

Optimal Instantiation of Abstract Workflows using Logic and Circuits

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Abstract. The typical Service Oriented Architecture consists of two main layers. The concrete layer with concrete services whose functionalities are described in terms of pre- and post-conditions and non-functional properties in terms of QoS parameters, and the abstract layer with software applications whose functionalities are described in terms of abstract workflows and non-functional properties in terms of restrictions on QoS. During the execution of a workflow, the abstract services are instantiated into concrete services that meet the functional and non-functional requirements. This instantiation, that must be done on-the-flight, consists in a search on a combinatorial space of possibilities. In this paper, we propose a framework to efficiently solve the instantiation problem that is firmly grounded on logic. The framework adopts the Local-As-View approach in which the functionality of concrete services is described using views of abstract services, the quality of an instantiation as an overall utility function that combines the different QoS parameters, and the abstract workflows as conjunctive queries on abstract services. Using this representation, the problem of workflow instantiation is cast as a problem of query rewriting, from the area of integration systems. Then, building on related work, we devise an encoding of the workflow instantiation problem as a logical theory whose models are in correspondence with the instantiations of the workflow, and the best ranked models are in correspondence with the optimal instantiations of the workflow. Thus, by exploiting known properties of logical theories in d-DNNF format, we provide an efficient and scalable solution to the workflow instantiation problem. The approach does not only scale up to large instances, as the experimental results show, but is also sound and complete since, being founded on logic, is amenable to formal analysis.

1 Introduction

Under the umbrella of the Semantic Web, and supported by Service Oriented Architectures (SOA), the number of Web data sources and services has exploded during the last few years. For example, the molecular biology database collection currently contains 1,170 databases [?], a number that is 95 more than the previous year [?] and 110 more than two years ago [?]; tools and services, as well as

the number of instances published by these resources, follow a similar progression [?]. Thanks to this wealth of resources, users' tendency is to rely more on automatic methods for handling them such as data retrieval from public sources and analysis using Web tools or services composed in complex workflows.

The typical SOA consists of two layers. The concrete layer that is made of concrete services whose functionalities are described in terms of pre- and post-conditions and non-functional properties in terms of QoS parameters, and the abstract layer that is made of software applications whose functionalities are described in terms of abstract workflows and non-functional properties in terms of restrictions on QoS. The execution of an abstract workflow involves the instantiation of the abstract services into concrete services that meet the functional and non-functional requirements. This instantiation process can be seen as a search for a target instantiation on the combinatorial space of all valid instantiations. Thus, one is interested in efficient techniques for performing this search that are able to scale up as the number of concrete services or the complexity of the workflow increases. We call the problem of instantiating a given abstract workflow with concrete services, from a given pool of concrete services, such that certain QoS demands are met, the Workflow Instantiation Problem (WIP).

In this paper, we consider a restricted version of WIP that adopts the Local-As-View (LAV) approach [?]. In LAV, all elements in a problem are specified with a common language that is grounded on *abstract services* such that concrete services are described as views of abstract services, the quality of an instantiation as an overall utility function that combine the different QoS parameters, and the abstract workflow as a conjunctive query on the abstract services; this representation is similar to the one that is semi-automatically generated for the DEIMOS system [?]. In this version of WIP, the rules that define workflows (conjunctive queries) and concrete services (views) are created in a way that all the functional restrictions on pre- and post-conditions of services and their combinations are satisfied, and the QoS measures are represented by annotating each concrete service description with a real number that represent the overall QoS utility of the service.

Under these assumptions, the WIP can be cast as the well-known Query Rewriting Problem (QRP) for LAV which is central to integration systems [?]. The QRP consists of a conjunctive query that must be answered in terms of views in which the query and the views are described using LAV with abstract relations. This problem is important in the context of data integration [?,?], and query optimization and data maintenance [?,?], and several approaches have been defined that scale to a large number of views [?,?,?,?,?].

The recent approach of Arvelo et al. [?] is based on the efficient enumeration of models of a propositional logic theory. Given a QRP, a logical theory is constructed such that each model of the theory encodes a valid rewriting, and thus all valid rewritings are obtained by enumerating all models of the theory. This enumeration can be efficiently performed if the logical theory is in a certain normal form called deterministic and decomposable negation normal form

(d-DNNF) [?]. Thus, the approach consists in transforming (called compiling in the field of knowledge compilation) the logical theory into d-DNNF format for enumerating its models efficiently.

