacent planning problem.

**Theorem 1**. *Be $\phi$ a theory in CNF. For all literal $\alpha$ in $\phi$, changing $\alpha$ by $\neg\alpha$ gives a theory $\phi'$ which is equi-satisfiable to $\phi$.*

*Proof.* $\phi$ and $\phi'$ are equi-satisfiable if $\phi$ is satisfiable if, and only if, $\phi'$ is satisfiable. If $\phi$ is SAT, then $\phi'$ is SAT too. Let $V$ be a valuation in $\phi$. If $\alpha$ is *true* (*false*) in $V$, so, by the transformation made, the same valuation with $\alpha$ as *false* (*true*) will be a model of $\phi'$. If $\phi'$ is SAT, then $\phi$ is SAT too. Let $V'$ be a valuation in $\phi'$. If $\alpha$ is *true* (*false*) in $V'$, so, by the transformation made, the same valuation with $\alpha$ as *false* (*true*) will be a model of $\phi$.

*Q.E.D.*

As showed by Bylander (1994), planning is PSPACE-Complete. As in CNF, SAT in MHF is NP-Complete and despite the use of MHF representation (where SAT theoretically has better complexity function), solving planning with satisfiability in MHF formulas remains in the PSPACE-Complete class of complexity.

## 4 | EXPERIMENTS

For evaluation of the efficiency of MHF compared to standard CNF encoding we used SATPLAN06 as our planner and used several domains of classical planning (STRIPS) from the ICAPS competition of various years. Our experiments were executed on an Intel Xeon 2.1GHz with 256GB of memory.

Each problem was executed with SATPLAN06  times for every combination. For all executions SATPLAN06 was set to run with LINGELING and GLUCOSE SAT solvers, for both encodings: default CNF and MHF. Each formula generated by SATPLAN06 was given a time limit of 3600 seconds to solve and the global time limit (including time spent solving formulas and the planner generating them) was set to 4000 seconds. All execution uses SATPLAN06 with configuration 4, explained in section 2.3.

Tables 1 to 14 show the average time in seconds of 10 executions of each problem. All tables are divided into two different results, one with CNF encoding and the other with MHF encoding, in both approaches it is shown average time of SATPLAN06 with LINGELING and GLUCOSE SAT solvers. Inside table, TO means timeout were reached, MEM means memory limit exceeded.

| | CNF | | MHF | |
|---|---|---|---|---|
| n | LING | GLUC | LING | GLUC |
| 1 | 57.688 | 12.945 | 56.925 | 14.300 |
| 2 | 28.897 | 10.101 | 35.936 | 10.155 |
| 3 | 228.196 | 35.283 | 227.794 | 36.409 |
| 4 | TO | 306.438 | TO | 304.40 |

TABLE 1: Domain: Storage.

| | CNF | | MHF | |
|---|---|---|---|---|
| n | LING | GLUC | LING | GLUC |
| 1 | 3.046 | 2.581 | 3.001 | 2.560 |
| 2 | 5.367 | 5.336 | 5.383 | 5.332 |
| 3 | 43.690 | 20.257 | 53.270 | 17.865 |
| 4 | 19.904 | 17.761 | 30.769 | 17.657 |

TABLE 2: Domain: Satellite

| | CNF | | MHF | |
|---|---|---|---|---|
| n | LING | GLUC | LING | GLUC |
| 1 | .678 | .695 | .667 | .679 |
| 2 | 1.149 | 1.171 | 1.128 | 1.161 |
| 3 | 1.233 | 1.211 | 1.216 | 1.197 |
| 4 | 4.370 | 4.088 | 4.323 | 4.065 |
| 5 | 24.375 | 29.546 | 24.321 | 29.373 |
| 6 | 106.738 | 161.330 | 106.054 | 160.248 |
| 7 | 333.911 | 494.478 | 330.293 | 491.316 |

TABLE 3: Domain: Blocks.

| | CNF | | MHF | |
|---|---|---|---|---|
| n | LING | GLUC | LING | GLUC |
| 1 | .662 | .679 | .648 | .658 |
| 2 | 1.524 | 1.453 | 1.549 | 1.432 |
| 3 | 3.325 | 2.461 | 3.200 | 2.432 |
| 4 | 10.639 | 4.833 | 9.554 | 4.696 |
| 5 | 36.527 | 15.645 | 50.317 | 16.509 |
| 6 | 239.897 | 90.239 | 462.487 | 90.275 |
| 7 | 2894.689 | 1236.842 | 3127.132 | 2104.082 |

