A Survey on Workflow Satisfiability, Resiliency, and Related Problems

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Abstract

Workflows specify collections of tasks that must be executed under the responsibility or supervision of human users. Workflow management systems and workflow-driven applications need to enforce security policies in the form of access control, specifying which users can execute which tasks, and authorization constraints, such as Separation of Duty, further restricting the execution of tasks at run-time. Enforcing these policies is crucial to avoid frauds and malicious use, but it may lead to situations where a workflow instance cannot be completed without the violation of the policy. The Workflow Satisfiability Problem (WSP) asks whether there exists an assignment of users to tasks in a workflow such that every task is executed and the policy is not violated. The WSP is inherently hard, but solutions to this problem have a practical application in reconciling business compliance and business continuity. Solutions to related problems, such as workflow resiliency (i.e., whether a workflow instance is still satisfiable even in the absence of users), are important to help in policy design. Several variations of the WSP and similar problems have been defined in the literature and there are many solution methods available. In this paper, we survey the work done on these problems in the past 20 years.

Keywords: Workflow satisfiability, Workflow resiliency, Authorization constraints

1. Introduction

A workflow specifies a collection of tasks, whose execution is initiated by humans or software agents executing on their behalf, and the constraints on the order of execution of those tasks. Workflows represent a repeatable and structured collection of tasks designed to achieve a desired goal. They are used to model business processes that capture the activities that must be performed in a business setting to provide a service or product.
Workflow enactment services provide the run-time environment that controls and executes workflows. Both functional and non-functional requirements need to be considered when implementing workflow-based applications [1]. Workflow patterns for control-flow, data-flow, and organizational resources [2, 3, 4] can be used to elicit functional requirements, whereas security-related dependencies are specified in workflows as authorization policies and additional constraints on the execution of the various tasks.

Authorization policies specify that, in an organization, a workflow task is executed by a user who should be entitled to do so; e.g., the teller of a bank may create a loan request, whereas only a manager may accept it. Additional authorization constraints are usually imposed on task execution, such as Separation or Binding of Duties (SoD or BoD) whereby two distinct users or the same user, respectively, must execute two tasks. Workflows equipped with an authorization policy and constraints may be called “security-sensitive” [5].

While the enforcement of authorization policies and constraints is fundamental for security [6], it may also lead to situations where a workflow instance cannot be completed because no task can be executed without violating either the authorization policy or the constraints. These deadlock situations emphasize the conflict between business compliance and business continuity. Business compliance states that the business processes must follow the modeled workflows, respecting control-flow constraints, authorization policies and authorization constraints. Business continuity, on the other hand, states that the business must not stop even in adverse conditions, e.g., in the absence of authorized users. These conflicts may be resolved by an administrator granting additional permissions to a user, which violates the original intended policy and therefore hurts compliance. In alternative, an administrator can cancel the execution of a business process instance, which violates business continuity. An ideal solution is to avoid that any instance execution ever reaches a situation where this choice must be made.

The Workflow Satisfiability Problem (WSP) consists of checking if there exists an assignment of users to tasks such that a security-sensitive workflow successfully terminates while satisfying all authorization constraints. The run-time version of the WSP consists of answering sequences of user requests at execution time and ensuring successful termination together with the satisfaction of authorization policies and constraints. Such problems have been studied in several papers and there are many available solutions. Other related problems have also been studied in the literature. Workflow Resiliency amounts to checking if a workflow can still be satisfied even in the absence of a certain number of users, while Workflow Feasibility concerns the existence of a possible configuration of the authorization policy (considering, e.g., delegation or administrative policies) in which the workflow is satisfiable.

In this paper, we present a survey of the most relevant work in the areas of workflow satisfiability, resiliency, and related problems. Despite the number of published papers in these areas (Google Scholar returned 136 results to the query “workflow satisfiability” on June, 2017) and the considerable time span of the research (20 years, considering the work of Bertino et al. in 1997 [7] as the first),
to the best of our knowledge, there is only one previous survey on WSP [8]. That survey, however, is rather brief and only considers papers published until May 2014 (out of the 136 results described above, 59 have been published after 2015). There is also a related survey by Leitner and Rinderle-Ma [6] that explores the literature on security in process-aware information systems. Although there is some overlap between [6] and this paper, the former is very broad, considering several aspects of security. It is also brief when discussing workflow satisfiability or resiliency (the problems are only mentioned, there is no discussion about the solutions).

The rest of this paper is organized as follows. Section 2 describes the methodology adopted for the survey and some statistics about the published literature. Section 3 describes the specification of security-sensitive workflows, which is necessary to understand the many variants of the WSP; Section 4 discusses solutions to the WSP; Section 5 does the same for the workflow resiliency problem; Section 6 presents other related problems that have been less studied; and Section 7 concludes the paper.

2. Methodology

The methodology used in this paper is similar to that of [6, 8], which, in turn, follows widely accepted guidelines for research synthesis [9] and systematic literature review [10, 11]. The methodology is composed of 4 steps. First, we define the research questions (Section 2.1). Second, we perform an extensive literature search (Section 2.2). Third, we select the relevant papers found in the previous step (Section 2.3). Fourth, we classify the literature in terms of problems and solutions (Section 2.4).

2.1. Research identification

Our goal is to identify, classify, and evaluate the literature related to workflow satisfiability. To do so, we started by examining classic papers in this domain (e.g., [12, 13]) and identified the following research questions (RQ) to be answered:

RQ1 What kinds of control-flow patterns and authorization constraints are currently supported by WSP solutions?

RQ2 What related problems have been defined in the literature and how are they solved?

RQ3 What are the current research challenges in the WSP and related problems?

The first question (RQ1) concerns the current state of solutions to the WSP and its many variants (e.g., ordered WSP [14], valued WSP [15], and run-time WSP [16]). An answer to this question helps us in identifying a broad set of relevant related work. The second question (RQ2) concerns currently identified problems that have a strong connection to the WSP (e.g., resiliency [13], feasibility [17], and minimum users [18]). An answer to this question enlarges the
set of relevant work by considering other problems. The third question (RQ3) concerns the identification of challenges and gaps in the current solutions and points to possible future research directions.

