D-VAL: An automatic functional equivalence validation tool for planning domain models *

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Abstract. In this paper, we introduce an approach to validate the functional equivalence of planning domain models. Validating the functional equivalence of planning domain models is the problem of formally confirming that two planning domain models can be used to solve the same set of problems. The need for techniques to validate the functional equivalence of planning domain models has been highlighted in previous research and has applications in model learning, development and extension. We prove the soundness and completeness of our method. We also develop D-VAL, an automatic functional equivalence validation tool for planning domain models. Empirical evaluation shows that D-VAL validates the functional equivalence of most examined domains in less than five minutes. Additionally, we provide a benchmark to evaluate the feasibility and scalability of this and future related work.

1 Introduction

Validation of planning domain models is a key challenge in Knowledge Engineering in Planning and Scheduling (KEPS). Among other tasks, this activity is concerned with checking the correctness of a planning domain model with respect to its specification, requirements or any other reference. If the reference is described informally, then the process of validating the correctness of domain models is also informal [9]. On the other hand, when the requirements are described formally, it is feasible to perform formal validation and to automate this process.

Our research focuses on validating the functional equivalence of planning domain models. Two planning domain models are functionality equivalent if both can be used to solve the same set of planning problems. The need for a technique to analyse planning domain models for functional equivalence has been highlighted in the literature [11, 12, 9]. One example application is the evaluation of the quality of planning model learning algorithms [1, 14]. This can be achieved by using hand-crafted models to generate a number of plans which are then fed to the model learning method to produce the learnt planning domain models.

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The functional equivalence of the original and learnt models is then checked to evaluate the quality of the learning algorithm.

Another application is to validate that the modifications performed by optimisation methods that are applied to planning domain models do not alter the functionality of the original domain. This includes reformulation, representation [13] and tuning [8] of domain models in order to increase the efficiency of planners using them. Examples of domain reformulation include macro-learning [10,3] and action schema splitting [2].

To prove functional equivalence of two planning domains, we introduce a method that uses a planner to match each operator from one domain with potentially equivalent macros from the other domain. A Satisfiability Modulo Theories (SMT) solver is then used to find a consistent and legal mapping between the predicates of the two domains. Thus, it (constructively) proves the functional equivalence of two planning domain models. Our algorithm is the VAL [7] equivalent for validating the functional equivalence of planning domain models. Hence, we refer to it as D-VAL.

In this paper, we first formally define the functional equivalence of two planning domain models. We then prove that if two domains are functionally equivalent, then our method can find a consistent predicate mapping that makes the two domains functionally redundant. Furthermore, we introduce a test benchmark covering a range of published domains and perform empirical experiments on this benchmark to demonstrate the feasibility and scalability of our method. This work considers typed domains STRIPS subsets of PDDL without implicit equality predicates.

This paper is organised as follows. 2 contrasts our method with related work. 3 presents planning theory background. 4 introduces the planning domain model functional equivalence definition and theories. An example is provided in 5. 6 explains our method. 7 reports and discusses the experimental results. Finally, 8 concludes the paper and suggests future work.

2 Related work

Our definition of planning domain model functional equivalence is a relaxed version of [11] equivalence definition. They defined planning domain model weak equivalence as a relation between two domains when both can represent the same set of planning problems and every valid plan that can be produced from the first domain is also a valid plan in the second domain under a certain bijective mapping of the components of the two domains.

We relax their definition in two ways. Firstly, we require a bijective mapping between the predicates only, not between other parts of the domains. Secondly, we consider planning domain models to be functionally equivalent if they can solve the same set of planning problems, even if the solutions differ.

In fact, it can be argued that their weak and strong equivalence are identical. For two domains to produce the same set of plans for the same set of problems, the directed graphs representing the reachable state space of both domains must
be isomorphic. Isomorphism is a strong bi-simulation relation. For the directed graphs of the reachable state space of two domains to be isomorphic, both domains should be identical apart from the names of the domains’ components. Hence, the requirement to generate the same plans for every planning problem can be achieved only through strong equivalence.

The logic behind our definition is that if two methods are proven to always find similar answers for any set of problems, then they can do the same job regardless of the steps taken by each method. Thus, we consider them functionally equivalent. With this mindset, we propose our planning domain model functional equivalence definition. If two domains can be used to solve the same set of problems (under a certain mapping) regardless of the actions taken, then we call them functionally equivalent domains. This paper extends the work in [11] by formally defining planning domain model functional equivalence, and proposing a method to prove this equivalence. Moreover, we provide two theories along with their proofs to form the theoretical basis of our method.