TABLE 4: Domain: Gripper

| | CNF | | MHF | |
|---|---|---|---|---|
| n | LING | GLUC | LING | GLUC |
| 1 | 6.747 | 6.162 | 6.816 | 6.137 |
| 2 | 6.728 | 6.143 | 6.799 | 6.103 |
| 3 | 58.443 | 82.510 | 57.055 | 81.727 |
| 4 | 532.297 | 494.540 | 525.645 | 485.740 |
| 5 | 877.930 | 820.832 | 1003.564 | 813.832 |

TABLE 5: Domain: Depots.

| | CNF | | MHF | |
|---|---|---|---|---|
| n | LING | GLUC | LING | GLUC |
| 1 | 2.148 | 1.824 | 2.116 | 1.777 |
| 2 | 5.477 | 4.203 | 5.418 | 4.094 |
| 3 | 9.429 | 7.053 | 9.400 | 6.903 |
| 4 | 150.633 | 44.106 | 134.581 | 44.842 |
| 5 | 1398.500 | 1691.914 | 543.222 | 535.163 |

TABLE 6: Domain: Logistic.

| | CNF | | MHF | |
|---|---|---|---|---|
| n | LING | GLUC | LING | GLUC |
| 1 | 3.913 | 2.831 | 3.901 | 2.820 |
| 2 | 30.701 | 8.340 | 25.789 | 8.343 |
| 3 | 21.816 | 10.215 | 23.541 | 10.114 |
| 4 | 49.446 | 24.298 | 50.025 | 23.838 |
| 5 | 85.416 | 19.327 | 98.968 | 19.924 |
| 6 | 1569.046 | 972.555 | 1655.302 | 978.371 |

TABLE 7: Domain: Drivelog.

| | CNF | | MHF | |
|---|---|---|---|---|
| n | LING | GLUC | LING | GLUC |
| 1 | 4.130 | 3.529 | 4.375 | 3.544 |
| 2 | 8.101 | 4.424 | 7.690 | 4.384 |
| 3 | 6.967 | 4.444 | 8.822 | 4.428 |
| 4 | 30.288 | 10.541 | 30.886 | 9.653 |
| 5 | 151.592 | 39.544 | 158.124 | 36.591 |
| 6 | 1177.997 | 949.610 | 1125.387 | 1122.207 |

TABLE 8: Domain: Elevator.

| | CNF | | MHF | |
|---|---|---|---|---|
| n | LING | GLUC | LING | GLUC |
| 1 | 31.169 | 27.620 | 31.260 | 27.510 |
| 2 | 55.887 | 35.541 | 54.953 | 35.319 |
| 3 | 76.951 | 75.865 | 74.593 | 76.543 |
| 4 | 1310.279 | 420.913 | 1363.944 | 394.910 |

TABLE 9: Domain: TPP.

| | CNF | | MHF | |
|---|---|---|---|---|
| n | LING | GLUC | LING | GLUC |
| 1 | 3.046 | 2.581 | 3.001 | 2.560 |
| 2 | 5.367 | 5.336 | 5.383 | 5.332 |
| 3 | 43.690 | 20.257 | 53.270 | 17.865 |
| 4 | 19.904 | 17.761 | 30.769 | 17.657 |

TABLE 10: Domain: Thoughtful Bootstrap.

| | CNF | | MHF | |
|---|---|---|---|---|
| n | LING | GLUC | LING | GLUC |
| 1 | 1.774 | 1.768 | 1.776 | 1.734 |
| 2 | 35.109 | 29.692 | 36.313 | 29.765 |
| 3 | 9.844 | 15.917 | 9.609 | 15.916 |
| 4 | 402.043 | 486.056 | 421.980 | 367.658 |
| 5 | 2295.060 | TO | 2151.280 | TO |

TABLE 11: Domain: FreeCell.

| | CNF | | MHF | |
|---|---|---|---|---|
| n | LING | GLUC | LING | GLUC |
| 1 | 97.892 | 52.732 | 97.851 | 54.316 |
| 2 | 284.710 | 382.130 | 288.636 | 384.086 |
| 3 | 154.948 | 94.122 | 163.359 | 86.735 |
| 4 | 369.755 | 405.247 | 348.846 | 397.876 |
| 5 | 517.795 | 457.101 | 481.796 | 452.125 |

TABLE 12: Domain: PipesWorld.

