A Systematic Literature Review on Extensions to the Role-Based Access Control Reference Model

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Abstract

Context: Since the United States National Institute of Standards and Technology proposed Role-Based Access Control (RBAC) as documented in the RBAC Reference Model in the late 1990's, domain-targeted extensions have been proposed. For example, the mobile domain has identified a need for permission granting and role activation.

Objective: The goal of our work is to aid practitioners and researchers in choosing an RBAC extension model, and in understanding how RBAC extension models are evaluated by providing an assessment of the state of RBAC extension models.

Method: We performed a systematic literature review of RBAC extension models that began with 1,716 papers of which 27 were deemed as primary sources for inclusion.

Results: We identified and classified the RBAC extension models into eight extension categories: Constraint, Context, Organization, Privacy, Task, Spatio-Temporal, Spatial, and Temporal. Only 8 of the 27 papers provided an implementation of their model in the form of an enterprise application or prototype. The primary domains that inspired extensions were the medical domain with 9 of the 27 models, enterprise workflows with 5 of 27, and mobile computing with 5 of 27.

Conclusions: Our literature review shows that all eight of the RBAC extension categories we identified deal with context whereby the privileges provided to a role are environmental depending upon factors such as location or time. RBAC extension model evaluation lacks a consistent set of metrics and evaluation of current models was found to range from providing scenario examples of the model in action to comparison to the RBAC standard. The magnitude and scope of extensions to the RBAC standard suggests a revised standard may be beneficial but in the meantime this work can serve as a starting place for researchers and practitioners.

Keywords: RBAC, access control, systematic literature review

1. Introduction

Software systems use access control mechanisms to determine which subjects can access which resources. Role-Based Access Control (RBAC) is a widely used access control mechanism designed for maintaining and managing an organization's access control based on assigning permissions to roles, and roles to users, instead of assigning the permissions directly to individual users. RBAC is used for securing various applications including web services, database applications, and healthcare applications. In RBAC, roles represent a set of permissions needed to perform a particular job function within an organization. Multiple users who are involved in that specific job function within the organization can then be assigned to a single role to inherit the required access. The ability to logically group users into roles associated with permissions becomes paramount for managing access control as an organization grows and the number of permissions and users scales upward. As permissions can be managed by role instead of by user, RBAC has been shown to significantly reduce complexity of security administration [1]. For example, if a user requires access to resources associated with a manager role within a given organization, security policy administrators need only associate the user with the manager role instead of assigning a set of individual permissions.

The use of RBAC has become popular since the National Institute for Standards and Technology (NIST) first proposed the RBAC standard in 2000 [2]. NIST requested that a unified standard be created by combining the Ferraiolo and Kuhn model [3] with the framework proposed by Sandhu et al. [4]. In 2004, this standard was adopted as ANSI/INCITS 359-2004 approved by American National Standards Institute[1] (ANSI) and the InterNational Committee for Information Technology Standards[2] (INCITS). The development of a standard was inspired by an economic impact study done during the 1990s [5], again in 2002 [1] and later confirmed in 2010 [6]. The study showed the cost savings of RBAC implementation and maintenance. Prior to the development of the RBAC standard, vendors proposed and implemented their own RBAC definition without general agreement on a unified definition of RBAC or RBAC features (e.g., inheritance relationships among roles). The RBAC standard includes the RBAC Reference Model which serves as a basis for defining the scope and functional specifications of RBAC features.

Since the introduction of the RBAC standard, researchers and practitioners have proposed domain-targeted extensions that add one or more features on top of components in the RBAC Reference Model [7]. For example, extensions that target the medical and mobile domains provide dynamic context or privacy around the access control policies. Further, Ni et al. [8] proposed an RBAC extension model to incorporate privacy concerns in to the RBAC Reference Model noting that the RBAC Reference Model is "not designed to enforce privacy policies and barely meet privacy protection requirements" with the introduction of privacy concerns in to the medical domain. These extension models are each building upon and adding features to a standard that was designed to reduce the economic impact experienced by enterprises and to increase interoperability [6].

The goal of our work is to aid practitioners and researchers in choosing an RBAC extension

[1] http://www.ansi.org/

[2] http://www.incits.org/

model, and in understanding how the RBAC extension models are evaluated by providing an assessment of the state of RBAC extension model1s. We established a set of extension categories, examined the state of the art in evaluations of the RBAC extension models, and categorized the motivations that have led to the RBAC extension models. To accomplish this goal, we seek to answer following research questions:

- RQ1: How can RBAC extension models be classified?
- RQ2: What are motivations behind the RBAC extension models?
- RQ3: How are RBAC extension models implemented by their authors?
- RQ4: How are RBAC extension models evaluated by their authors?
- RQ5: What domains have been targeted by RBAC extension models?
- RQ6: What commonalities exist across RBAC extension models?

We performed a systematic literature review to explore the current body of research in the area of extensions to the RBAC Reference Model. The review began with 1,716 papers, of which 27 were deemed primary sources for inclusion as extension models to the RBAC Reference Model. Our research provides the following:

- A starting place for researchers in the realm of authorization and as a reference guide for discovering the current state of the RBAC extension models.
- A basis for comparison and look up for what extension model to use for developers looking to find a model to fit their access control needs.
- A summary of current evaluation methods used in research on RBAC extension models.