2.2. Literature search

After defining the research questions, we performed the literature search and selection process, which is shown in Figure 1 and detailed in the next sections. The process was composed of 5 steps (the rectangles at the top of Figure 1), each producing as output a set of papers (the rectangles at the bottom of the same Figure). The number of papers in each set is shown in parentheses and the arrows represent the flow of the steps.

We performed a semi-automated search for literature published until June, 2017 using Google Scholar\(^1\) which indexes popular computer science research repositories, e.g., ACM DL\(^2\), IEEE Xplore\(^3\), SpringerLink\(^4\), DBLP\(^5\), and arXiv\(^6\). Since Google scholar does not have a publicly available search API, we used the scholar.py\(^7\) crawler. The search terms used were “workflow satisfiability”, “workflow resilience”, “workflow resiliency”, and “workflow feasibility”. We excluded patents from the search. The number of potentially relevant papers after this first step was 221 (cf. Fig 1). We then automatically removed duplicate results based on exact title matching (e.g., “Satisfiability and Resiliency in Workflow Authorization Systems” \(^8\) is a result for the queries “workflow satisfiability” and “workflow resiliency”). The resulting number of unique potentially relevant papers was 196 (cf. Fig 1). The next steps in the literature selection were performed manually.

2.3. Literature selection

We started by reading the title, abstract, and keywords of the results from the previous step. Many results contain exactly the terms used in the search

\(^{1}\)http://scholar.google.com/
\(^{2}\)http://dl.acm.org/
\(^{3}\)http://ieeexplore.ieee.org/
\(^{4}\)http://link.springer.com/
\(^{5}\)http://dblp.uni-trier.de/
\(^{6}\)http://arxiv.org/
\(^{7}\)https://github.com/ckreibich/scholar.py

Figure 1: Literature search and selection
but are out of scope for this paper. For instance, terms such as “feasibility” and “resiliency” have different meanings outside the access control and security literature. Most PhD theses and papers from the arXiv repository were also removed, because their contents are described in other publications. After this step, we were left with 77 papers to read. We then proceeded to fully read these papers and check if they were relevant to the survey. In some cases, even though the title and abstract indicate that the paper is relevant, it turns out not to be. After reading all the papers, we identified 63 unique relevant papers. Since there are many different “names” for the WSP and related problems (e.g., policy-based deadlock [19], obstruction [20]), our search did not capture every relevant paper (we did not include keywords such as “obstruction” in our search since it greatly increases the number of irrelevant results). We then extended the set of relevant papers by manually checking the references of the papers in the set and adding the relevant papers that we missed during the initial search (this process is known in literature review as backward snowballing [21]). In the end, the total number relevant papers was 78. We proceeded by analyzing the relevant papers and classifying them.

### 2.4. Results

Table 1 shows how we classified the relevant papers. There are three main categories of works, based on the problem solved (column ‘Problem’): WSP, resiliency, and others. Each category has sub-categories, based on the approach taken (column ‘Approach’), e.g., fixed-parameter tractable (FPT) algorithms and model checking. We list the papers in each category and sub-category (column ‘Papers’). Notice that some papers appear in two categories because they solve two problems (e.g., [13] is classified as “initial works” for the WSP and as “static, dynamic” for workflow resiliency.)

| Problem          | Approach                  | Papers      |
|------------------|---------------------------|-------------|
| WSP              | Initial works             | [7] [22]    |
|                  | FPT algorithms            | [26] [27]   |
|                  | Model checking            | [38] [39]   |
|                  | Others                    | [10]        |
| Resiliency       | Static, dynamic           | [13] [64]   |
|                  | Quantitative              | [65] [66]   |
|                  | Others                    | [70] [71]   |
| Others           | Workflow feasibility      | [17] [23]   |
|                  | WSP with delegation       | [74] [75]   |
|                  | Minimum users             | [18] [19]   |
|                  | Purpose                   | [80] [81]   |
|                  | Policy properties         | [82] [83]   |

Table 1: Classification of the papers
We describe all the papers in Sections 4, 5, and 6, ignoring formal details, but presenting the main results and key intuitions behind each work. Before presenting the papers in more detail, though, we outline the literature in terms of year and venue of publication, as well as author affiliation.

Figure 2 shows a histogram with the number of papers by year, from 1997 to 2017, while Table 2 shows the venues and journals where research in this area is usually published (the Table only shows those venues and journals with more than one publication). It is clear that this area of research is more popular than ever, with the number of papers growing each year and 2016 being the most popular year so far (16 papers). The most popular venue for research is SACMAT, with 13 papers, and the most popular journal is ACM TOPS, with 6.

Figure 3 shows, on the left, the distribution of papers by type of publication (conference, workshop or journal); in the middle, the distribution of papers by field of the venue where they were published (security, software engineering, which includes BPM, and others, e.g., algorithms, theory, etc.); and on the right, the distribution of authors by type of affiliation (academia, industry or both). The pie charts show relative numbers and absolute numbers in parentheses. As expected, most works are published in conferences (40 papers) about security (48) by authors working in academia. Figure 4 shows the distribution of authors by country of affiliation. In Figures 3 and 4, each author is counted only once, even if he/she has published more than one paper. The total number of authors is 103, which mostly work in academia (89), either in the United States (22) or in Europe (56 authors from 6 countries).

*SACMAT was called ACM Workshop on Role-Based Access Control (RBAC) until 2000, whereas TOPS was called ACM Transactions on Information and System Security (TISSEC) until 2017*
Table 2: Journals and venues with more than one publication

| Venue                                                                 | Acronym | #  |
|----------------------------------------------------------------------|---------|----|
| ACM Symposium on Access Control Models and Technologies               | SACMAT  | 13 |
| ACM Conference on Data and Applications Security and Privacy          | CODASPY | 3  |
| Business Process Management Workshops                                | BPMW    | 3  |
| Computer Security Foundations Symposium                              | CSF     | 3  |
| European Symposium on Research in Computer Security                   | ESORICS | 3  |
| International Frontiers of Algorithmics Workshop                     | FAW     | 3  |
| International Workshop on Security and Trust Management               | STM     | 3  |
| ACM Symposium on Information, Computer and Communications Security   | ASIACCS | 2  |
| IFIP Conference on Data and Applications Security and Privacy         | DBSec   | 2  |
| International Workshop on Software Engineering for Resilient Systems  | SERENE  | 2  |

| Journal                                                              | Acronym | #  |
|----------------------------------------------------------------------|---------|----|
| ACM Transactions on Privacy and Security                             | TOPS    | 6  |
| Journal of Computer Security                                         | JCS     | 3  |

Figure 3: Distribution of papers by type of publication (left) and field (middle). Distribution of authors by type of affiliation (right)

Figure 4: Distribution of the authors by country of affiliation

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3. Workflows and authorization

To understand why there are so many variants of the WSP and so many different possible solutions, it is necessary to understand the relationship between workflow models and authorization, as well as how security-sensitive workflows are specified.