| | CNF | | MHF | |
|---|---|---|---|---|
| n | LING | GLUC | LING | GLUC |
| 1 | 13.692 | 16.172 | 13.566 | 15.994 |
| 2 | 13.691 | 16.179 | 13.495 | 15.991 |
| 3 | 18.711 | 29.480 | 18.434 | 29.238 |
| 4 | 25.335 | 46.123 | 24.981 | 45.756 |
| 5 | 35.531 | 78.851 | 35.001 | 78.547 |
| 6 | 35.483 | 78.812 | 34.910 | 78.360 |
| 7 | 52.280 | 46.895 | 51.055 | 41.637 |
| 8 | 51.976 | 42.452 | 50.810 | 41.675 |
| 9 | 75.915 | 61.691 | 74.840 | 60.234 |
| 10 | 76.071 | 61.350 | 74.634 | 60.196 |
| 11 | 100.243 | 80.574 | 98.256 | 79.517 |
| 12 | 100.081 | 80.418 | 98.594 | 79.988 |
| 13 | 144.287 | 117.127 | 142.867 | 114.805 |
| 14 | 202.641 | 160.025 | 193.888 | 168.339 |
| 15 | 203.591 | 159.455 | 192.476 | 156.243 |
| 16 | 252.118 | 201.425 | 251.550 | 194.885 |
| 17 | 345.853 | 281.009 | 345.302 | 263.331 |
| 18 | 464.029 | 350.808 | 457.279 | 348.500 |
| 19 | MEM | MEM | MEM | MEM |
| 20 | MEM | MEM | MEM | MEM |

| | CNF | | MHF | |
|---|---|---|---|---|
| n | LING | GLUC | LING | GLUC |
| 1 | 1.097 | 1.065 | 1.127 | 1.084 |
| 2 | .734 | .732 | .703 | .747 |
| 3 | 1.239 | 1.198 | 1.209 | 1.232 |
| 4 | .671 | .685 | .742 | .705 |
| 5 | 2.334 | 1.753 | 2.099 | 1.804 |
| 6 | 16.898 | 4.362 | 16.734 | 4.507 |
| 7 | 1.719 | 1.486 | 1.714 | 1.509 |
| 8 | 31.470 | 4.730 | 34.578 | 4.782 |
| 9 | 5.740 | 4.402 | 5.758 | 4.445 |
| 10 | TO | 21.418 | TO | 20.151 |
| 11 | 10.002 | 11.325 | 10.013 | 11.356 |
| 12 | 12.683 | 3.357 | 13.184 | 3.417 |
| 13 | TO | 162.792 | TO | 175.692 |
| 14 | 8.779 | 7.134 | 8.615 | 7.109 |
| 15 | 45.830 | 26.160 | 38.673 | 26.424 |
| 16 | TO | 59.306 | TO | 53.972 |
| 17 | TO | 182.810 | TO | 169.837 |
| 18 | TO | 88.624 | TO | 88.513 |
| 19 | TO | TO | TO | TO |
| 20 | TO | TO | TO | TO |
| 21 | TO | TO | TO | TO |
| 22 | TO | TO | TO | TO |
| 23 | TO | TO | TO | TO |

| | | | | |
|---|---|---|---|---|
| 24 | TO | TO | TO | TO |
| 25 | 939.990 | 808.109 | 938.461 | 787.637 |
| 26 | TO | 1199.304 | TO | 1181.282 |

TABLE 13: Domain: Childsnack.

TABLE 14: Domain: Rovers.

With these results, we can conclude that solving classical planning problems using SAT with MHF formulas is feasible. As we can see, the results using MHF are close to the results using traditional CNF. State-of-the-art SAT solvers are generic solvers for the Satisfiability problem and might not always take advantage of the specific structural information rooted in the formula, therefore a specific SAT solver to solve MHF is needed to enhance solving time, small changes to the branching heuristics and learning structures might improve the performance.

Despite the closer times, some problems are solved faster in MHF. In the Logistics domain, table 6, problem 5 takes 1398.5s to solve with LINGELING in CNF while it takes 543.222s in MHF. The main reason is the last formula (the SAT formula to be solved) that takes 777s to be solved in CNF and is just 67s in MHF. Other domains have this behavior too, but we are still studying this phenomenon.

Analyzing all executions, we need to know if there is a statistical difference between the $K$ = 4 configurations and $N$ = 93 databases (taking only bases with execution was successful in all configurations). Friedman test (DEMSAR, 2006) is used to make paired data analysis using performance positions (rank) of all executions. For all $N$ databases, each execution is ranked and an average for each $K$ configuration is calculated.