The rest of the paper is organized as follows. Section 2 presents background and the RBAC standard. Section 3 presents methodology and process, which we used in conducting the systemic literature review. Sections 4-9 present analysis and discussion of the research questions. Section 10 discusses issues about the RBAC extension models. Section 11 concludes the paper.

2. Role-Based Access Control Standard

RBAC provides effective and efficient permissions management for operations, especially when sharing resources within an organization. Prior to the creation of the NIST RBAC standard, no general agreement on the definition of RBAC existed among practitioners or within the research community. Without a unified definition of RBAC, software developers described similar concepts and features of RBAC models using different terminology. The lack of consistent terminology was shown to slow the implementation of RBAC [6]. Moreover, in cases where organizations were concerned with adopting RBAC, evaluation and comparison of RBAC technologies developed by different vendors was difficult. NIST, in collaboration with industry and academics, worked on defining a set of consensus RBAC concepts and terminology and proposed a standard for RBAC that addressed these cost and interoperability issues by developing a common definition that can be used across different vendors.

NIST's work can directly benefit organizations by lowering the cost of early phase research and development, and implementation of RBAC. Since the RBAC standard was first introduced, a 2010 report by RTI International showed that the rate of RBAC adoption has rapidly grown [6]. The analysts estimate that the use of RBAC technology has saved industry \$6.1 billion from 1992 to 2009 and the research and development work by NIST to produce an RBAC standard has saved an additional \$1.1 billion that wold have otherwise been spent across the industry doing research and development on RBAC.

The RBAC standard includes three components of RBAC: core RBAC, hierarchical RBAC, and constrained RBAC. Each component includes a corresponding RBAC Reference model. We first describe the core RBAC, associated entities and other terminology. We next describe hierarchical RBAC and constrained RBAC, which are developed by incorporating new features into core RBAC.

2.1. Core RBAC

The four entities of the core RBAC Reference Model are:

- *Users*: A user is defined as a human being. Although the concept of a user can be extended to include machines, networks, or intelligent autonomous agents, the definition is limited to a person in the RBAC standard.
- *Roles*: A role is a job function within the context of an organization with some associated semantics regarding the authority and responsibility conferred on the user assigned to the role.
- *Permissions*: A permission is an approval to perform an operation on one or more RBAC protected objects in the system.
- *Sessions*: A session is a mapping between a user and an activated subset of roles that are assigned to the user.

In RBAC, a user can exercise a permission only if the user is assigned to a role that contains the permission. In addition to the four basic entities, two functions are defined: user assignment (UA) and permission assignment (PA) functions. UA represents assignment of users to roles. PA represents assignment of permissions to roles. Permissions are associated with possible users' pre-defined operation on an object (e.g., execute a file). Note that, at user or role activation, a session associated with user or role is established.

2.2. Hierarchical RBAC

The hierarchical RBAC Reference Model adds role hierarchies (RH) as a feature to the core RBAC Reference Model. RH incorporates a structure of roles in an organization using inheritance relationships among attributes such as roles. The role structure in an organization may use a role r_1, which inherits all permissions of another role r_2. For example, a manager role may inherit all permissions of an employee role. Role hierarchies help simplify access control policy creation and maintenance by reducing the number of individual role assignments for a user. Concept of the role inheritance describes the many-to-many mapping role inheritance relations among roles. Therefore, more than one role (e.g., two roles r_1 and r_1') can inherit all permissions of r_2 General role hierarchies can be extended to use the concept of multiple inheritances where r_1 inherits all permissions from more than one role (e.g., two roles r_2 and r_2') .

2.3. Constrained RBAC

The constrained RBAC Reference Model adds separation of duty relations to the core and hierarchical RBAC Reference Models. Separation of duty relations enforce conflicts of interest among roles. The Constrained RBAC model defines two types of separation of duty relations: static and dynamic.

- Static Separation of Duty (SSoD): SSoD restricts the conflicting-roles, which can be assigned to a single user statically. Suppose roles $Role_A$ and $Role_B$ conflict with each other. On situations where multiple roles can be associated with a single user, no permission is given to a user who is assigned to both $Role_A$ and $Role_B$ statically. SSoD is known to be too rigid for practical use in cases where a user should have permissions when a user is assigned to both $Role_A$ and $Role_B$. For example, an accounting clerk role requests a check and an accounting manager role approves the check. These two roles must be mutually exclusive to avoid a situation where one approves the check that the other requested.

- Dynamic Separation of Duty (DSD): DSD is known to be more flexible than SSoD. DSD restricts the conflicting-role assignments dynamically that are associated with a user. Suppose roles $Role_A$ and $Role_B$ conflict with each other. For situations where multiple roles can be associated with a single user, no permission is given to a user who is assigned to both $Role_A$ and $Role_B$ dynamically. Consider that a user can be assigned to the accounting clerk and accounting manager role at the same time. In such a situation, DSD can enforce that the accounting manager role does not approve her/his requested checks but can only approve checks that others have requested.