Yet d-DNNF theories not only support the efficient enumeration of models but other operations too. Among them, the enumeration of the best ranked models can also be performed efficiently on d-DNNF. Given a literal ranking function $r(\ell)$ that assign ranks to each literal ℓ , one defines the rank $r(\omega)$ of a model ω as the sum of the ranks of the literals made true by ω (i.e., $r(\omega) \doteq \sum_{\omega \models \ell} r(\ell)$), and say that ω is a best (ranked) model if there is no model ω' such that $r(\omega') < r(\omega)$.

Given a theory in d-DNNF, one computes the rank of the best models, and a best model, in time linear in the size of the d-DNNF. This computation transforms the DAG of the d-DNNF into a arithmetic circuit by replacing the AND nodes with ‘+’ and the OR nodes with ‘min’. The literal ranking function assigns values to the leaves of the circuit that are propagated to the root in linear time. The value of the root is the rank of the best model [?].

In this paper, we exploit the properties of d-DNNFs by constructing a logical theory whose models encode the valid workflow instantiations and best models encode the optimal (best) instantiations. Thus, the combinatorial search is reduced to the computation of a best model of a logic theory which can be efficiently performed once the theory is transformed into d-DNNF format.

The paper contains six more sections. The next section illustrates and motivates the WIP with a simple yet typical example. Section 3 summarizes the existing related work in three areas of selection of services, query rewriting, and knowledge compilation. Then, Sections 4 and 5 describe the architecture of the system and report our empirical results over different benchmark problems respectively. For the interested reader, Section 6 presents a formal description of the proposed approach together with an analysis. The paper concludes with a final discussion in Section 7.

2 Motivating Example

Consider a simple flight-information system which contains information about flights between cities and information about which cities are in the US. Such a system can be described using LAV with the two abstract services $flight(x, y)$ and $uscity(x)$. The former relates two cities x and y if there is a direct flight between them, and the latter tells whether x is a US city or not.

For the concrete services, assume that the available data sources on the Internet contain the following information:

- $national(x, y)$ relates two US cities that are connected by a direct flight,
- $one-way(x, y)$ relates two cities that are connected by a one-way flight,
- $one-stop(x, y)$ relates two cities that are connected by a one-stop flight,
- $flight-to-pa(x)$ tells if there is a direct flight from x to Paris,
- $onestop-to-pa(x, y)$ relates x and y if there is a flight from x to Paris with a stop at y , and

– $from-ny(x)$ tells if there is a flight from New York into x .

Furthermore, the concrete services are described using the abstract services:

$$\begin{aligned}
national(x, y) &:- flight(x, y), uscity(x), uscity(y). \\
one-way(x, y) &:- flight(x, y). \\
one-stop(x, z) &:- flight(x, y), flight(y, z). \\
flight-to-pa(x) &:- flight(x, PA). \\
onestop-to-pa(x, y) &:- flight(x, y), flight(y, PA). \\
from-ny(x) &:- flight(NY, x).
\end{aligned}$$

Now suppose that a user is interested in constructing a workflow able to retrieve the one-stop round-trip flights from US cities to any city in the world, such that flights can stop at any city.

$$W(x, w, y, z) :- uscity(x), flight(x, w), flight(w, y), flight(y, z), flight(z, x).$$

The following conjunctive query represents the workflow that defines this request in terms of abstract services. The workflow is defined in way that all issues about the binding of input/output parameters between services had been resolved such that any instantiation of the abstract services in terms of concrete services is a valid implementation of the workflow. Implementations correspond to compositions of concrete services in which a concrete service may implement one or more abstract services from the workflow, but each abstract service can be implemented by exactly one concrete service. For example, the following composition corresponds to one such implementation.

$$I(x, w, y, z) :- national(x, w), flight-to-pa(w), one-way(PA, z), national(z, x).$$

However, the following two compositions are not valid.

$$\begin{aligned}
I'(x, w, y, z) &:- national(x, y), flight-to-pa(y), from-ny(z), national(z, x). \\
I''(x, w, y, z) &:- one-stop(x, y), one-way(y, z), national(z, x).
\end{aligned}$$

The first composition is not valid because it maps the workflow variable y into constants PA and NY that denote different cities. On the other hand, I'' does not implement the workflow because the concrete service $one-stop(x, y)$ does not receive as input, or produce as output, the middle city where the flight stops and thus is not possible to ensure that this city is bound to the city w that is returned by the workflow.

These examples show that a proper workflow instantiations must handle constants such that not two different constants are mapped to each other either directly or indirectly via transitivity, and that all attributes that appear in a join or in the output need to be produced by the selected concrete services.