A workflow specification spans at least three perspectives: control-flow, data-flow, and authorization (also called the resource perspective) [2]. Control-flow constrains the execution order of the tasks (e.g., sequential, parallel, or alternative execution); the data-flow defines the various data objects consumed or produced by these tasks; and the authorization specifies the organizational actors responsible for the execution of the tasks in the form of authorization policies and constraints. These three dimensions are interconnected, as each one of them influences the others. The set of behaviors (i.e., possible executions of the workflow) allowed by the control-flow is further constrained by conditions on the data, as well as by user assignments and constraints in the authorization perspective.

Consider a simple Loan Origination Process with four tasks (as shown in Figure 5 using the BPMN notation [2]): Request Loan (t1), Evaluate External Credit Rating (t2), Evaluate Internal Credit Rating (t3), and Approve Loan (t4). If task t1 has to be executed first, followed by t2 and t3 (in any order), followed by t4, then the behaviors t1, t2, t3, t4 and t1, t3, t2, t4 are allowed, whereas, e.g., t1, t4, t3, t2 is not (where t1, . . . , tn represents a sequence of n tasks executed in order, i.e., ti+1 is executed after ti). Now imagine that t2 is only executed for loans of more than 10k Euro, then behavior t1, t3, t4 becomes allowed, but only for some instances (those where the data object “loan amount” is less than 10k). If the organization running this workflow adopts the policy shown on the right of Figure 5 and the SoD constraints between t2 and t3 and between t3 and t4 (shown as dashed lines labeled by $\neq$ in the Figure), then any behavior containing, e.g., t2(a) and t3(a) is not allowed (where t(u) means that user u executes task t).

Given the conflicting goals of business compliance and business continuity, finding good (or even optimal) trade-offs has been a topic of research in the
Business Process Management (BPM) and security communities. The problems raised by these opposing views are further complicated by the interplay between the three perspectives (control-flow, data-flow, and authorization) introduced above. Notice that a common practice in the analysis of workflow satisfiability and resiliency is to abstract away from parts of a workflow specification. For instance, few works take into account the data-flow (some completely disregard it, e.g., [36], and some model it with non-deterministic decisions, e.g., [20]). It is also usual practice to limit the allowed control-flow constructs and supported authorization constraints. Different formulations of the WSP are concerned with at least three dimensions: control-flow models, supported authorization constraints, and problem setting.

3.1. Control-flow

There are three basic categories of control-flow support: linear workflows, which only admit a sequential execution of tasks (e.g., [22]); partial orders, which also allow parallel executions (e.g., [36]); and others (e.g., CSP [91] and Petri nets [92]), which add support for conditional branches and loops (e.g., [20]). It is known that a family of partial orders is needed to characterize one Petri net [93], which means that modeling the control-flow with Petri nets has the advantage of compactly representing a workflow that has to be specified as potentially many partial orders. It is also always possible to obtain a safe Petri net from a CSP process [94]. As described in [36], conditional execution can lead to execution paths of different lengths, which means that WSP solutions that try to assign users to every task in a workflow cannot be immediately applied.

3.2. Authorization

A plan \( \pi : T \rightarrow U \), where \( T \) is the finite set of tasks in the workflow and \( U \) is a finite set of users, is an assignment of tasks to users representing a workflow execution where \((t, u) \in \pi \) means that user \( u \) takes the responsibility of executing task \( t \). An authorization constraint \( c \in C \) can be seen as a pair \((T', \Theta)\), where \( T' \subseteq T \) is called the scope of \( c \) and \( \Theta \) is a set of functions \( \theta : T' \rightarrow U \) [36]. The functions in \( \Theta \) specify the assignments of tasks to users that satisfy the constraint. Instead of enumerating every function \( \theta \in \Theta \), it is common to define \( \Theta \) implicitly by using a specification device. Several classes of authorization constraints for workflows have been identified in the literature. They can all be used, with some ingenuity, to define the functions \( \theta \in \Theta \), so they can be recast in the form \((T', \Theta)\) shown above [31].

Counting constraints are of the form \((t_l, t_r, T')\), where \( 1 \leq t_l \leq t_r \leq k \). A plan satisfies a counting constraint if a user performs either no tasks in \( T' \) or between \( t_l \) and \( t_r \) tasks. One example of counting constraint is \((1, 2, \{t_1, t_2, t_3\})\), which is satisfied if a user \( u1 \) executes 0, 1 or 2 tasks among those in \( \{t_1, t_2, t_3\} \).

Entailment constraints are of the form \((T_1, T_2, \rho)\), where \( T_1 \cup T_2 = T' \) and \( \rho \subseteq U \times U \). A plan satisfies an entailment constraint iff there exist \( t_1 \in T_1 \)
and \( t_2 \in T_2 \) such that \((\pi(t_1), \pi(t_2)) \in \rho\). In Type 1 constraints, both sets \( T_1 \) and \( T_2 \) are singletons. In Type 2 constraints, at least one of the sets must be a singleton, whereas in Type 3 there are no restrictions on the cardinality of sets. Examples of Type 1, 2 and 3 constraints are \(\{\{1\}, \{2\}, \neq\}\), \(\{\{1, t_2\}, \{t_3\}, \neq\}\), and \(\{\{t_1, t_2\}, \{t_3, t_4\}, \neq\}\), respectively. The first constraint is satisfied if a user \( u_1 \) executes \( t_1 \) and \( u_2 \) executes \( t_2 \) (because \( u_1 \neq u_2 \)). The second and third constraints are satisfied if \( u_1 \) executes \( t_1 \) and \( u_2 \) executes \( t_3 \). Those are examples of SoD constraints, BoD constraints can be similarly defined by using \( = \) instead of \( \neq \). A special class of Type 1 constraints are equivalence-based constraints, of the form \((t_1, t_2, \sim)\), where \( \sim \) is an equivalence relation on \( U \). A plan satisfies this kind of constraint if the user who executes \( t_1 \) and the user who executes \( t_2 \) belong to the same equivalence class, e.g., same role (or to different classes for \( \neq \) constraints).