3. Methodology and Process

We adopted and applied a systematic literature review process following recommendations from Kitchenham and Charter's suggested processes [9]. The systematic literature review process was broken down into four stages and the rest of this section is broken down by each stage. The stages were as follows:

- Step 1: Development of a search strategy
- Step 2: Elimination of papers based on title criteria
- Step 3: Elimination of papers based on abstract criteria
- Step 4: Elimination of papers based on content and elimination criteria

Table 1: Paper counts after applying Step 1

	RBAC	**role based access control**	**role-based access control**	**Total**
Google Scholar	651	213	435	1299
ACM Portal	500	20	720	1240
IEEExplore	200	40	230	470
CiteSeerX	100	100	150	350
Totals	1451	373	1535	3359
Combined				**1716**

3.1. Step 1: Search Strategy

For the first phase of our systematic literature review, we developed a search strategy for finding papers. The search strategy was executed by an automated comprehensive search taking as input a set of academic search engines and a list of search terms. The search was performed by applying each search term to each engine incrementally until the stopping criteria were met. Table 1 lists the four search engines along the left most column with the three search terms across the top row along with the papers for each criterion and engine combination. The total column represents the total for each individual search engine with a grand total across all search engines. The combined total represents the net paper total after removing duplicate entries. The search algorithm was performed as follows:

1. Call to search engine with current search position and current search term.
2. Parse results and extract paper title, authors and year of publication.
3. Compare results against stopping criteria:
    - If the size of the result set is greater than or equal to 1000 then stop.
    - If the last ten results did not contain the search term phrase within the title then stop.
4. If stopping criteria not met, increment search position and go back to step one.

The result set size stopping criteria was chosen due to a technical limitation of some search engines. The stopping criteria related to the last ten titles are meant to stop after relevant results are no longer being returned by the search engine. After gathering all 12 data sets, we combined the papers into a master list, which includes only distinct papers by systematically comparing the bibliographic information for each. Out of the master list of 1,716 papers, two reviewers conducted a series of elimination rounds to narrow the list of papers and identify primary sources. The two reviewers are denoted by Author 1 and Author 2 where the former is the first author on the paper (Eric) and the latter is the second author on the paper (JeeHyun). Table 2 shows the total number of papers selected by each reviewer for each round and how many papers from the disjoint set for each round survived to the next round.

3.2. Steps 2-4: Elimination Rounds

The elimination rounds were conducted based on reading of the title, abstract, and finally the paper itself. While each elimination stage had a unique set of criteria for elimination, the general procedure for elimination for the researchers was as follows.

- The two first authors independently classified papers as relevant, irrelevant or uncertain based on elimination criteria
- Those papers marked as relevant by both reviewers were kept and those marked irrelevant by both were thrown out.
- Papers marked as relevant or irrelevant by a single reviewer were combined with all papers marked as uncertain and discussed by both reviewers. From this discussion, papers were either thrown out or kept until the next round of the review.

3.2.1. Step 2: Title Elimination

The first round of elimination was performed by examination based on the title. Each author was tasked with deciding on elimination by answering the following questions:

- Did the title contain a reference to 'role-based access control' or 'RBAC'?
- Did the title contain a reference to 'model'?

The title elimination round resulted in Author 1 selecting 305 papers, and Author 2 selecting 176 papers with 149 papers of overlap between the two. All 149 papers found to be in both reviewers lists were kept. The 332 papers found not to be in common were then slated for a second round of review. The second round of review consisted of the reviewers discussing their perception of each paper title as the title related to the elimination criteria and making a joint decision to keep or reject. The second review resulted in 149 rejections and 141 being retained.

3.2.2. Step 3: Abstract Elimination

The second round of elimination was based on reading of the abstracts of papers that survived title elimination. The reviewers read each abstract and evaluated relevancy based off:

- Does the abstract mention a proposed model?
- Does the abstract mention extension of role-based access control?
- Does the abstract mention an implementation, evaluation, or domain for their model?

The abstract elimination round resulted in Author 1 selecting 86 papers, and Author 2 selecting 102 papers with 51 papers of overlap between the two. All 51 papers found to be in both reviewers lists were kept. The 137 papers found not to be in common were then slated for a second round of review. The second round of review consisted of the reviewers discussing their perception of each the paper abstract as each related to the elimination criteria and making a joint decision to keep or reject based on the joint outcome of the discussion. The second review resulted in 116 rejections and 21 being retained.

Table 2: Elimination Rounds

		Title	Abstract	Content
Author 1		305	86	46
Author 2		176	102	42
	Overlap	149	51	24
	Disjoint	332	137	64
	Rejected	191	116	61
	Retained	141	21	5
	Num Left	290	72	27

3.2.3. Step 4: Content Elimination

The final elimination round involved reading the entire paper and answering five questions that would serve as the basis for elimination. The data collected by answering these questions served as the basis towards answering the research questions. Each reviewer seeks to answer following questions based on the content of the paper:

1. Does this model extend the RBAC Reference Model (Exclusion)
2. Do the researchers give evidence that the RBAC Reference Model needs extension? (Inclusion)
3. Was the paper and subsequent model inspired by a real world example? (Conditional Inclusion)
4. Did the researchers offer any evaluation of the proposed model? If yes, how did they do one? If no, why? (Conditional Inclusion)
5. Did the authors implement their model? (Inclusion)

Question 1 was a definitive exclusion criterion as any paper that failed in the affirmative was rejected. Questions 3 and 4 were marked as conditional includes given that they were connected in making a decision. A paper that met question 3 but not 4, or met 4 but not 3 would be included because for some cases the real world examples served as research evaluations and without this conditional include the paper list size would be too small to be significant.