The QoS parameters are modeled by annotating the concrete services with utilities that characterize their behavior which are then aggregated during instantiation. Thus, as said before, the best instantiation is the one that minimizes (or maximizes) the aggregation of utilities.

3 Related Work

In this section we summarize the existing approaches that provide solutions to the problems of service selection, query rewriting and discuss related work in the area of Artificial Intelligence called knowledge compilation.

3.1 Service Selection

The problem of selecting the services that implement an abstract workflow and best fit the QoS-based criteria is known as the QoS-aware service selection or composition problem, which has been shown to be NP-hard [?]. This problem is a combinatorial optimization problem and several heuristics have been proposed to find a relatively good solution in a reasonably short period of time.

Rahmani et al. [?] present a distance metric-based heuristic that focus a backward search algorithm; this metric induces an order of the services in a way that sink nodes are unlikely to be visited. In a series of papers, Berardi and others [?, ?, ?] describe services and workflows in terms of deterministic finite-state machines that are encoded using Description Logic theories whose models correspond to solutions of the problem. Although reasoning methods for Description Logics formalisms could be exploited, scalability or performance of the proposed solution has not been reported.

Ko et al. [?] propose a constraint-based approach that encodes the non-functional permissible values as a set of constraints whose violation needs to be minimized; to traverse the space of possibly optimal solutions, a hybrid algorithm that combines tabu search and simulated annealing meta-heuristics is implemented. Experimental results show that the proposed solution is able to scale up to a large number of services and abstract processes. Cardellini et al. [?] encode one part of the QoS-aware service composition problem as a Linear Programming problem [?]. On the other hand, Wada et al. [?] treat the problem as a multi-objective optimization problem where the different QoS parameters are considered equally important instead of aggregating them into a single function. Then, a genetic-based algorithm is proposed to identify a set of non-dominated service compositions that best fit all the QoS requirements.

Alrifai and Risse [?] propose a two-fold solution that uses a hybrid integer programming algorithm to find the decomposition of global QoS into local constraints, and then, selects the services that best meet the local constraints.

Recently, two planning-based approaches have been proposed. Kuter and Golbeck [?] extend the SHOP2 planning algorithm to select the trustworthy composition of services that implement a given OWL-S process model, while Sohrabi and McIlraith [?] propose a HTN planning-based solution where user preference metrics and domain regulations are used to guide the planner into the space of relevant compositions. Finally, Lécué [?] proposes a genetic-based algorithm to identify the composition of services that best meet the quality criteria for a set of QoS parameters.

Although these solutions are able to solve the optimization problem and scale up to a number of abstract processes, none of them are tailored to semantically

describe the services in terms of abstract process, nor to use these descriptions to identify the services that implement a given workflow or best meet the user’s non-functional criteria.

3.2 Query Rewriting

A number of algorithms have been developed to find the rewritings of a given query; the most prominent being the bucket algorithm [?], the inverse rules algorithm [?,?], the MiniCon algorithm [?], and the MCDSAT algorithm [?]. Generally, query rewriting algorithms work in two phases. During the first phase, the algorithms identify the views that rewrite at least one sub-goal of the query, and during the second, these partial rewritings are combined into complete rewritings. The main difference between the algorithms is the criteria used to choose the relevant views to reduce the space of non-useful rewritings.

The bucket algorithm reduces the number of possibilities by just considering each sub-goal in the query in isolation, and selecting the views that are able to produce at least the attributes projected by the query. Since the attributes involved in the joins in the query are not verified, a large number of rewritings comprised of Cartesian products may be generated.

The Inverse Rules algorithm constructs a set of rules that invert the view definitions and establish how to compute tuples for the database relations from the tuples of the views. Similarly to the bucket algorithm, it can produce a large number of non-useful rewritings.

The MiniCon algorithm overcomes the limitations of the previous algorithms by identifying only views that rewrite a set of the sub-goals of the query, and that can be combined with the rest of the sub-goals. The key idea is to identify the mappings between the variables in each sub-goal to the variables in one or more sub-goals in the views, in a way that join variables in the query are mapped to join variables in the body of a view or to the distinguished variables of the view. Mappings between variables and sub-goals are represented in the so-called MiniCon Descriptions (MCDs) [?].