[9] argued the correctness of domain models is an essential factor in the overall quality of the planning function. They considered a knowledge model to be a planning domain model and a planning problem instance and suggested to translate the components of the knowledge model into assertions. A knowledge model is then defined to accurately capture their requirements, if the interpretation given by the requirements satisfies the assertions in the knowledge model.

Our notion of “functional equivalence” is closely related to their notion of “accuracy”. If two planning domain models are functionally equivalent, then both domain models satisfy the same requirements and both represent these requirements to the same degree of accuracy.

In addition to that, [9] outlined an approach to check the accuracy of operators from a planning domain model with the help of a single planning instance. Their approach is limited to individual planning instances, whereas our proposed method is independent from the planning problems. Besides that, this paper describes a working implementation of our method and it reports on its feasibility by the means of empirical evaluation.

[4] defined the equivalence of two domains with regards to a planning instance using graph isomorphism. According to their definition, two domains are equivalent if the directed graphs representing the reachable state space of both domains are isomorphic. This criterion proves the equivalence between the two domains for individual planning instances. On the contrary, our method proves the functional equivalence for any set of problems. Another subtle difference is that our method is invariant to the domains’ state space paths as it is weak equivalence, whereas their approach checks strong equivalence. Hence, their approach is sensitive to any variation in the possible state space paths between the two domains. The paths sensitivity in their method is due to the fact that their definition is based on graph isomorphism. Furthermore, proving isomorphism between two graphs is computationally dependent on the size of the planning problems, whereas, the computational cost of our method is dependent only on the size of the given domains.
3 Preliminaries

In classical planning, world objects are represented by unique constants which are the elements of the finite set \( \text{Obj} \). The properties of the objects are described using predicates. Let \( P \) be a finite set of the predicates of all objects of a world.

A state of the world, \( s \), is defined by the status of all objects in this world. The status of an object is defined by the truth evaluation of its predicates. The state space of a world is the set \( S \), of all states, where \( |S| = 2^{\text{number of all ground predicates}} \). False predicates are not included in the state definition and a closed-world assumption is made.

A planning domain model is a tuple \( D = (P, O) \) where \( P \) is a set of predicates and \( O \) is a set of operators.

A planning operator, \( o \), is a tuple

\[
\text{name}(o), \text{pre}(o), \text{eff}^-(o), \text{eff}^+(o)
\]

where \( \text{name}(o) = \text{op name}(x_1, \ldots, x_k) \), \( \text{op name} \) is a unique operator name and \( x_1, \ldots, x_k \) are variable symbols (arguments) appearing in the operator, and \( \text{pre}(o), \text{eff}^-(o) \) and \( \text{eff}^+(o) \) are sets of (ungrounded) predicates, specifying preconditions, negative and positive effects, respectively, with variables taken only from \( x_1, \ldots, x_k \).

An action is a ground instance of an operator. Actions are instantiated from operators by grounding the predicates of the operators, i.e. by substituting their variables with objects.

An action name is the same as the name of the operator from which the action has been instantiated. An action's precondition, positive effect and negative effects are sets of ground predicates. Action \( a \) is applicable in state \( s \) iff \( \text{pre}(a) \subseteq s \). The application of \( a \) in \( s \) results in the successor state \( \gamma(s, a) = (s \setminus \text{eff}^-(o)) \cup \text{eff}^+(o) \) provided that \( a \) is applicable in \( s \).

4 Definitions and theorems

The functionality of a planning domain model is characterised by the set of planning problems that can be solved using this domain. For a domain to be able to solve a planning problem, it has to be able to produce the required transitions in the state space from the initial state to one of the goal states. Thus, a domain model can be described by the set of transitions that can be produced by this domain model for a given planning problem. For a given set of objects, we call the set of all transitions for a domain model the reach set of this domain. Defining the reach set of a planning domain model requires the following definitions.