The content elimination round resulted in Author 1 selecting 46 papers, and Author 2 selecting 42 papers with 24 papers of overlap between the two. Between the two reviewers selections, there were 64 papers not in common, of which, 59 were rejected and 5 retained after a second review.

3.3. Extraction

After selection of primary sources, the next step was to extract data from each paper that pertained to our research questions to look for trends. The first step was to take the individual data generated from the final elimination round and organize this information around the research questions. During the paper reading round and resulting data, the fact that the papers were falling into a number of categorizations became evident. Thus, the first step undertaken was to answer the question of what categories exist for the RBAC extension models and what papers fell into what categories.

4. RQ1: Classification

How can RBAC extension models be classified?

During the paper reading phase, we identified that a variety of common terms were emerging to describe the RBAC extension models. We developed a process by which to build a classification of the RBAC extension models based upon observations during the paper reading phase. For example, the paper "Privacy-aware role-based access control" [8] brings in the notion of privacy explicitly within the title of the paper and the name of their model. Some papers appeared to present a direct pronouncement of their classification, whereas others were less obvious. Thus, we developed a set of guidelines to aide in determining a set of eight categories. In developing these guidelines, we defined each category by a single noun-phrase descriptor. The guidelines were as follows:

- Model Name - Does the name of the model classify itself?
- Self Assessment - Do the authors of the paper directly identify a descriptor for their model within the body of the paper?
- Repetition of Phrase - Does the body of the paper present the same phrase repeatedly when discussing their model?

The previous example paper "Privacy-aware role-based access control" [8] contained "privacy" in the title and in the name of the model leading to the creation of the Privacy category and the subsequent placement of the paper under that category. By comparison, the paper "An extended RBAC model based on granular logic" [10] does not contain a direct categorization in the title or model name. However, in reading the body of the paper, we determined that the paper discussed RBAC extension based on context. In Section 4.1, we offer definitions for each of the eight observed categories.

4.1. Results

We provide a definition for each observed model category based on data extracted from the primary sources and the English definitions for each noun-phrase. Some category descriptors contain abbreviations in parenthesis that match the shortened name found in Table 6 (within Appendix 1) which presents each primary source within it's designated category.

- **Context**: The extension model integrates contextual information into the RBAC standard model. Context is defined as a user's current state and environment (e.g., location, time, system resources, network state, network security configuration, etc). The user's access privileges are dependent upon the values of the current state and environment at any given time.
- **Constraint (Const)**: The extension model provides conditional restrictions on permissions of given roles. The constraint is either static or dynamic. For example, a doctor may modify any medical record for which the doctor is assigned as the designated primary care physician.

This example describes a doctor's permission with a conditional restriction - "only when the doctor is assigned as the designated primary care physician may the doctor modify a particular medical record".

- **Organizational (Org)**: The extension model is concerned with providing mechanisms and entities that allow for RBAC across multiple organizations. Typically, users may have the same role name in different organizations, but may have different access privileges due to departmental variations.

- **Privacy (Priv)**: The extension model provides entities and mechanisms to describe privacy policies, which are legal statements or documents about disclosure or management of personally identifiable information such as name, address, or date of birth.

- **Task**: The extension model provides task entities which are associated with permissions and roles. A task is a fundamental unit of a business activity. Different from core RBAC, in task-role-based access control model, roles are not directly associated with permissions. Roles are associated with tasks that are associated with permissions. For example, the employee role is associated with a task to write a report. This task is then associated with a permission.

- **Spatio-Temporal**: The extension model combines the use of either or both spatial (location-based) and temporal (time-based) constraints in specifying access control policies. For example, specific locations permit roles to conduct actions from 8:00 a.m. to 5:00 p.m.

- **Spatial**: The extension model provides spatial (location-based) constraints in specifying access control policies. For example, in organizations, locations are enforced whereas a specific role is permitted to conduct an action. Consider that an employee works only at a specific location. In such cases, a role should allow access to required resources only when the user is in that location. Spatial constraints can integrate with roles, user-role assignments, or role-permission assignments.

- **Temporal (Temp)**: The extension model provides temporal (time-based) constraints in specifying access control policies. For example, in organizations, periodic temporal durations are enforced whereas a specific role is permitted to conduct an action. Consider that a temporal employee works only from 9:00 a.m. to 3:00 p.m. In such cases, the temporal employee role should only be allowed to access required resources during the interval. Temporal constraints can integrate with roles, user-role assignments, or role-permission assignments.