Finally, the MCDSAT algorithm is able to identify the query rewritings of a query by translating the problem of rewriting into the problem of enumerating the models of a propositional theory whose models are in correspondence with the rewritings of the query. The algorithm exploits the properties of d-DNNFs to efficiently enumerate the models of the theory. The MCDSAT algorithm has demonstrated to scale better than the MiniCon algorithm over a large number of benchmarks often showing performance improvements of several orders of magnitude. However, the MCDSAT algorithm was not designed for rewriting problems involving explicit constants, nor to compute the best rewritings with respect to a given utility function or cost model. In this paper, we propose an extended encoding that overcomes these limitations and apply the encoding to the Workflow Instantiation Problem.

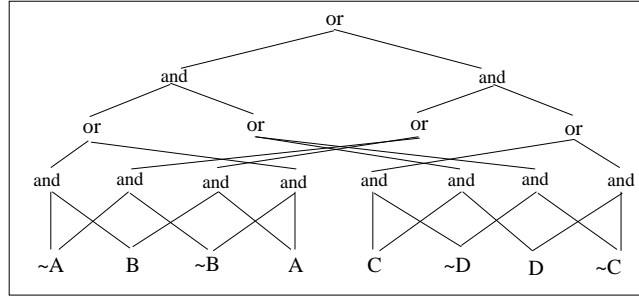


Fig. 1. A decomposable and deterministic NNF.

3.3 Knowledge Compilation

Knowledge compilation is the area in AI concerned with the problem of mapping logical theories into suitable fragments that make certain desired operations tractable [?]. Different compilation languages have been defined, for instance, Ordered Binary Decision Diagrams (OBDDs) [?], Negation Normal Form (NNF) [?], and Decomposable Negation Normal Form (DNNF) [?]. In this work, we make use of the properties of the deterministic DNNFs (d-DNNF) [?] to provide an scalable and efficient solution to the service selection problem.

A Negation Normal Form (NNF) theory is constructed from literals using only conjunctions and disjunctions [?], and it can be represented as a directed acyclic graph in which the leaves are labeled with literals and the internal nodes are labeled with \wedge and \vee ; see Fig. 1 for an example. This fragment is universal meaning that for every logical formula there is an equivalent one in NNF format. An NNF is said to be decomposable (DNNF) [?] if for each conjunction $\bigwedge_i \phi_i$, its variables are pairwise disjoint; i.e., $Vars(\phi_i) \cap Vars(\phi_j) = \emptyset$ for $i \neq j$. A DNNF supports a number of operations in polytime in the size of its DAG. For example, we can test whether a DNNF is satisfiable by a single bottom-up pass over its DAG in linear time. A DNNF is said to be deterministic (d-DNNF) [?] if for each disjunction $\bigvee_i \phi_i$, the disjuncts are pairwise logically contradictory; i.e., $\phi_i \wedge \phi_j \equiv \text{false}$ for $i \neq j$. The NNF in Fig. 1, for example, is decomposable and deterministic. A d-DNNF supports model counting in polytime in the size of its DAG, and model enumeration in polytime in the size of the output. Furthermore, given a literal ranking function r , one can compute the rank of the best model in polytime for DNNFs [?].

The fragments DNNF and d-DNNF are universal yet translating a CNF theory to DNNF format has an exponential cost in the worst case. This translation is referred to as compilation in the field. There is a publicly available compiler, called c2d,¹ that performs this compilation process and that makes use of modern SAT techniques such as conflict-directed backtracking, clause learning and caching [?]. This compiler incurs in the worst case in exponential space in a

¹ <http://reasoning.cs.ucla.edu/c2d>

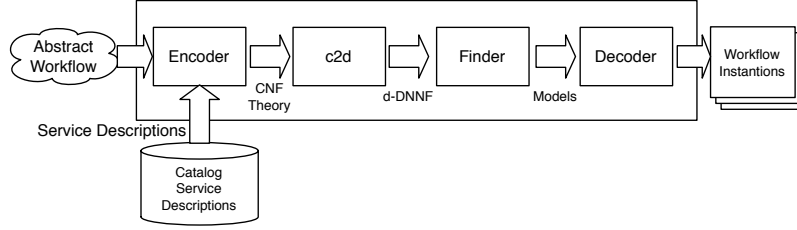


Fig. 2. System Architecture

parameter called the width of the decomposition tree that is related to the “connectivity” of the CNF theory. However, in our experiments, the CNF theories that are compiled are of low width.

4 System Architecture

We use an architecture that is comprised of a Catalog of service descriptions, the Encoder, the compiler c2d, the best model Finder, and the Decoder. Figure 2 depicts the overall architecture of the system. In this framework, an instance of Workflow Instantiation Problem is defined as an abstract workflow represented by a conjunctive query on abstract services which is given as input together with a set of concrete services defined by views of abstract services.