**Definition 41** The reach set of an operator \( o \) over a set of objects \( \text{Obj} \) is defined using the set of actions \( A_{\{o, \text{Obj}\}} \) which is instantiated from the operator \( o \) with the set of objects \( \text{Obj} \) as \( \Gamma(o, \text{Obj}) = \{(s, \gamma(s, a)) \mid s \in S, a \in A_{\{o, \text{Obj}\}} \text{ and } a \text{ applicable in } s\} \).
Definition 42 The reach set of a sequence of operators \( \text{seq} \) over a set of objects \( \text{Obj} \) is defined using the set of action sequences \( \Pi_{\text{seq}, \text{Obj}} \) which are instantiated from the sequence of operators \( \text{seq} \) with the set of objects \( \text{Obj} \) as \( \Gamma(\text{seq}, \text{Obj}) = \{(s, \gamma(s, \pi)) \mid s \in S, \pi \in \Pi_{\text{seq}, \text{Obj}} \text{ and } \pi \text{ applicable in } s\} \). Where \( \gamma(s, \pi) \) is the successor state of a state \( s \) when the sequence \( \pi \) of actions is applied. A sequence of operators could consist of a single or many operators where some items can be repeated.

Definition 43 The reach set of a planning domain model \( D \) over a set of objects \( \text{Obj} \) is then defined as: \( \Gamma(D, \text{Obj}) = \bigcup_{\text{seq} \in \text{Seq}} \Gamma(\text{seq}, \text{Obj}), \) where \( \text{Seq} \) is the set of all possible sequences of operators generated from \( D \).

Now we can informally define planning domain model functional equivalence. Two planning domains \( D_1 \) and \( D_2 \) are \text{functionally equivalent} if and only if there is a bijective mapping from the predicates of \( D_1 \) to the predicates of \( D_2 \) such that when the predicates of \( D_1 \) are substituted with the predicates from \( D_2 \) using the predicate mapping, the reach set of each domain is equal to the reach set of the other domain for any set of objects.

Definition 44 Two planning domain models \( D_1 = (P_1, O_1) \) and \( D_2 = (P_2, O_2) \) are \text{functionally equivalent}, \( D_1 \equiv_{\text{Func}} D_2 \), \text{iff}:

1. \( \exists f : P_1 \to P_2 \) where \( f \) is a bijective function.
2. \( D'_1 = \Theta(D_1) \) where \( \Theta \) is a substitution function that substitutes the predicates \( P_1 \) in \( D_1 \) with \( f(P_1) \).
3. \( \forall \text{Obj} : \; \Gamma(D'_1, \text{Obj}) = \Gamma(D_2, \text{Obj}) \).

The following theorems are essential for us to prove the correctness of our planning domain model functional equivalence method.

Theorem 41 For a set of objects and two planning domain models, \( D_1 \) and \( D_2 \), with the same set of predicates, the reach set of the planning domain model \( D_1 \) is a subset of the reach set of the planning domain model \( D_2 \) if and only if the reach set of each operator from the domain \( D_1 \) is a subset of the reach set of a sequence of operators from the domain \( D_2 \).

Formally, for two planning domain models \( D_1 = (P_1, O_1) \) and \( D_2 = (P_2, O_2) \) with the same set of predicates and a set of objects \( \text{Obj} \), \( \Gamma(D_1, \text{Obj}) \subseteq \Gamma(D_2, \text{Obj}) \) if and only if for all \( o' \in O_1 \), there exists \( \text{seq} = \langle o_0, o_1, \ldots, o_n \rangle \), where \( o_i \in O_2 \), such that \( \Gamma(o', \text{Obj}) \subseteq \Gamma(\text{seq}, \text{Obj}) \).

To prove this theorem, the biconditional is broken into forward and backward implications that are proven separately. For brevity, the set \( \text{Obj} \) is dropped from the reach set notation in the proofs as it is common to all reach sets.

First, we prove the forward implication: \( \Gamma(D_1) \subseteq \Gamma(D_2) \implies \) for all \( o' \in O_1 \), there exists \( \text{seq} = \langle o_0, o_1, \ldots, o_n \rangle \), where \( o_i \in O_2 \), such that \( \Gamma(o') \subseteq \Gamma(\text{seq}) \).
Proof. The contrapositive of the forward implication is there exists $o' \in O_1$ such that for all $seq = \langle o_0, o_1, \ldots, o_n \rangle$, where $o_i \in O_2$, $\Gamma(o') \not\subseteq \Gamma(seq) \implies \Gamma(D_1) \not\subseteq \Gamma(D_2)$.