4.2. Analysis and Discussion

The 27 primary sources produced a set of eight hierarchical categories. Table 6 summarizes each primary source under their designated category and furthermore, displays the perceived hierarchy of the categories. Figure 1 shows the hierarchy structure among categories and the counts of primary sources for each. For categories that have sub-categories, the totals of the category and sub-categories is provided as the second number in the figure. The Constraint, Organizational,

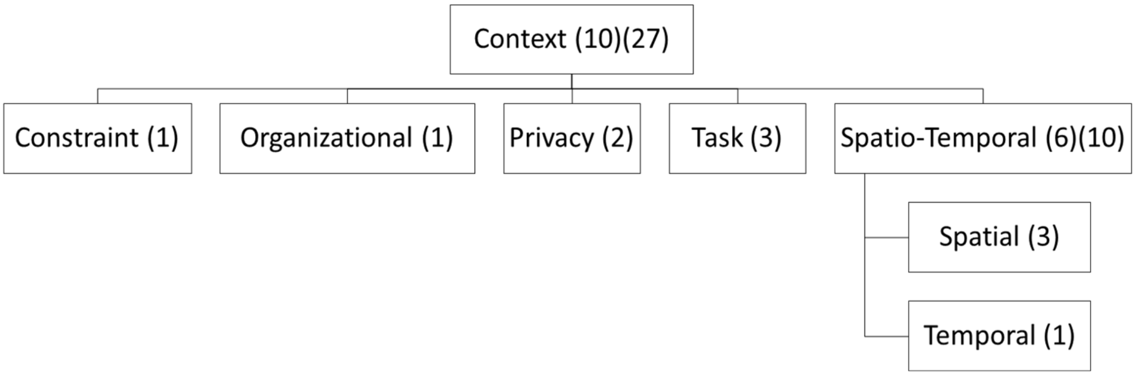

Figure 1: Structure of categories within the RBAC extension models.

Privacy, Task, and Spatial and Temporal categories can be special cases of the Context category. The Spatial and Temporal categories were treated as subsets of the broader category of Spatio-Temporal since this category encompasses them individually and the Spatio-Temporal category was derived from primary sources directly.

When looking across all categories, we noted that each category added specific features on top of the RBAC Reference Model. These features were under the surface adding contextual relationships between the core user, permission and role entities. Thus, we concluded that all categories stemmed from the context category, of which some primary sources were already deemed direct members.

For example, in the case of the Privacy category, the models added entities such as purpose binding to represent within the model data collected for one purpose should not be used for another purpose without user consent [8]. While the new entity provided by the Privacy based models is inspired by domains such as healthcare where privacy is of legal concern, the underlying mechanism that drives purpose binding is providing context around making an access control decision. The system must take into account not just a static set of permissions a user has through their roles, but also the context of the data being accessed as that data relates to privacy policy. In the spatio-temporal models, a users location and the time of day are two factors that can be taken into account when activating a role or verifying a permission. The concepts of location and time are properties of the user and place specific contexts around the role and permission entities.

We found eight categories that exist within the RBAC extension models: Constraint, Context, Organization, Privacy, Task, Spatio-Temporal, Spatial and Temporal. The context category was a superset of all other categories since all categories were found to consider context.

5. RQ2: Motivations

What are motivations behind the RBAC extension models?

During the paper reading phase, we identify motivations of the RBAC extension models by category. We identify motivations by looking for issues regarding why the RBAC reference model was inadequate and how the authors addressed the issues. For example, the papers in the Spatial Category argue that the RBAC reference model does not support spatial constraints, which are used in determining users' access decisions based on spatial dimensions (i.e., location). To address this issue, the authors developed the RBAC extension models by incorporating additional spatial entities and their relations with existing entities of the RBAC Reference Model.

5.1. Results

We describe motivations behind the RBAC extension models by category as follows:

- **Context**: The RBAC Reference Model does not support the notion of context constraints related to changes in environments. Therefore, RBAC belongs to the static access control model, which may not capture changes in environments.
- **Constraint**: The RBAC Reference Model has limitations on its features such as delegation and role hierarchy. For example, partial inheritance in role hierarchy needs to be developed.
- **Organizational**: The RBAC extension model does not handle RBAC administrative tasks efficiently across multiple organizations. The model needs to reduce the administrative complexity of RBAC across multiple organizations.
- **Privacy**: The RBAC extension model does not support the notion of privacy. For example, the model lacks components, constraints, and obligations to handle privacy in RBAC.
- **Task**: The RBAC extension model does not support the notion of a task, team, purpose, and organizational roles, which help specify a business activity in enterprises.
- **Spatio-Temporal**: The RBAC extension model does not support spatial (location-based) and temporal (time-based) constraints, which specify role-assignment, role-activation and permissions based on location and time.
- **Spatial**: The RBAC extension model does not support the notion of spatial (location-based) constraints, which specify role-assignment and permissions based on location.
- **Temporal**: The RBAC extension model does not support the notion of temporal (time-based) constraints, which specify role-assignments and permissions based on time.