The Catalog is populated with descriptions of abstract and concrete services; each service is described in terms of input and output attributes, and annotated with a real value that represents the QoS utility of the service. The description of the concrete services, that are defined as views of abstract services, can be generated semi- or automatically using tools such as the DEIMOS system [?].

An input instance of WIP is encoded as a CNF theory whose models correspond to the instantiations of the workflow by the Encoder. The compiler c2d, an off-the-shelf component, compiles the CNF formula into d-DNNF. The Encoder translates the WIP instances into CNF theories, that are then converted into d-DNNF using c2d. The Finder computes a best model given the QoS parameters in linear time in the size of the resulting d-DNNF. It is important to remark that the compilation process needs to be performed only once as it does not depend on the value of the QoS parameters. Thus, even if the compilation happens to be costly in terms of time, this cost can be amortized since the resulting d-DNNF can be used to find best instantiations with respect to multiple values of the QoS parameters. Finally, the Decoder translates the best model returned by the Finder into a workflow instantiation that solves the WIP.

Given a CNF that encodes a WIP, its d-DNNF is a compact representation of all the workflow instantiations. That is, one can generate in a backtrack-free manner all the instantiations of the workflow. If the user is interested in a best instantiation given the QoS parameters, then it can be computed in linear time in

the size of the d-DNNF. If the user is interested in all the best instantiations, these can be computed in linear time in the number of them. Finally, if the user is interested in all instantiations, these can be also computed in linear time in the number of them. In the latter two cases, if such number is exponential (in the size of the input), the enumeration of the instantiations is also exponential but this complexity is intrinsic to the problem and thus cannot be avoided.

In order to make our results more accessible to a general audience, we decided to present the experimental results in the next section, and leave the formal and theoretical results for the following section. In this way, the interested reader may skip the formal details of the approach on a first reading.

5 Experimental Results

We conducted an empirical analysis on three benchmarks. All the experiments were run on a desktop machine with an Intel Core 2 Duo 2GHz CPU and 4Gb of memory, and the time was measured with the Unix time command.

The objective of the experiment is to assess the performance of the proposal on varying conditions. The main benefit of our approach is that one can compile the logical theory for a problem instance and then calculate all the instantiations, or the best ones, any number of times. The cost model for finding best instantiations can be changed with no need to recompile the logical theory. Therefore, the time complexity of our approach is basically the time to encode the WIP as a CNF plus the time to compile the CNF into a d-DNNF and the time to decode the models. The times to encode and decode are negligible compared to the time to compile the CNF. Because of this, we focus on the time to compile the benchmark problems.

The first benchmark consists of problems for air-travel queries. Concrete services are of the form $V_i(x, y) :- flight(x, y, AL_i)$ where AL_i is a constant that denotes the name of an airline, and $flight(x, y, AL_i)$ relates the cities x and y such that there is a flight between x and y served by AL_i . This concrete service is assumed to return all flights between two cities with an specific airline. The workflow has the form

$$W(x_1, \dots, x_n) :- flight(PA, x_1, z), flight(x_1, x_2, z), \dots, flight(x_n, NY, z).$$

The benchmark includes instances for workflows with 2 to 5 sub-goals and sets of 10 to 100 concrete services. The results for the compilation are shown in panel (a) of Fig. ?? . This is a plot in logarithmic scale that suggests a sub-exponential behavior. In any case, the results show good performance since realistic instances of the problem (sets of 100 airlines with 5-stop flights) can be compiled in 328 seconds. The size in disk of the d-DNNF for 100 airlines and 5-stop flights is 3.4Mb. On this d-DNNF, the best model can be computed in 0.29 seconds, and the enumeration of all models in 0.47 seconds.

In an attempt to induce an exponential growth in the compilation time, in the second benchmark we add a second concrete service for each airline. This modification increases the number of valid instantiations from linear to