**User-independent constraints** are those where given a plan \( \pi \) that satisfies \( c \) and any permutation \( \phi : U \rightarrow U \), the plan \( \pi' = \phi(\pi(s)) \) also satisfies \( c \). I.e., user-independent constraints are those whose satisfaction does not depend on the individual identities of users. The SoD constraints presented so far are user-independent, whereas a constraint requiring a specific user to perform at least one task in a set is not user-independent.

**Class-independent constraints** are those whose satisfaction depends only on the equivalence classes that users belong to. Formally, let \( c \) be a constraint, \( \sim \) be an equivalence relation on \( U \), \( U^\sim \) be the set of equivalence classes induced by \( \sim \), and \( u^\sim \in U^\sim \) be the equivalence class containing \( u \). Then, for any plan \( \pi \), we can define a function \( \pi^\sim : T \rightarrow U^\sim \) as \( \pi^\sim(t) = (\pi(t))^\sim \). Finally, \( c \) is class-independent for \( \sim \) if for any function \( \theta \), \( \theta^\sim \in \Theta \) implies \( \theta \in \Theta \), and for any permutation \( \phi : U^\sim \rightarrow U^\sim \), \( \theta^\sim \in \Theta^\sim \) implies \( \phi \circ \theta^\sim \in \Theta^\sim \). One example of class-independent constraint is \(\{\{1\}, \{2\}, \sim\}\), where the classes induced by \( \sim \) corresponds to departments of a company. This constraint is satisfied if \( u(t_1) \sim u(t_2) \), i.e., the user executing \( t_1 \) and the user executing \( t_2 \) are in the same department. Indeed, every equivalence constraint \((t_1, t_2, \sim)\) (or \((t_1, t_2, \neq)\)) is class-independent and every user-independent constraint is class-independent with respect to the identity relation.

Other approaches to authorization constraint specification include Bertino et al.’s constraint specification language \([22]\) and Li and Wang’s Separation of Duties Algebra (SoDA) \([95]\). The first is based on rules built on pre-defined logic predicates. The resulting set of rules, called constraint base, is a stratified normal program. The second is an algebra for high-level policies that allows to express and formalize policies based on users’ attributes and the number of users executing tasks. The policies are enforced by low-level mechanisms such as static and dynamic separation of duties in Role-Based Access Control (RBAC) \([96]\).

Unlike for control-flow, it is not easy to classify authorization constraints in terms of expressiveness, partly because there are many different frameworks
to express them. For instance, entailment constraints of Type 3 clearly include those of Types 1 and 2, but counting constraints can also be used to express some forms of SoD [38], so entailment and counting constraints are not disjoint (i.e., in some cases, it is possible to express the same set of behaviors using a counting constraint or an entailment one). Also, clearly user-independent and class-independent constraints subsume parts of the other classes, but it is not clear which parts.

Figure 6 shows an attempt to systematically classify some classes of authorization constraints for workflow systems presented in the literature. The Figure shows the sets $\text{Ent.}$ of entailment constraints (the subsets of constraints of Types 1, 2, and 3 are not shown to keep the figure readable), $\text{Count.}$ of counting constraints, $\text{Eq.}$ of equivalence constraints, $\text{CI}$ of class-independent constraints and $\text{UI}$ of user-independent constraints. Naturally, $\text{Eq.} \subset \text{Ent.}$ and $\text{CI} \subset \text{Ent.}$, since an equivalence relation is an instance of a binary relation. The facts $\text{UI} \subset \text{CI}$ and $\text{Eq.} \subset \text{CI}$ were shown by Crampton et al. [36].

The Figure also shows the following intersections: $I_1 = \text{Ent.} \cap \text{Count.}$, $I_2 = \text{Eq.} \cap \text{Count.}$, $I_3 = \text{Eq.} \cap \text{UI}$, $I_4 = \text{Count.} \cap \text{UI}$, $I_5 = \text{Count.} \cap \text{CI}$. We can show that these intersections are non-empty by using SoD and BoD constraints as examples. $I_1$ and $I_2$ are non-empty because SoD and BoD can be specified using entailment: $(t_1, t_2, \neq)$ and $(t_1, 2, =)$, resp.; counting: $(1, 1, \{t_1, t_2\})$ and $(2, 2, \{t_1, t_2\})$, resp.; or equivalence, since $=$ is an equivalence relation. $I_3$, $I_4$, and $I_5$ are non-empty because both constraints are user-independent [32], which also makes them class-independent [36].

To the best of our knowledge, there has never been a comparison between the expressive power of other frameworks, e.g., SoDA and the constraint classes defined by Crampton et al. In any case, the most widely adopted kinds of constraints in practice (and in the examples of the works that we describe below) are simple forms of SoD and BoD.
3.3. Problem setting

Different formulations of the WSP consider at least two distinguishing characteristics: (i) is the order of the tasks considered? and (ii) is satisfiability checked at design-time (before the execution of any instance of the workflow) or at run-time (during execution)?

The separation between ordered and unordered WSP was presented in [14]. The unordered WSP admits as solution a plan $\pi$ assigning users to tasks in such a way that all tasks have an assigned user and all constraints are satisfied. The ordered version admits as solution a plan $\pi$ with an execution schedule $\sigma$, which is a tuple $(t_1, \ldots, t_k)$ such that $1 \leq i < j \leq k, t_i \neq t_j$, i.e., the assignment must respect the ordering of tasks defined by the control-flow. The ordered and unordered versions of the WSP are only equivalent for the class of well-formed workflows [14], i.e., workflows with the following property: for all tasks $t_i, t_j$ that can be executed in any order, $(t_i, t_j, \rho) \in C$ if and only if $(t_j, t_i, \tilde{\rho}) \in C$, where $\tilde{\rho}$ is defined as $\{ (u, u') \in U \times U : (u', u) \in \rho \}$ and $C$ is a set of entailment constraints.