5.2. Analysis and Discussion

The RBAC standard provides the RBAC Reference Model, which is an abstraction on top of authorization based on UA and PA. RBAC Reference Model presents four entities: roles, sessions, users, and permissions, and their relations. While the RBAC Reference Model is considered fundamental in any RBAC systems, the RBAC Reference Model has limitations on providing features such as dealing with context for emerging applications such as healthcare and mobile devices. For example, in cases where the RBAC extension model does not support the notion of specific constraints, the RBAC extension model incorporates additional entities with regards to context/constraints and their relations with existing entities of the RBAC Reference Model. The

Table 3: Implementation types found and the count of primary sources

Implementation Type	**Papers**	**Count**
Enterprise	[11] [12] [13]	3
Prototype	[14] [15] [16] [17]	4
None	[18] [19] [20] [10] [21] [22] [23] [24] [8] [25] [26] [27] [28] [29] [30] [31] [32] [33] [34] [35]	20

RBAC extension model provides general agreement on the definition for specific features. The RBAC extension model helps simplify theoretical modeling and practical implementation of features in the model.

Motivations for RBAC extension models vary across category but are rooted in adding new entities or relationships to allow authorization flexibility in meeting the demands of emerging requirements.

6. RQ3: Implementations

How are RBAC extension models implemented by their authors?

When designing and proposing a model targeted at a feature that is rooted in practical usage by real software systems, implementing the model is evidence that the proposed model can work in practice. The presence of an actual implementation substantiates the robustness of the design and/or the need for the extension. We analyzed the primary sources to see how many proposed models actually had implementations associated with them. We quantified whether the implementation was enterprise (i.e., an implementation used in a production environment) was for a real system) or a prototype implementation (i.e., proof of concept to demonstrate the feasibility).

6.1. Results

Table 3 shows the breakdown of implementations found within the primary sources. Of the 27 papers surveyed, RBAC extension models in four papers were prototypes developed by the authors whereas RBAC extension models in three papers were claimed to be implemented within a real system. The remaining 20 papers provide no mention of an implementation.

6.2. Analysis and Discussion

The RBAC standard is designed such that when practitioners implemented RBAC into their systems, the RBAC standard demonstrates reasonable assurance being based off a well thought out model. As extensions to the RBAC Reference Mode come along, thought and time would be given to how features and nuances of their models may impact implementation to achieve the same goals as the original standard. The primary sources showed a lack of implementation with over 70% of the models having no notion of attempting to implement them. Prototype implementation shows the feasibility of the RBAC extension models in the four papers. Of the models that produced an

Table 4: Evaluation types by primary source

Evaluation Type	Papers	Count
Time-Based Performance	[8] [12]	2
Complexity Analysis	[16] [24] [30] [29]	4
Comparison to Standard RBAC	[16] [22] [24] [36] [33]	5
Mathematical Modeling	[26] [28] [29] [30] [35]	5
Example Scenarios of the Model in Action	[18] [19] [14] [15] [16] [10] [20] [22] [33] [31] [35] [13] [17] [34]	14
Case Study of the Model in Practice	[11]	1
None	[25] [32] [27]	3

implementation within the enterprise world, two were from within the medical domain and one was implemented using web application technologies.

Research on RBAC extension models shows a lack of implementations in the real world scenarios that the models are ultimately designed for.

7. RQ4: Evaluations

How are RBAC extension models evaluated by their authors?

The 27 primary sources were examined for evidence that evaluations of the proposed model were presented by the model authors. We identified a set of evaluation types found within each of the primary sources and provide a list of the evaluation types and which primary sources provided which type. A primary source may use multiple evaluation types. For example, Aich et al. conducted performance and complexity analyses to show the effectiveness of their proposed RBAC extension model [12].

7.1. Results

Table 4 shows evaluation types. Based on the diverse evaluation criteria, 12 models presented no evidence of an evaluation. Fourteen models presented example scenarios and how application of their model would apply and resolve the situation. Six models provided some form of performance or complexity analysis of their model. The performance and complexity analysis included graphs of the model's time to determine calculate authorization as the number of entities grew, and the size of the role space for the extension model compared to the RBAC Reference Model. Five models provided mathematical descriptions and analysis as a way to provide evaluation in the form of completeness. The most widely used evaluation approach was providing sample scenarios with accompanying workflows of how the extension model would tackle those scenarios.

7.2. *Analysis and Discussion*

When proposing an access control model, providing an evaluation of the model is a key component in establishing the validity of the model. Further, in the case of extensions to the RBAC Reference Model, the model is accompanied by validation of the model as a stand-alone access control model and in comparison to the model upon which the enhancements are being made. The results show that robust evaluations of extension models are lacking.

The primary source of validation a developer or practitioner may encounter is a qualitative discussion of real-world scenarios and how the proposed model can tackle those situations. For five of the primary sources [16] [22] [24] [36] [33] the model authors provide some discussion of how the RBAC Reference Model is deficient in tackling the scenario. In Table 4, we observe that one paper includes a case study to examine how the proposed model works in practice. Discussions of how an extension model handles a real-world scenario provides developers and practitioners anecdotal evidence at best for what types of situations the proposed model could handle. Further, by not providing a comparison to the RBAC Reference Model, developers may be left implementing a more complex model to address their requirements when the RBAC Reference Model would have sufficed. Further, given the nature of access control models as grounded in application to enterprise implementations, case studies of a model in action provide developers with evidence that the model works as intended when applied.