Since both reach sets of operators and sequences are sets of transitions, we have

$$\exists t \in S^2 : t \in \Gamma(o') \implies t \notin \Gamma(seq).$$  \hspace{1cm} (1)

As $seq$ is quantified over all possible sequences $Seq_2$ from $D_2$, the right-hand side of (1) can be rewritten as

$$t \notin \bigcup_{seq \in Seq_2} \Gamma(seq).$$  \hspace{1cm} (2)

From Definition 43, we infer

$$t \notin \Gamma(D_2).$$  \hspace{1cm} (3)

From the left-hand side of (1) and because the reach set of any operator is contained in the reach set of its domain as per Definition 43, we deduce

$$t \in \Gamma(D_1).$$  \hspace{1cm} (4)

The implication in (1) can therefore be rewritten as

$$\exists t \in S^2 : t \in \Gamma(D_1) \implies t \notin \Gamma(D_2).$$  \hspace{1cm} (5)

Thus, $\Gamma(D_1) \not\subseteq \Gamma(D_2)$. This proves the contrapositive of the forward implication of Theorem 41.

Second, we prove the backward implication: For all $o' \in O_1$, there exists $seq = \langle o_0, o_1, \ldots, o_n \rangle$, where $o_i \in O_2$, such that $\Gamma(o') \subseteq \Gamma(seq) \implies \Gamma(D_1) \subseteq \Gamma(D_2)$.

Proof. Let $D_3 = (P_3, O_3)$ be a planning domain model where $P_3 = P_1 = P_2$, and the set of its operators $O_3 = \{ seq : seq \in Seq_2, \forall o' \in O_1 : \Gamma(o') \subseteq \Gamma(seq) \}$. From the construction of $O_3$, we have $O_3 \subseteq Seq_2$, thus $\Gamma(D_3) \subseteq \Gamma(D_2)$. Furthermore, the definition of $O_3$ implies $\Gamma(O_1) \subseteq \Gamma(O_3)$, which means any transition made by $D_1$ can be matched by a transition made by $D_3$. Thus we have $\Gamma(D_1) \subseteq \Gamma(D_3)$. Therefore, $\Gamma(D_1) \subseteq \Gamma(D_2)$.

Though Theorem 41 requires $D_1$ and $D_2$ to have the same set of predicates, it can be easily extended to two domains with different predicates as long as there is a bijective mapping between the predicates of the two domains.

**Theorem 42** For two planning domain models $D_1$ and $D_2$ and two bijective functions $f : P_1 \to P_2$ and $g : P_2 \to P_1$, Let $D'_1 = f(D_1)$ be the image of $D_1$ using $f$ to substitute its predicates with those of $D_2$ and $D'_2 = g(D_2)$ be the similar image of $D_2$ under $g$. Then we have for a set of objects $Obj$:
1. $\Gamma(D'_1, \text{Obj}) \subseteq \Gamma(D_2, \text{Obj})$ and $\Gamma(D'_2, \text{Obj}) \subseteq \Gamma(D_1, \text{Obj}) \implies \Gamma(D_1, \text{Obj}) = \Gamma(D'_2, \text{Obj})$ and $\Gamma(D'_1, \text{Obj}) = \Gamma(D_2, \text{Obj})$

2. $f = g^{-1}$

Proof. First, substitute $D'_1$ with $f(D_1)$ and $D'_2$ with $g(D_2)$ in the antecedent of the implication to obtain:

\begin{align*}
\Gamma(f(D_1)) \subseteq \Gamma(D_2) & \text{ and } \quad (6) \\
\Gamma(g(D_2)) \subseteq \Gamma(D_1). & \text{ (7)}
\end{align*}

$f(D_1)$ and $D_2$ have the same predicates and the reach set of $f(D_1)$ is a subset of the reach set of $D_2$. If we rename the predicates of $f(D_1)$ and $D_2$ in the same way, say using $f^{-1}$, then $f^{-1}(f(D_1))$ and $f^{-1}(D_2)$ both have the same predicates and the reach set of $f^{-1}(f(D_1))$ is a subset of the reach set of $f^{-1}(D_2)$. Therefore,

\begin{align*}
\Gamma(D_1) \subseteq \Gamma(f^{-1}(D_2)) & \text{ and } \quad (8) \\
\Gamma(D_2) \subseteq \Gamma(g^{-1}(D_1)). & \text{ (9)}
\end{align*}