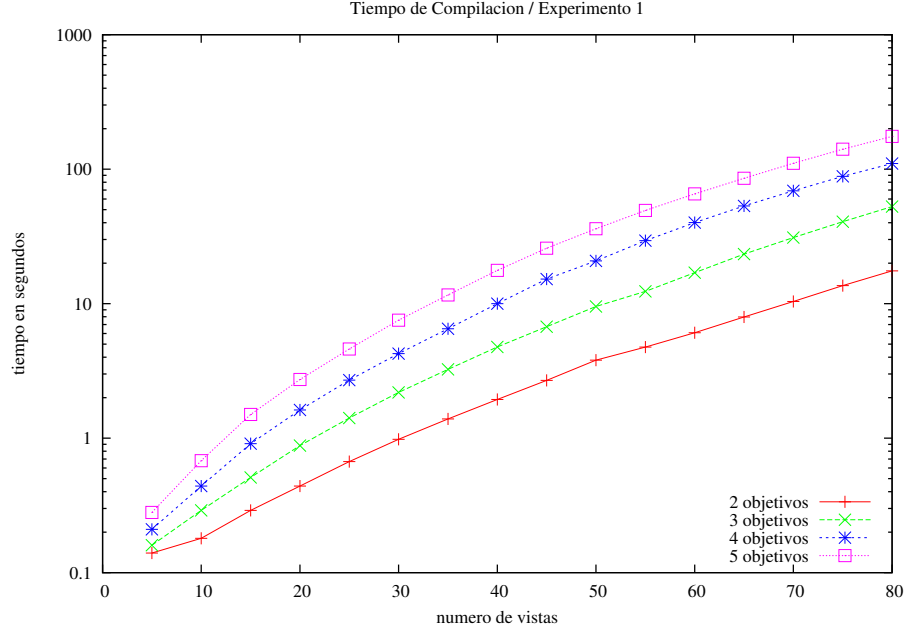


Fig. 3. Compilation times for experiments I and II for different number of goals and different number of views. The plots are in logarithmic scale, and the time is in seconds.

exponential since each leg of a flight can now be instantiated by two concrete services and thus a flight with n legs may have up to 2^n instantiations. We ran the compiler for instances comprising the same number of workflow sub-goals and total number of concrete services. The results plotted in logarithmic scale are shown in panel (b) of Fig. ??.

These tests show good performance for this type of problems, but they do not involve concrete services with multiple sub-goals. We therefore designed a third experiment that consists unstructured, randomly generated instances. Each instance contains three variables per abstract service, ten distinct variables and ten distinct constants, six sub-goals in the workflows, 2 to 5 sub-goals in the concrete services, and a varying number of services. The chance that an argument of an abstract service is bound to a constant is 50%. The results are depicted in Fig. ?. The compilation time for these instances does not grow monotonically since they are randomly generated. The same happens for the size of the theories and the number of models. For example, the d-DNNF for a problem with 45 views each with 5 sub-goals is of size 5.1Mb and has 1.26×10^8 models. The time to find the best model for this d-DNNF is 0.46 seconds while the time to enumerate all models is about 17 hours.

These are preliminary experiments, yet the results show that the proposed approach efficiently scales for problems with several goals and views. We believe

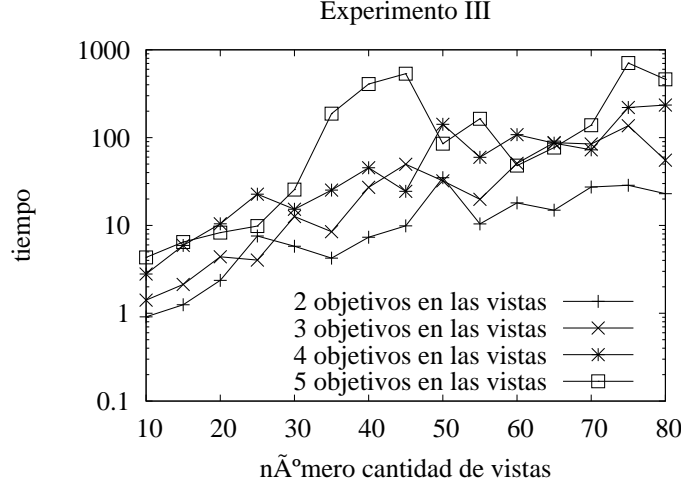


Fig. 4. Compilation times for experiments III for different number of goals and different number of views. The plots are in logarithmic scale, and the time is in seconds.

that these results are encouraging and motivate us to continue this research. We plan to conduct additional experiments with other types and sizes of workflows and, when possible, compare with other approaches.

6 Formalization

We consider service catalogs of the form $C = \langle S, T \rangle$ where S is a set of predicates that represent abstract services and $T = \{T_s\}_{s \in S}$ is a collection of tables that represents the result of evaluating the abstract services. In the context of the WIP, a service catalog C is an idealized description of the output produced by abstract workflows implemented by concrete services described as views. A workflow W over S is a conjunctive query of the form

$$W(\mathbf{x}) \text{ :- } s_1(\mathbf{x}_1), s_1(\mathbf{x}_2), \dots, s_m(\mathbf{x}_m),$$

where $s_i \in S$, \mathbf{x} is a vector of variables, and each \mathbf{x}_i is a vector of variables and constants. The result of W over C , denoted as $W(C)$, is the table with $|\mathbf{x}|$ columns that result of the projection of the relational join $\bowtie \{T_{s_i}\}_{i=1}^n$ over \mathbf{x} . The atoms in the body of W are called the (sub)goals of W , and the variables in the head of W are called distinguished.