A classification of WSP approaches in the design-time/run-time dimension was done in a recent survey [8]. Design-time techniques ensure the existence of at least one satisfying assignment, whereas run-time techniques enforce that a workflow instance follows a satisfying execution. As shown in [79], it is possible to use, at run-time, an algorithm that statically solves the WSP, but this is very inefficient, as it entails solving a new instance of the problem for each user request.

4. Workflow Satisfiability

Below, we describe the papers in the WSP category of Table 1. Each subcategory of Table 1 is reflected on a sub-section. Table 3 presents a comparison of relevant papers in each category (column ‘Paper’) in terms of control-flow models (column ‘Control-flow’), authorization constraints (column ‘Constraints’), and problem setting (ordered/unordered and execution time in columns ‘Ordered’ and ‘Time’, respectively), as described in the previous Section. Notice that, for the sake of readability, only the most relevant papers described in the next Sections are shown in the Table.

4.1. Initial works

The seminal works of Bertino et al. [7, 22] described the specification and enforcement of authorization constraints in workflow management systems, presenting constraints as clauses in a logic program and an exponential algorithm for assigning users and roles to tasks without violating them, but considering only linear workflows. Tan et al. [23] defined a model for constrained workflow systems that includes constraints such as cardinality, SoD and BoD. They defined the notion of a workflow specification as a partial order on the set of tasks and of a constrained workflow authorization schema, associating roles to tasks. Their main result is to find conditions for the set of constraints that ensure that for any
Table 3: Comparison of works in workflow satisfiability

| Paper | Control-flow | Constraints | Ordered | Time       |
|-------|--------------|-------------|---------|-----------|
| Initial works | | | | |
| [22] | Linear | Constraint Spec. Language | Yes | Design-time |
| [12] | P. order | Type 1 | Yes | Design-time |
| [13] | P. order | Type 2 | No | Design-time |
| FPT algorithms | | | | |
| [27] | P. order | Type 3 + Count + Equiv. | No | Design-time |
| [14] | P. order | Type 3 | No | Design-time |
| [31] | P. order | User-independent + Equiv. | No | Design-time |
| [32] | P. order | User-independent + Count | No | Design-time |
| [36] | P. order | Class-independent | No | Design-time |
| [37] | Conditional | User-independent | No | Design-time |
| Model checking | | | | |
| [13] | P. order | Type 1 | Yes | Design-time |
| [16] | 1-safe PN | First-order logic | Yes | Run-time |
| Others | | | | |
| [20] | CSP | SoD + BoD | Yes | Run-time |

user authorized to a task, there is at least one complete workflow instance when this user executes this task. Crampton [12] extended these ideas by defining Type 1 constraints, and developing an algorithm to determine whether there exists an assignment of users to tasks that satisfies the constraints. Solworth [24] defined an approvability graph to describe sequences of actions defining the termination of workflows with an RBAC policy, linear or conditional executions and the possibility of loops. In the same work, the author shows a polynomial algorithm to determine the minimum number of users per role to ensure that a workflow can terminate.

Wang and Li [25, 13] introduced the unordered version of the WSP, showed that it is NP-complete and that this intractability is inherent in authorization systems supporting simple constraints. They reduced the problem to SAT, which allows the use of off-the-shelf solvers, and showed that, with only equality and inequality relations (BoD/SoD), the WSP is Fixed-Parameter Tractable (FPT) in the number of tasks (since the number of tasks is typically smaller than the number of users). Wang and Li’s FPT proof motivated many later works by Crampton et al., mostly considering the unordered version of the WSP for workflows specified as partial orders.

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9FPT is a parameterized complexity class which contains the problems that can be solved in time $f(k) \cdot n^a$ for some computable function $f$, parameter $k$, and constant $a$. Many hard problems become less complex if some natural parameter of the instance is bounded. An example is the satisfiability problem parameterized by the number of variables: a given formula of size $n$ with $k$ variables can be checked by brute force in time $O(2^k n)$. The WSP is FPT when parameterized by the number of tasks (i.e., $k = |T|$).
4.2. FPT algorithms

Crampton et al. [26, 27] improved the complexity bounds for the WSP and showed that it remains FPT with counting and equivalence constraints. Later [14], they used the notion of constraint expressions (logical combinations of constraints) to support conditional workflows and Type 3 constraints by essentially splitting one instance of the problem into many instances, e.g., an instance of WSP for SoD/BoD constraints of Type 3 can be transformed into multiple instances of the WSP with SoD/BoD constraints of Type 1, and an instance of the WSP for a conditional workflow can be solved as many instances for parallel workflows. They also showed that the ordered version of the WSP is FPT for constraints of Type 1. In [28], they showed that the WSP remains FPT with seniority constraints.

Crampton et al. first presented FPT algorithms for the WSP with user-independent constraints in [29] and improved them in [30] with pattern backtracking. Cohen et al. [31] solved the WSP using techniques for the Constraint Satisfaction Problem, which allowed the authors to devise a general algorithm that works for several families of constraints. Their solution builds executions incrementally, discarding partial executions that can never satisfy the constraints. The authors showed that their algorithm is optimal for user-independent constraints. Cohen et al. [32] demonstrated the practicality of the previously designed algorithm by adapting it to the class of user-independent counting constraints and showing its superiority when compared with the classical SAT reduction of the problem. Gutin et al. [33, 34] studied the kernelization of the WSP and demonstrated that $O^*(2^{k \log_2 k})$ is a tight lower bound for the WSP with user-independent constraints (assuming the Strong Exponential Time Hypothesis).

Crampton et al. [35, 36] extended the notion of user-independent constraints to that of class-independent constraints, showed that the WSP remains FPT in this case and provided an algorithm to solve it. Crampton et al. [36] and Cohen et al. [32] experimentally compared the results of FPT algorithms against those of a SAT solver on workflows of up to 30 tasks and concluded that FPT algorithms are better because those based on the SAT solver run out of memory. Finally, Crampton et al. [37] extended the applicability of their FPT solution to support conditional workflows with release points, which specify that a constraint may be active only for some execution branches; as in [14], the solution is to split a workflow instance into many ones and solve multiple instances of the WSP.