Since $\Gamma(D'_2) \subseteq \Gamma(D_1)$ and from (8) we have

\begin{align*}
|\Gamma(D_1)| & \geq |\Gamma(g(D_2))| \text{ and } \quad (10) \\
|\Gamma(D_1)| & \leq |\Gamma(f^{-1}(D_2))| \text{ respectively. } \quad (11)
\end{align*}

Since $f$ and $g$ are bijective functions, $|\Gamma(g(D_2))| = |\Gamma(f^{-1}(D_2))| = |\Gamma(D_2)|$. Thus $|\Gamma(D_1)| = |\Gamma(g(D_2))| = |\Gamma(f^{-1}(D_2))| = |\Gamma(D_2)|$.

$\Gamma(D_1)$ contains $\Gamma(g(D_2))$ as per (7) and both have equal cardinality, hence:

\begin{equation}
\Gamma(D_1) = \Gamma(g(D_2)). \quad (12)
\end{equation}

$\Gamma(D_1)$ is a subset of $\Gamma(f^{-1}(D_2))$ as per (8) and both have equal cardinality, hence:

\begin{equation}
\Gamma(D_1) = \Gamma(f^{-1}(D_2)). \quad (13)
\end{equation}

From (12) and (13) we infer that $\Gamma(g(D_2)) = \Gamma(f^{-1}(D_2))$. Hence, $g = f^{-1}$. Moreover, (12) can be rewritten as $\Gamma(D_1) = \Gamma(D'_2)$. This proves the first part of the consequent of the implication. Following the same steps we can prove $f = g^{-1}$ and $\Gamma(D_2) = \Gamma(D'_1)$.

The concept of a sequence of operators will be referred to as a macro hereafter. It is useful to define the terms potentially functionally equivalent and functionally equivalent between a macro and an operator as follows.
Definition 45 A macro from domain $D_1$ is potentially functionally equivalent to an operator from domain $D_2$ iff the reach set of the macro is equal to the reach set of the operator for all sets of objects and under a mapping of the predicates of the macro and the operator.

In addition to the previous conditions, we say the macro is functionally equivalent to the operator if the predicate mapping is also consistent among all macros and operators of the two domains.

5 Example

This example illustrates the steps required to prove that two domains are functionally equivalent. A detailed explanation of how each step can be realised is provided in 6.

Suppose we have two versions of the Rover planning domain model, $D_1$ and $D_2$. Let $D_1$ be the original version, and $D_2$ be a copy of $D_1$ with additional operator “calibrate-take-image-M”. Also let the predicates and operators of $D_2$ be suffixed with “-M”. First, find a list of potentially functionally equivalent macros from $D_1$ for each operator from $D_2$. 1 lists some interesting operators in the domain $D_2$ with their potentially equivalent macros from $D_1$.

| $D_2$                    | $D_1$                          |
|-------------------------|--------------------------------|
| calibrate-take-image-M  | (calibrate, take-image )       |
| sample-soil-M           | (sample-soil ) or (sample-rock ) |
| sample-rock-M           | (sample-soil ) or (sample-rock ) |
| communicate-soil-data-M | (communicate-soil-data ) or (communicate-rock-data ) or (communicate-image-data ) |
| navigate-M              | (navigate )                    |

Table 1: Potentially functionally equivalent macros of some of the $D_2$ operators.

The second step is to choose for every operator from $D_2$ a macro from the list of the potentially functionally equivalent macros from $D_1$. Each selection will impose a certain mapping on the predicates of the relevant $D_2$ operator and its respective potential macro. Only when a consistent mapping among all $D_2$ operators and their respective $D_1$ macros is found, can $D_1$ and $D_2$ be considered functionally equivalent.

To explain the idea of the consistent mapping between the predicates of $D_1$ and $D_2$, let us explore how the predicate (at-M ?x ?p) from the precondition of sample-soil-M will be mapped. The preconditions, add effects and delete effects of sample-soil-M must be mapped to the predicates of either sample-soil or

1 Can be obtained from http://ipc.icaps-conference.org.
sample-rock in their preconditions, add effects and delete effects, respectively. For instance, predicate (at-M ?x ?p) in the precondition of sample-soil-M can be assigned to either any one of the predicates in the precondition of sample-soil, namely (at ?x ?p), (at-soil-sample ?p),
(equipped-for-soil-analysis ?x), (store-of ?s ?x), (empty ?s), or any one of the predicates in the precondition of sample-rock, namely (at ?x ?p) (at-rock-sample ?p),
(equipped-for-rock-analysis ?x), (store-of ?s ?x), (empty ?s).