When looking for an enterprise ready access control mechanism, developers must balance usability with security. Two of the primary sources examined provided time-based performance analysis of their extension model compared to the RBAC Reference Model. This inclusion of time analysis provides some assurances to developers that any non-functional requirements surrounding time to compute authorizations compete or beat the RBAC Reference Model. Further, four of the models provided some form of complexity of their model. This complexity analysis plays a key role in the management of the access control mechanism over the course of the models implementation lifetime. As the number of roles, users and additional entities grows, developers will need to ensure non-functional requirements are met that deal with the ability for a system administrator to effectively manage these entities.

RBAC extension model research lacks comprehensive evaluation of the models both in theory and in practice.

8. RQ5: Domains

What domains have been targeted by RBAC extension models?

Business needs have historically driven RBAC research and development. The primary mode of evaluation for model extensions has been the presentation of business scenarios in various domains and how the model uniquely handles those particular scenarios. Thus, looking for trends in the domains used in the example scenarios might serve to illuminate a trend worth further examination into the reason for the explosion of RBAC extensions. We identified domains presented within the primary sources by looking for example scenarios cast within a particular domain or mention of domain requirements within the body of the paper.

Table 5: Domains by primary source

Domain	Papers	Count
Medical Domain	[18] [19] [11] [8] [26] [28] [31] [12] [17]	9
Pervasive Computing Environments	[15] [30] [33]	3
Web Applications	[25] [23]	1
Mobile Computing	[21] [22] [32] [12] [27]	4
Organizations with Many Sub-departments	[20] [13]	2
Enterprise Workflows	[14] [16] [24] [34] [35]	5
None	[10] [**?**]	2

8.1. Results

Table 5 shows domains mentioned and their associated sources.

The predominant domain for which extension models have been generated for is that of the medical domain with 9 of 27 mentioning scenarios or requirements of that industry. Mobile computing and enterprise workflows were each represented by five papers claiming to be influenced by the requirements for access control within these domains. The final set of domains was pervasive computing environments and large-scale organizations with three each and web applications with one. Two papers [10, 29] do not mention domains explicitly since Aich et al. [12] fall under both the medical domain and mobile computing.

8.2. Analysis and Discussion

The medical domain produced the largest selection of papers when analyzing the domains influencing the proposals of RBAC extension models. Moreover, we observed that the categories associated with papers identifying the medical domain were not limited to one or two but cut across each of the eight categories except for the Organizational category. The cross-category nature of the medical domain papers appears indicative of the complex nature of medical applications and requirements. Given the growth of the research and development of medical applications over the past decade this result does not appear to be surprising. However, the RBAC standard was originally created to reduce cost and increase interoperability - two goals of current regulation around the standardization of electronic health record systems. The large number of proposed models, and the cross-category result stand in direct opposition of the goals of both the RBAC standard and current regulations.

The RBAC standard has been re-enforced by the economic impact that standardization has had on enterprises needing to apply access control. The inclusion of extension models targeted at the enterprise workflow domain is indicative of the expansion of requirements for enterprises. Developers and researchers would take care when looking at extension models designed to address the newer requirements of enterprise workflows to achieve the same economic implementation and maintainability benefits the RBAC Reference Model presents.

Figure 2 shows domain distribution by 3-year period. We observed that medical and enterprise domain papers constantly appear for every period in Figure 2. For a domain that has roots in medical and enterprise computing, protecting the data of both through access controls is paramount given their ubiquity. Mobile computing has seen a dramatic increase in the number of available devices, operating systems and applications since 1997 when the first smart phone was introduced [37]. Since 2004, the domain analysis results produced five papers that targeted extensions that are designed to address the requirements of mobile computing.

RBAC extension models were found targeting domains such as medical, pervasive computing, web applications, enterprise workflows and mobile computing.

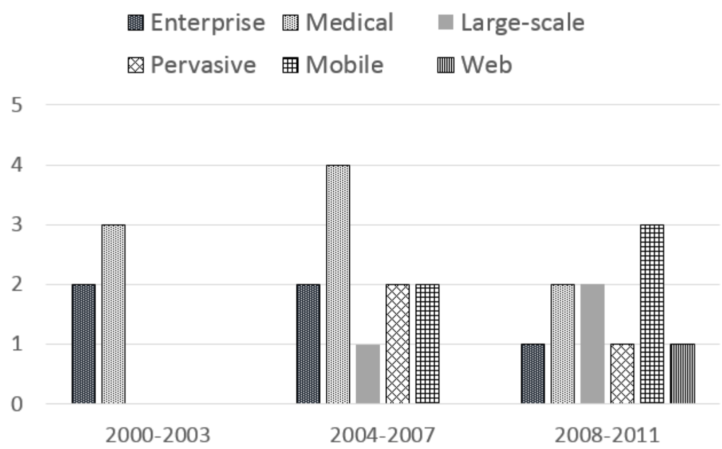

Figure 2: Domain distribution by 3-year period. Y-axis represents the number of corresponding domain papers. X-axis represents 3-year period from 2000 to 2011.