4.3. Model checking

Xiangpeng et al. [38] presented a framework to integrate RBAC into the Business Process Execution Language (BPEL) [90], with authorization constraints expressed in temporal logic. They used model checking to verify that a given

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10A kernelization of a parameterized problem $Q$ is a polynomial-time computable function $K : (x, k) \rightarrow (x', k')$ such that $(x, k) \in Q$ iff $(x', k') \in Q$, and such that $|x'|, k' \leq h(k)$ for some $h(k)$. Here, $(x, k)$ is an instance of $Q$, and $h(k)$ is the size of the kernel.
BPEL process satisfies its security constraints. Wolter et al. [39] presented an approach to verify security properties of an annotated business process model by automatically translating it into a process meta language and using SPIN\footnote{http://spinroot.com/} for verification. Their implementation was integrated as a plug-in for the modeling tool Oryx\footnote{http://bpt.hpi.uni-potsdam.de/Oryx}.

Crampton and Huth [40, 41] showed that model checking on an NP-complete fragment of Linear Temporal Logic (LTL), called LTL(F), can be used to create and validate plans for security-sensitive workflows and argued that this approach is more robust, uniform, and expressive than previous formalizations. Later [42], they investigated a propositional encoding with Binary Decision Diagrams (BDDs) and compared it with the model checking approach to guarantee the satisfiability of workflow instances statically or dynamically. They showed that the propositional encoding is too costly because it has to be called for each access request at run-time, whereas the model checking approach can pre-compute a set of solutions for a workflow instance. In yet another work, Crampton et al. [43] presented three encodings in LTL(F) that can compute a set of solutions to the WSP. The slowest encoding considers the ordered WSP, while the other two consider unordered versions. They experimented with workflows of up to 220 tasks. The synthesis of monitors was left as future work.

Bertolissi and Ranise [44] introduced a class of symbolic transition systems, called composed array-based systems, capable of representing collections of security-sensitive workflows. They studied the verification of reachability properties of such systems and found sufficient conditions for the termination of a reachability analysis procedure. Later [45, 46], the same authors used this class of systems and proposed a methodology based on Satisfiability Modulo Theories (SMT) solving [98] to build run-time monitors capable of ensuring the successful termination of workflows subject to authorization constraints. This methodology was extended in [16] with a fully automated technique, an implementation, and an experimental evaluation. The technique works by synthesizing run-time monitors capable of ensuring that all executions terminate and authorization constraints in a workflow are satisfied. In [47] an extension of this technique was described. It is based on a refinement of the transition systems used to specify security-sensitive workflows. The refined transition systems are associated to a suitable notion of interface, forming a so-called security-sensitive component. The authors then show how to synthesize monitors for components and how to combine these monitors in a principled way.

This approach was implemented in two tools. The first, called Cerberus [48], integrates constraint specification, monitor synthesis, and run-time enforcement in workflow management system. The second, called Aegis [49] can synthesize run-time monitors for workflow-driven web applications. The monitors are capable of enforcing control-flow and data-flow integrity, authorization policies and constraints, as well as ensuring the termination of workflows.
4.4. Others

Basin et al. [50] considered the problem of choosing authorization policies that allow a successful workflow execution and an optimal balance between system protection and user empowerment. They treated the problem as an optimization problem (finding the cost-minimizing authorization policy that allows a successful workflow execution) and showed that, in the role-based case, it is NP-complete. They generalized the decision problem of whether a given authorization policy allows a successful workflow execution to the notion of an optimal authorization policy that satisfies this property.

Burri and Karjoth [51] studied the flexible scoping of authorization constraints in workflows containing loops. They introduced the notion of release points, which remove associations between users and their previously executed tasks, and extended the Business Process Model Notation (BPMN) [90] to support it.

In a following work [52], the authors used SoDA to enforce SoD constraints in a dynamic, service-oriented enterprise environment. They generalized SoDA’s semantics to workflow traces and refined it for control-flow and role-based authorizations. Their formalization, based on CSP, is the base for provisioning SoD as a Service, with an implementation using a workflow engine and a SoD enforcement monitor. Finally, in [53] [20], they used CSP to model workflows in two levels: control-flow and task execution, allowing them to synthesize monitors that enforce at run-time obstruction-free, or satisfying, workflow executions. However, the monitor in [52] only verifies if a trace of a workflow satisfies a SoDA term with respect to the past, being incapable of checking whether there is a future trace that can be concatenated in order to satisfy the workflow. On the other hand, the monitor in [20] enforces obstruction-freedom (which is equivalent to solving the WSP) but in an approximated way and may be too restrictive. The authors call their monitors Enforcement Processes and the problem of deciding the existence of such a monitor for a constrained workflow is called Enforcement Process Existence (EPE). Their naive solution to the EPE is double exponential in the number of users and constraints because it depends on checking failure-equivalence in CSP [99]. They present two approximate solutions, one is exponential and one is polynomial. The approximations are based on solutions to the graph coloring problem [100] and are overly restrictive because they may return ‘No’ even if an enforcement process does exist for the constrained workflow taken as input (although they make no approximations in the other direction, i.e., if there does not exist an enforcement process, the procedures always return ‘No’). They also implemented tool support for the specification and enforcement of constraints, but the evaluation was limited to a few workflows used as examples.

Schefer et al. [54] focused on BoD constraints in workflows with RBAC. They categorized these constraints into subject-binding and role-binding and provided algorithms to check their satisfiability. Yang et al. [55] defined several formulations of the WSP, considering different control-flow patterns, studied their complexity, and showed that, in general, the problem is intractable. Bo et al. [56] proposed a method to solve the WSP without exploring the space
of all possible user-task assignments. Their method is based on an Improved Separation of Duties Algebra (ISoDA) to describe a WSP instance, which is reduced to multi-mutual-exclusion expressions, whose satisfiability is determined by a bespoke algorithm.

Hummer et al. [57] studied the specification and enforcement of entailment constraints in distributed business processes, and how to detect—but not avoid—deadlocks. Ayed et al. [58, 59] considered the WSP and its complexity in distributed workflows, which can be intra- or inter-organizational. They used Petri nets to model the control-flow and Organization-Based Access Control (OrBAC) [101] for authorizations. Their approach starts from a global policy and derives local policies that can be enforced by components running parts of a workflow.