The options of mapping the predicate (at-M ?x ?p) are further constrained by the options of mapping the predicate (at-M ?x ?y) from navigate-M. This additional constraint is required because (at-M ?x ?p) and (at-M ?x ?y) both have the same name, therefore they must be assigned to the same predicate in $D_1$. The operator navigate-M has navigate as the only potential macro, see 1. Therefore, the predicate (at-M ?x ?y) from navigate-M can be assigned only to (at ?x ?y) from the macro navigate. Consequently, predicate (at-M ?x ?p) in the precondition of sample-soil-M would need to be assigned to the predicate (at ?x ?p) specifically. The process of resolving these constraints ensures a consistent assignment of the predicate with the name “at” among all operators and their respective potential macros. Only with a consistent mapping, some of the potential macros will be valid macros and under the found predicate mapping, they can substitute their relevant operators.

6 Method

We propose a method to prove the functional equivalence between two planning domain models $D_1$ and $D_2$. Our method finds at least one functionally equivalent macro from each domain for every operator in the other domain. Therefore, in accordance with Theorem 41, the reach set of each domain is proven to be a subset of the reach set of the other domain under a certain mapping. Consequently, and in agreement with Theorem 42, $D_1$ and $D_2$ will have equal reach sets under a certain mapping. Hence, $D_1$ and $D_2$ will be functionally equivalent according to Definition 44.

6.1 Find potential functionally equivalent macros for an operator

To find potential functionally equivalent macros for a given operator, we use FF planner [6] with a macro building planning domain model, let us call this domain a meta domain. Our meta domain consists of meta operators which add the operators of the given domain in a sequential order until the required macro is reached. For each type in the given domain, a set of constants is added to the meta domain. The number of these constants is equal to the larger number of same-type parameters in the considered operator. In our meta planning problem, the goal is a signature of the required macro. This signature is specified by the number of predicates in the macro’s preconditions, the delete effects of predicates that are not in the preconditions, the delete effects of predicates that are in the preconditions and the add effects. We refer to these values by prem-count,
delm-not-prem-count, delm-prem-count and addm-count, respectively. An operator is added to the macro if the macro does not have a delete effect of one of the preconditions of the considered operator. Every time an operator is added to the macro, the values of the variables of the macro signature are updated according to the following rules.

Let the considered operator be \( o \) and the macro under construction be \( m \). For all \( p \) in \( \text{pre}(o) \) (\( \text{add}(o) \)), prem-count (add-count) is increased by one and \( p \) is added to \( \text{pre}(m) \) (\( \text{add}(m) \)) if \( p \) is neither in \( \text{add}(m) \) nor in \( \text{pre}(m) \). For all \( p \) in \( \text{add}(o) \), delm-not-prem-count (delm-prem-count) is deceased by one and \( p \) is removed from \( \text{del}(m) \) if \( p \) is in \( \text{del}(m) \) and not in \( \text{pre}(m) \) (in \( \text{pre}(m) \)).

For all \( p \) in \( \text{del}(o) \), \( p \) is added to \( \text{del}(m) \) and:

1. addm-count is deceased by one and \( p \) is removed from \( \text{add}(m) \) if \( p \) is in \( \text{add}(m) \),
2. delm-not-prem-count (delm-prem-count) is increased by one if either:
   (a) \( p \) is in \( \text{pre}(o) \), in \( \text{add}(m) \) (not in \( \text{add}(m) \)) and was not in \( \text{del}(m) \); or
   (b) \( p \) is not in \( \text{pre}(o) \), not in \( \text{pre}(m) \) (in \( \text{pre}(m) \)) and was not in \( \text{del}(m) \).