Although the Friedman test uses a $X^2$ distribution, (DEMSAR, 2006) recommends a less conservative version proposed by Iman and Davenport (1980), which uses $F$ distribution with ($K$-1) and ($K$-1) ($N$-1) degrees of freedom.

Evidencing the statistic difference, we applied the Nemenyi post-hoc to show it (NEMENYI, 1963). According to it, the effectiveness of the two methods is significantly different if their ranks differ at least for a critical difference value, using a level of significance.

Table 15 shows the average ranking made using all executions.

| | CNF | | MHF | |
|---|---|---|---|---|
| | LING | GLUC | LING | GLUC |
| Average rank | 3,21505376344086 | 2,12903225806452 | 2,91397849462366 | 1,74193548387097 |

TABLE 15: Average ranking Average of execution ranking of formulas. To generate valuable results, we used only formulas solved by both solvers in both encodings. For each database, all executions are ranked (1-4) from best time execution to worst. Then, for each encoding, the average of all rankings is calculated.

Applying Friedman test with $K$ = 4 configurations, $N$=93 databases, and significance level at 5%, Friedman statistic results $F_f$= 35.59910199 and *p-value*=1.76238*E* - 19, pointing to statistical difference.

To evidence this difference, we applied the Nemenyi post-hoc at critical difference *CD*=0.486370723, $q_{0.05}$ = 2.569032073. Figure 1 shows the resulting difference diagram. In this diagram, the x-axis represents the average rank for each configuration. Lines below the x-axis connect configurations without a statistical difference at 95% of confidence level. Critical difference (CD) is showed above the x-axis.

From this diagram, we can see there is no statistical difference because of problem encoding, but the solver used.

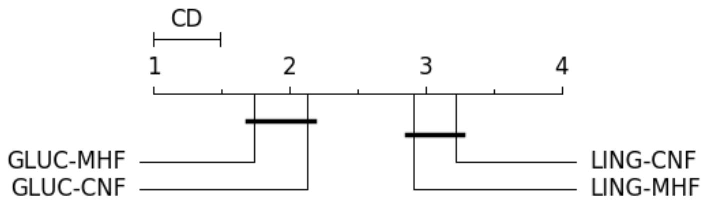


FIGURE 1: Difference graphic for Nemenyi post-test.

## 5 I CONCLUSION

This paper presented a new way to encode Planning as SAT using Mixed-Horn Formulas. It is important to focus on ways to represent problems as techniques and SAT solver improvements are not the only factor to reduce solving time, as discussed by Hooker (2007).

Analyzing formulas generated by planners that use satisfiability as an engine, we note that clauses are close to MHF. With an equi-satisfiable modification, we can generate MHF instead of CNF and this new encoding is now an option for solvers.

MHFs have received much attention recently (KOTTLER; KAUFMANN; SINZ, 2008) (PORSCHEN; SCHMIDT; SPECKENMEYER, 2009). Many NP-complete problems were proved to have encoding to MHF (PORSCHEN; SCHMIDT; SPECKENMEYER, 2009). In this paper, we show classical planning also can be solved using MHF and have a promising area of study.

In (PORSCHEN; SPECKENMEYER, 2005) and (PORSCHEN; SPECKENMEYER, 2007), they showed that the worst-case satisfiability of an MHF is $O(2^{0.5284n})$ and despite this complexity, it is still NP-complete. They showed too that any SAT instance can be encoded in MHF in polynomial time. In our encoding, the same process that generates CNF is used to generate MHF, without any overhead.

In this paper, we show that MHF can be used successfully to encode a planning problem, modified SATPLAN06 to generate MHFs instead of normal CNF, and executed many experiments using the same domains applied in IPC. The results show no significant improvements over the traditional CNF encoding, but an implementation of a new SAT solver based on MHF structure can improve our experiments.

We show there is no statistical difference between encodings used, despite some better executions when MHF is applied. This can occur because the solvers used in MHF encoding are not optimized to take advantage of the MHF structure.

As future work, specific SAT solvers for MHF must be used to compare executions. Even a new implementation using specific MHFs for planning can be studied. Besides, as described by Porschen and Speckenmeyer (2007), we can study the effect of reducing the number of essential variables, and if it is applied to our domain (classical planning).

For now, we are studying the phenomena described in problem Logistics-5, trying to identify domains with this behavior and solving UNSAT formulas faster in MHF.

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