Jemel et al. [60] presented how the ECA (Event-Condition-Action) paradigm and agent technology can be exploited to steer authorization plans in order to satisfy dynamic constraints. Especially, they studied inter-instance constraints, i.e., constraints across instances of execution of the same workflow model. Inter-instance authorization constraints and their satisfiability in workflow systems have also been studied in [61], where the authors define a constraint specification language and propose methodologies to identify cases in which SoD constraints result in an anomaly (unsatisfiability is one of the identifiable anomalies, besides inconsistency and overlaps). These anomalies can be detected at design-time and prevented at run-time.

Holderer et al. [62] presented a hybrid solution to complete workflow instances whose execution was stopped because of the constraints. If a log is provided, they partition its traces into “successful” and “obstructed” by analyzing the given workflow and its authorizations. An obstruction can then be solved by finding its nearest match in the successful traces. If no log is provided, they flatten the workflow and its authorizations into a Petri net and encode the obstruction with a corresponding “obstruction marking”. The structural theory of Petri nets is used to provide a vector that may violate some firing rules, but reaches a final marking that completes the workflow.

Combi et al. [63] studied workflows with Temporal RBAC and the satisfaction of temporal constraints for these workflows. They comment that there are currently no approaches to workflow satisfiability and resiliency that take into account temporal constraints and leave this as future work.

5. Workflow Resiliency

Static, dynamic. Li et al. [102] introduced the notion of resiliency policies for access control systems, i.e., policies that require the system to be resilient to the absence of users. They defined the Resiliency Checking Problem (RCP), which amounts to checking if an access control state satisfies a given resiliency policy. Wang and Li [13] then studied resiliency in workflow systems and its relation to the WSP, defining three levels of resiliency based on when the users are allowed to be absent and whether they are allowed to return. In static resiliency, a number of users may be absent before a workflow instance execution; in decremental

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resiliency, users may be absent before or during a workflow instance execution, but absent users do not become available again; and in dynamic resiliency, users may become absent and available again. They showed that checking static workflow resiliency is in NP, while checking decremental and dynamic resiliency is in PSPACE. The authors observed that there are other possible formulations of resiliency that can be of interest.

The solution to workflow resiliency described in [64], relies on pre-computing reachability graphs [16] with a model checker and refining them with a given authorization policy. The refinement is performed by a depth-first search of the graph to prune those executions that do not satisfy the authorization policy used in the deployment context under consideration. This is combined with a (heuristic) method to generate subsets of users not containing \( k \) users (by adapting the pruning strategy from [12]) in order to find scenarios guaranteeing the termination of a workflow despite the absence of \( k \) users. The authors only consider static workflow resiliency, but they note that the solution could be adapted for quantitative resiliency by assigning weights representing availability to the edges in the reachability graph, as hinted at in [89]. This work is an extension of [79], where the authors define a class of Scenario Finding Problems, i.e. finding WSP solutions that also satisfy other properties defined by the user (e.g., a particular user executing a task or a minimal number of users). Each of these problems is solved by a different refinement of a reachability graph.

Quantitative. Mace et al. [65] defined quantitative workflow resiliency, in which a user wants to know how likely a workflow instance is to terminate given a user availability model. The authors solve the problem by finding optimal plans for Markov Decision Processes (MDP). The same authors [66] showed that alternative executions may lead to different resiliency values for each path, and defined resiliency variance as a metric to indicate volatility, claiming that a higher variance increases the likelihood of workflow failure. User availability models were discussed in more details in [67], categorized into non-deterministic, probabilistic, and bounded, with several encodings for the PRISM probabilistic model checker[13]. The same group studied the impact of policy design (adding or removing authorization constraints) on workflow resiliency computation time [68]. They were able to compute sets of security constraints that can be added to a policy in order to reduce computation time while maintaining resiliency. The authors then developed WRAD [69], a tool for workflow resiliency analysis and design, which automatically encodes workflows into PRISM, evaluates their resiliency and computes optimal changes for security constraints to ensure a resiliency threshold.

Crampton et al. [15] studied the Bi-Objective WSP, which is the problem of minimizing two weight functions associated to a valid plan, one representing the violation of constraints and one representing the violation of the authorization policy. The authors related this problem to workflow resiliency, claiming that

[13] http://www.prismmodelchecker.org/
Mace et al.’s translation to MDP is not necessary since the same metrics can be computed by constructing a graph where the nodes are partial valid plans, and the edges, connecting successive plans, are labeled with the probability of a user being available to execute the next task (checking every possible partial plan has exponential-time complexity). The Bi-Objective WSP is a generalization of the Valued WSP [87], which has as single objective minimizing the sum of both weights. Crampton et al. [89] reduced the RCP to the WSP and showed how to solve it using an FPT algorithm for the WSP. The RCP differs from workflow resiliency by considering three parameters: $s$ users, forming $d$ teams of size $t$, such that all teams are authorized to access the resources in a policy $P$. In contrast, $k$-resiliency for workflows just considers $k$ absent users and whether the remaining users can execute all tasks. However, the RCP is always static. The basic solution in the original paper about RCP [102] is to enumerate all subsets of $s$ users and check for satisfiability (using a procedure for $s = 0$ as a black-box), but there is a pruning strategy based on the redundancy of some subsets, to have a more efficient solution. Crampton et al. [89] solved the same RCP problem, using the same pruning strategy and their FPT algorithm as the black-box to decide satisfiability (by translating the resources in $P$ to a workflow). The authors mention that this basic reduction cannot be applied directly to decremental or dynamic workflow resiliency, but they point to their work on Valued WSP [87] as a possibility to do it, by using weights to represent the availability of users.

Others. Paci et al. [70] investigated resiliency in business processes specified in RBAC-WS-BPEL (an extension of BPEL that supports the specification of authorization policies and constraints). They extended RBAC-WS-BPEL with resiliency constraints and the notion of user failure resiliency, then proposed an algorithm to determine if a WS-BPEL process is user failure resilient. Lowalekar et al. [71] proposed a quadratic programming algorithm to generate user-task assignments that respect a security policy and are statically resilient. Lu et al. [72] studied dynamic workflow adjustment, i.e., how to minimally adjust existing user-task assignments, when a sudden change occurs, e.g., absence of users, so that the workflow can still be satisfied.