### 6.2 Find consistent and legal mapping between the predicates of two domains

In the previous section we showed how to find potential functionally equivalent macros from \( D_1 \) for every operator in \( D_2 \). To find a consistent and legal mapping from the predicates of \( D_2 \) to the predicates of \( D_1 \), we task the Z3 SMT solver [5] to find an assignment that satisfies the following constraints. Firstly, legal mapping constraints:

1. Predicates from \( D_2 \) should be mapped to predicates from \( D_1 \) with equal arity. Semantically, predicates are descriptors of the state of objects (unary predicates) or relations between two or more objects (binary, ternary or n-ary predicates). Therefore, mapping predicates from across arity groups, e.g. mapping a unary predicate (state of one object) to a binary predicate (relation between two objects), would not make sense in a practical set-up.
2. Operators from \( D_2 \) should be matched with macros from \( D_1 \) with the same number of parameters. Operators are tools that can be applied to some objects to change their status or relations. Therefore, for macros to be semantically sound, they should have the same number of parameters as the operators that they are functionally equivalent to.
3. The predicates mapping must be bijective as per Definition 44.

Secondly, consistent mapping constraints:

1. Predicates in preconditions, add effects and delete effects of operators from \( D_2 \) should be assigned to predicates in preconditions, add effects and delete effects of the same potential macro from \( D_1 \), respectively.
2. Operators from \( D_2 \) should be matched with one of their functionally equivalent macros from \( D_1 \).
7 Experiment

To demonstrate the feasibility and evaluate the scalability of our method, we modified some domains from the International Planning Competition (IPC). We then applied our method to verify the functional equivalence of the original domains and their modified versions. Table 2 lists the domains and the applied modifications. For functionally equivalent macros, our approach returns a consistent predicate mapping that makes the two domains functionally redundant. The verdict of functionally inequivalent domains could be either that no potential functionally equivalent macro can be found for an operator; or a consistent predicate mapping cannot be found between the potentially equivalent macros and their respective operators from the two domains.

To manage computing resources, the method is first applied in agile mode and then, if necessary, in normal mode. In agile mode the planner is allowed 180 seconds time slots to find subsequent macros after it finds the first potential functionally equivalent macro for an operator. In normal mode, the planner goes through the entire search space when searching for all potential functionally equivalent macros for each operator. If no consistent predicate assignment is found in the agile mode, the method is restarted in the normal mode.

Our implementation is applicable only to typed domains STRIPS subsets of PDDL without implicit equality predicates. This has limited the range of IPC domains that are suitable as inputs to our implementation. The experiments were run on a 2 x 2.6GHz 8-core Intel E5-2670 chip and 4GB of RAM per core. The algorithm had a time limit of 30 minutes to terminate.

7.1 Results and discussion

The experiments show that our algorithm managed to decide on the functional equivalence of the small to medium sized domains within a short period of time. The size of the domain can be linked to the number of its predicates, operators and the counts of their same-type parameters. The size of a meta planning problems (the problem of finding potential macros using a meta domain) is related to the size of the input domains, and is expressed by the number of grounded meta operators (GMO). The algorithm decided on all domains with GMO less than 3192 apart from the Rover and Scanalyzer domains with a deleted operator. In these two cases, our method has to fully explore the search space of the meta planning problem in the search for a proof of unsolvability of the problem of finding a potential macro for the deleted operator.

On the other hand, the algorithm could not terminate within the time limit when validating two versions of the Freecell domain and one Pipesworld version with GMOs from 17572. Note that our algorithm managed to terminate for the Freecell domain against its renamed version. Although this task has a GMO of 17572, our algorithm managed to reach a conclusive decision thanks to using the agile mode first. The huge increase of the number of grounded meta operators in association with the input domain size shows that our method suffers from the state space explosion problem. This is because our method formulates the task of
finding a potential macro as a combinatorial problem. Additionally, the use of a planner to prove the unsolvability of the meta planing problems has limited the size of the input domains that can be validated within the time limit. Searching for all potential macros necessitates proving unsolvability of the meta planning problem with the goal of finding one more potential macro. Moreover, the planner using a general heuristic did not help in reducing the impact of the the curse of dimensionality.