A concrete service is described as a view V over C that, following LAV, is a query over S . Given a catalog C , a workflow W and a collection of n views $E = \langle \{V_i\}_{i=1}^n, \{E_i\}_{i=1}^n \rangle$, we are asked to find all the tuples in $W(C)$ that can be obtained from the views in E . That is, we need to find all the *instantiations*

$$R(\mathbf{x}) \text{ :- } V_{i_1}(\mathbf{x}_1), V_{i_2}(\mathbf{x}_2), \dots, V_{i_{m_i}}(\mathbf{x}_{m_i})$$

such that $R(E) \subseteq Q(C)$. A Workflow Instantiation Problem is a tuple $\langle S, W, \{V_i\}_i \rangle$ where S is a set of predicates that represent abstract services, W is a workflow over S , and $\{V_i\}_i$ is a collection of views that define the concrete services. We assume *safe* problems in the sense that all variables mentioned in the head of the workflow (resp. in the head of each view) appear in the body of the workflow (resp. in the body of each view). Further, we only deal with WIPs with no arithmetic predicates inside the workflow or views. An instantiation R is *valid* if for all catalogs $C = \langle S, T \rangle$ and extensions $\{E_i\}_i$, $R(E) \subseteq Q(C)$. A collection \mathcal{R} of valid instantiations is a solution if for all service catalogs $C = \langle S, T \rangle$ and extensions $\{E_i\}_i$, there is no \mathcal{R}' such that $\mathcal{R}(E) \subset \mathcal{R}'(E) \subseteq Q(C)$.

6.1 Logical Theories

We use an approach similar to the one described in [?] to encode the WIP. We have limited space to make a comprehensive description of the logical theory so the reader is referred there for details and formal results.

We identify workflow instantiations by enumerating the models of a logical theory $\Delta = \Delta_{com} \cup \Delta_{id}^1 \cup \dots \Delta_{id}^N$ where Δ_{com} specifies how to combine N independent copies theories Δ_{id} that cover the goals in W . Each Δ_{id}^i is a tagged copy Δ_{id} in which each literal ℓ is tagged as ℓ^i . The Instantiation Description (ID) theory Δ_{id} consists of different groups of clauses that guarantees that its models are in correspondence with partial instantiations, while the theory Δ_{com} contains additional clauses to guarantee a sound and complete combination of partial instantiations into a complete instantiation. The ID theory Δ_{id} consists of the following variables:

- $\{v_0, \dots, v_n\}$ to indicate which V_i is used, or v_0 to indicate the null ID.
- $\{g_1, \dots, g_m\}$ to indicate the goals covered by the view.
- $\{z_{j,k,i}\}$ to indicate that the j th goal in W is covered by the k th goal in V_i .
- $\{t_{x,y}\}$ to indicate that the variable/constant x in W is mapped into the variable/constant y in the view.

The ranges of the indices for the z and t variables depend on the problem.

The following clauses encode the WIP problem in terms of the WIDs. Rajaraman et al. [?] showed that for queries without negation or arithmetic comparisons, but with constants, and m goals and k variables in the head of the workflow, it is enough to consider instantiations of length at most $N = m + k$.

- C1. (At least one view is used): $\bigvee_{i=0}^n v_i$.
- C2. (At most one view is used): $\neg v_i \vee \neg v_j$ for $i \neq j$.
- C3. (Null view equals null): $v_0 \Rightarrow \neg g_j$ for $1 \leq j \leq m$.
- C4. (Views are useful): $v_i \Rightarrow \bigvee_{j=1}^m g_j$ for $1 \leq i \leq n$.
- C5. (Subgoals covered at most once): $z_{j,k,i} \Rightarrow \neg z_{j,l,i}$ for appropriate i, j, k, l .
- C6. (Scope of views): $v_i \Rightarrow \neg g_j$ for goals that cannot be covered by V_i .
- C7. (Consistency): $v_i \wedge g_j \Leftrightarrow \bigvee z_{j,k,i}$ for appropriate i, j, k .
- C8. (Dead variables): $v_i \Rightarrow \neg t_{x,y}$ for all x, y with $y \notin V_i$.
- C9. (1-1 for \exists vars): $v_i \wedge t_{x,y} \Rightarrow \neg t_{x,y'}$ for all existential variables $y, y' \in V_i$.