6. Related problems

Besides satisfiability and resiliency, there are other problems of interest to users designing an authorization policy or deploying a workflow in their organization. In this Section, we explore these related problems that have been identified in the literature.

Workflow feasibility. Khan and Fong [17] defined the problem of workflow feasibility, when there are rules to update the authorization relation (e.g., Administrative RBAC [96]). A workflow is feasible if there is at least one reachable access control configuration where the workflow is satisfiable. Later, Mehregan
and Fong [73] adapted the notions of workflow satisfiability, resiliency, and feasibility to define a protocol for policy negotiation on Relationship-Based Access Control (ReBAC) [103] with multiple ownership.

**WSP with delegation.** One way of avoiding the problems caused by absent users is to use delegation, a mechanism by which a user (delegator) can share or transfer a subset of his/her permissions with another user (delegatee), so that, e.g., absent users can transfer their permissions to available users in order not to disrupt the execution of workflows. There are several models for delegation in access control and Crampton and Khambhammettu [74, 75] discuss some models of delegation on workflow systems, depending on: execution model, task type, and delegation type. Crampton and Khambhammettu [74] described the relation between authorization delegation and workflow satisfiability, proposing algorithms for evaluating delegation requests in different workflow execution models, such that the requests are granted if the workflows remain satisfiable after the delegation. Crampton and Morisset [76] discussed an auto-delegation mechanism to automatically respond to the absence of authorized users, which they claim is useful in systems where the set of authorized users changes unpredictably over time. El Bakkali [77, 78] presented a solution to bypass WSP deadlocks at run-time and enhance the resiliency of workflow systems by using delegation and priority concepts.

**Cardinality-Constrained Minimum User Problem.** The Cardinality-Constrained Minimum User Problem (CMUP) [18] consists in finding the minimum number of users required for a satisfiable workflow instance. The original solutions to the CMUP apply either an integer programming solver or an algorithm based on a generalization of a greedy heuristic for coloring hypergraphs. Crampton et al. [15] showed that CMUP can be reduced to multiple instances of the WSP or a single instance of the BO-WSP. Kohler and Schaad [19] proposed a graph-based technique to compute minimal user bases to help policy designers avoid such situations. Their work is limited to RBAC policies. dos Santos et al. [79, 64] can compute minimal user bases by refining a reachability graph (as done for the resiliency problem) and Crampton et al. [43] can do the same with one of their encodings for LTL.

**Purpose.** Jafari et al. [80] developed a framework for formalizing and enforcing purpose-based privacy policies. They propose a language for expressing constraints about purposes of actions, whose semantics are defined over an abstract model of activities directly derivable from business processes. They show how to tie purpose-based constraints and authorization policies and present a model checking algorithm for verifying whether a state of the system complies with a set of policies. This algorithm is then used in a purpose reference monitor. The authors then comment that it is possible to define a workflow satisfiability problem which takes into account authorization and purpose constraints, but this is left as future work. De Masellis et al. [81] proposed a declarative framework based on a first-order temporal logic that allowed them to give a precise semantics to
purpose-aware policies and to reuse algorithms for the design of a run-time monitor enforcing purpose-aware policies. They also observe that handling purposes in the presence of authorization constraints requires to solve, at run-time, the WSP.

Access control policy properties. Sun et al. [82] analyzed the complexity of authorization in RBAC with security constraints by studying fundamental problems related to access control constraints and user-role assignment. They developed algorithms and complexity results for a series of problems and related them to the WSP. Intuitively, one can map each role in their setting to one step in a workflow, and the problem of assigning users to roles becomes the same as assigning users to steps. Ranise and Traverso defined an Action Language for Policy Specification (ALPS) [83] and used it to model access control for workflows. They showed that instances of the WSP fall in the larger category of reachability problems supported by their language. Garrison et al. [84] formalized the access control suitability analysis problem, which seeks to evaluate the degree to which a set of candidate access control schemes can meet the needs of an application-specific workload. Part of the solution to their problem is done via simulation, and during a simulation, they have to solve instances of the WSP. Calzavara et al. [85] studied the problem of detecting collusion attacks on workflows with administrative RBAC. Part of their static analysis technique amounts to solving instances of the WSP. Berge et al. [86] defined the class of Authorization Policy Existence Problems (APEP), where a positive answer means that an organization’s objectives can be realized. The WSP and the Bi-Objective WSP are both instances of an APEP. They also analyzed the complexity of these problems and, for particular sub-classes of constraints, developed FPT algorithms to solve them.

7. Conclusion

This survey investigated problems related to the satisfiability of authorization policies in workflow systems. We did not include other very broad and related areas, such as compliance, in order to limit the scope of the literature review. We examined 78 publications between the years of 1997 and 2017 and categorized them based on problems and approaches to solve them.

We found out that the area is more active than ever, that there are many variations on the basic WSP (e.g., ordered/unordered, design-time/run-time, valued), that the study of this problem has led to other interesting questions (e.g., resiliency and feasibility), and that some of these questions are even applicable outside the context of workflow management systems (e.g., web applications [49]). We can answer the three research questions posed at the beginning as follows.

RQ1 Virtually every group of authors defines their own control-flow and authorization specification models. It is common to limit control-flow support to either linear workflows (especially in the initial works) or partial orders,
although most recent works expand this to support also conditional executions and even loops. Likewise, authorization constraints are usually limited to Separation of Duties in its many forms. There are attempts to classify authorization constraints, but there is still no common framework to specify them.

RQ2 The main related problem is workflow resiliency and there is already a considerable amount of research on this topic. Besides that, all the problems described in Section 6 either have been identified from the study of the WSP or can be solved by reusing WSP techniques.

RQ3 It is clear that there is a trend of supporting more complex control-flow and constraints. Current works already consider realistic control-flow, but there is a need for more complex constraints (e.g., temporal, instance-spanning) and authorization policies. Developing a common understanding and classification of authorization constraints in security-sensitive workflows remains a challenge.

Acknowledgement

This work has been partly supported by the EU under grant 317387 SECENTIS (FP7-PEOPLE-2012-ITN).

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