| Domain     | Version   | Eq    | CPU time   | States | P | O | GMO $D_1 / D_2$ |
|------------|-----------|-------|------------|--------|---|---|----------------|
| Gripper    | Add macro | Yes   | 0.29       | 2413   | 4 | 3 | 40 / 30        |
| Gripper    | Del Pred. | No    | 0.04       | 43     | 4 | 3 | (22)           |
| Peg-solitaire | Add macro | Yes   | 0.43       | 772    | 5 | 3 | 46 / 43        |
| Peg-solitaire | Del Pred. | No    | 0.12       | 256    | 5 | 3 | (31)           |
| Blocksworld | Add macro | Yes   | 0.35       | 1710   | 5 | 4 | 28 / 24        |
| Blocksworld | Del Pred. | No    | 0.008      | 4      | 5 | 4 | (20)           |
| Elevator   | Add macro | Yes   | 0.51       | 1710   | 5 | 4 | 40 / 36        |
| Elevator   | Del Op    | No    | 0.04       | 2      | 5 | 4 | 26 / 18        |
| Parking    | Add macro | Yes   | 1.63       | 33452  | 5 | 4 | 264 / 96       |
| Parking    | Del Pred. | No    | 1.63       | 14437  | 5 | 4 | (96)           |
| hiking     | Add macro | Yes   | 127.93     | 352680 | 8 | 7 | (484)          |
| hiking     | Del Op    | No    | 103.68     | 458006 | 8 | 7 | (104)          |
| floor-tile | Add macro | Yes   | 113.56     | 380276 | 10| 7 | 450 / 252      |
| floor-tile | Del Op    | No    | 0.58       | 5764   | 10| 7 | 216 / 224      |
| ChildSnack | Add macro | Yes   | 0.51       | 518    | 14| 6 | 86 / 102       |
| ChildSnack | Del Op    | No    | 0.1        | 89     | 14| 6 | (81)           |
| Logistics  | Add macro | Yes   | 270.92     | 3228714| 10| 11| 464 / 338      |
| Logistics  | Del Pred. | No    | 76.73      | 1128360| 10| 11| 356 / 332      |
| CaveDiving | Add macro | Yes   | 91.35      | 762318 | 15| 7 | 329 / 297      |
| CaveDiving | Del Pred. | No    | 4.45       | 49753  | 15| 7 | (265)          |
| Rover      | Add macro | Yes   | 750.98     | 74192  | 25| 9 | 2236 / 2786    |
| Rover      | Del Op    | No    | -          | -      | 25| 9 | 1237 / 2678    |
| Pipesworld | Add macro | -     | -          | -      | 12| 6 | 29280 / 480    |
| Pipesworld | Del Pred. | No    | 6.16       | 30112  | 12| 6 | (480)          |
| scanalyzer | Add macro | Yes   | 747.61     | 6436   | 6 | 4 | 2904 / 3192    |
| scanalyzer | Del Pred. | No    | -          | -      | 6 | 4 | (2896)         |
| Freecell   | Add macro | -     | -          | -      | 11| 10| 50432 / 17572  |
| Freecell   | rename    | Yes   | 956*       | 61506  | 11| 10| (17572)        |
| Freecell   | Del Pred. | -     | -          | -      | 11| 10| (17572)        |

Table 2: Eq: functional equivalence. CPU time (s). States: number of explored states by the planner. P, O: number of predicates and operators in the tested domain (original version). GMO: the sum of the number of grounded meta operators of each macro finding task part of the validation process. GMO values in parentheses indicate GMO of $D_1$ and $D_2$ are equal. * Agile mode time limit set to 11 sec for this experiment.
8 Conclusions and future work

Validating the functional equivalence of planning domain models has many application in KEPS, yet this topic has not received much attention from researchers. In this paper, we formally defined the concept of functional equivalence between planning domain models. Additionally, we introduced D-VAL, an automatic functional equivalence validation tool that uses a planner and an SMT solver to validate the functional equivalence of planning domain models. The soundness and completeness of our approach is theoretically proven. For functionally equivalent domains, D-VAL finds a consistent predicate mapping; under this mapping the domains are functionally redundant. On the other hand, for functionally inequivalent domains, D-VAL identifies operators have no functionally equivalent candidates in the other domain. It also detects cases when all operators have potentially functionally equivalent macros but an overall consistent mapping cannot be found.

Our experimental evaluation confirms the feasibility of our method and presents its scalability limitation. The experiments show that the performance of our method is impacted when the number of parameters of similar types is increased in the predicates and the operators of the input domains. This is an inherent problem in combinatorial search tasks.

As future work, we intend to develop a heuristic to help direct the search for potential macros. In addition to that we aim to study different methods for proving the unsolvability of the meta planning problems as our approach requires all potential macros for all operators to decide on non equivalent domains. Another suitable research direction is to automatically set the value of the agile mode time limit. This can be approximated from the GMO of the meta planning problem.

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