- C10. (Distinguished): $v_i \Rightarrow \neg t_{x,y}$ for distinguished x and existential $y \in V_i$.
- C11. (Existential): $v_i \wedge t_{x,y} \Rightarrow g_j$ for exist. $y \in V_i$ and goals g_j that contain x .
- C12. (Match): $v_i \wedge z_{j,k,i} \Rightarrow t_{x,y}$ for all x, y that must match if g_j is covered by goal k in V_i .
- C13. (If all vars in V_i are distinguished, it covers only one goal): $v_i \wedge g_j \Rightarrow \neg g_k$ for appropriate views v_i .

These clauses are the same clauses used by MCDSAT to encode QRPs [?]. In order to properly manage constant symbols, the clauses must be enhanced with:

- C14. (Direct inconsistency 1): $t_{x,A} \Rightarrow \neg t_{x,B}$.
- C15. (Direct inconsistency 2): $t_{A,x} \Rightarrow \neg t_{B,x}$.
- C16. (Direct inconsistency 3): $\neg t_{A,B}$.
- C17. (Transitivity 1): $v_i \wedge t_{A,y} \wedge t_{x,y} \wedge t_{x,z} \Rightarrow t_{A,z}$.
- C18. (Transitivity 2): $v_i \wedge t_{y,A} \wedge t_{y,x} \wedge t_{z,x} \Rightarrow t_{z,A}$.

Recall that, as shown in Section 2, the main issue when handling constants is to be sure that not two different constants are mapped into each other either directly or indirectly. Clauses C14–C16 prune direct inconsistent mappings, while the last two clauses implement a restricted propagation of mappings that prune indirect inconsistencies. Likewise, the theory Δ_{com} that specifies complete instantiations contains the following clauses:

- C19. (Cover all goals): $\bigvee_{j=1}^m g_j^i$ for $1 \leq i \leq N$.
- C20. (Disjunctive cover): $g_k^i \Rightarrow \neg g_k^j$ for $i \neq j$.
- C21. (Prune symmetries): $g_j^i \Rightarrow \bigvee_{k=1}^{j-1} g_k^{i-1}$ for $1 \leq j \leq m$ and $1 \leq i \leq N$.
- C22. (Direct inconsistency 4): $t_{x,A}^i \Rightarrow \neg t_{x,B}^j$.

These clauses provide a sound and complete characterization of WIPs in the sense that their models are in correspondence with the instantiations of the workflow.

6.2 QoS Parameters

For the QoS parameters, we assume a simple additive aggregation model in which each view V_i is associated with a cost $c(V_i)$ (negative if utility), and a complete instantiation with the sum of the cost of its views. An optimal or best instantiation is one with minimum cost, and the optimal value of the WIP is the cost of an optimal instantiation. A WIP always has a well-defined optimal value (if there are no instantiations, its cost is ∞), but it may have multiple best instantiations. The WIP with costs consists in finding all optimal instantiations or one instantiation, this depends on the particular application. In our formulation, this can be done from the d-DNNF that encodes Δ using the literal ranking function r that assigns $r(\ell) = c(V_i)$ if $\ell = v_i$, and $r(\ell) = 0$ if $\ell \notin \{v_1, \dots, v_n\}$.

7 Conclusions and Future Work

We have shown how the propositional theory used in MCDSAT for computing rewritings of queries can be extended to support constants symbols and thus adapted to the problem of instantiating abstract workflows. In this work, we adopted a LAV formulation of the workflow instantiation problem typically found in SOAs. Our formulation assumes that all concrete services are described using views over abstract services and that the workflow is expressed as a conjunctive queries over the abstract services. This workflow has resolved all the issues related to the binding of input and output parameters of services. What remains is the problem of finding the best instantiation of the workflow in terms of the QoS parameters. This formulation of the problem is supported by systems like DEIMOS that are able to generate in semi- or automatic manner LAV descriptions as the one required.

The experimental results show that the approach can be applied to real-sized workflow problems. The whole approach is only possible when the compilation of the CNF theory into d-DNNF format succeeds. In the future, we plan to address this limitation by adapting a branch-and-bound optimization algorithm that searches the combinatorial space of instantiations but prunes suboptimal branches with admissible heuristics.

We also are interested in using other target compilation languages like Ordered Binary Decision Diagrams.