9. RQ6: Generalizations

What commonalities exist across RBAC extension models?

During the paper reading phase, we identified commonalities within the primary sources by looking for formal modeling of extending RBAC extension models.

9.1. Results

The RBAC standard is used in various aspects of computer systems. To reduce efforts for modeling access control used in various applications, researchers often focus on developing generalized core concepts of access control. The authors use propositional logic to describe access control model across all categorizations. Propositional logic is concerned with propositions and their logical relationships. In propositional logic, simple (i.e., atomic) or compound condition at given context is evaluated to true or false based on specified rules and access control logic. Researchers and practitioners are concerned to extend limited set of propositions specific to core RBAC to meet real-world scenarios such as dynamic constraints, temporal, or spatial constraints.

9.2. Analysis and Discussion

Since NIST proposed RBAC standard using propositional logic, researchers describe extended RBAC models using propositional logic. Given context, propositional logic is used to evaluate true or false based on specified rules and access control logic. As access control is typically evaluated to either true or false based on predicates, propositional logic is sufficient to describe key ideas and definitions. Propositional logic specifies what combination of attributes values a request must satisfy to be authorized to roles. Combination of attribute values may handle constraints such as temporal and spatial constraints. For example, we describe user-role authorization as $ae \Rightarrow r$ using propositional logic where ae is an attribute expression and r is a role. Propositional logic for RBAC has two parts. The left hand side (LHS) is an attribute expression ae. The right hand side (RHS) is a role. If a request satisfies the attribute expression, a user u in the request is authorized to the role specified in RHS.

We found that 27 papers of RBAC extensions use propositional logic to describe its extended model. However, propositional logic has limitations. While this logic is simple, this logic does not support for reasoning about RBAC, which helps reduce the administrative complexity of associations such as user- role associations. To support for reasoning of access control, one may describe the RBAC extended models in first-order logic. Given an RBAC extension model, Samuel et al. [31] proposed verification of the model using a specification language, which is based first-order logic. This logic is sufficient to model RBAC and extended RBAC for reasoning. Moreover, this logic supports for concise and elegant formulation of the Reference Model and its relation. First-Order logic is expressive enough to concisely represent access control systems. First-Order logic uses relations, variables, and quantifiers.

10. Discussion

The research questions we identified, presented results for and analyzed provide a view of the RBAC extension model landscape. By looking across all the research questions we can arrive at cross-cutting concerns and identify areas that may benefit from future work. We break the discussion into two issues: recommendations for the enhancement of the evaluation of RBAC extension models to role-based access control models and guidelines for developers needing to choose an RBAC extension model to meet their requirements.

10.1. Metrics for the Evaluation of RBAC Extension Models

A small percentage of primary sources presented robust evaluations or implementations of their model. This result leaves researchers and practitioners little data from which to compare one model to the next. Given the wide swath of popular and critical domains being targeted by RBAC extension models, Hu and Scarfone proposed metrics for access control system evaluation or a security system in general [38]. They collect metrics, which can be applicable for not only access control models, but also requirements, system implementation, and extended application such as verification and testing. For example, “Ease of Privilege Assignments” metric measures the number of steps for assigning, changing, or deleting a privilege for users and roles when a user or administrator manages RBAC. This metric can be applicable for not only the RBAC Reference Model but also RBAC extension models. We propose the metrics introduced by Hu and Scarfone should be applied to the extension models presented in this paper as well as any future models. A developer could attempt to apply these metrics to an RBAC extension model not already evaluated when attempting to choose a model. These metrics focus on comparing feature support of access control models.

10.2. Adoption of RBAC Extension Models

To adopt a model in practice, software developers would implement the model in real system environments based on intended use of the models. As shown by RQ6, all primary sources were found to provide an abstract formal representations of their extension model and the model's operation. The presence of an abstract formal representation of the model stands as a starting place for developers to configure intended use (i.e. which subjects can access which resources), and define an access control policy (i.e. which specifies high-level rules such as which subjects can access to which resources).

A formal representation of access control models is a critical step of designing high-level abstraction where which entities are used and how these entities are operated. One of the objectives of a formal representation is to help ensure the correct behaviors through formal verification. Given the formal representation of access control models, software developers may prove of properties (e.g., safety, consistency and completeness) and check whether these properties are satisfied.

While the concept of the Reference Model is clear and can be applicable to any system, it is challenging to implement the security mechanism of RBAC because the Reference Model is can be interpreted in more than one interpretation due to its complexity. To bridge gap between RBAC standard and its implementation, NIST published RBAC Implementation and Interoperability standard (RIIS/ ANSI INCITS-459) in 2011. This standard specifies how to implement RBAC system, which is consistent with NIST RBAC standard. Moreover, this standard describes interoperability specification where one RBAC implementation can be translated to another one.

This standard does not provide a specific guideline for implementation of various RBAC extension models. Moreover, when software developers implemented RBAC extension models, they require clear security requirements of extended role-based access control, which identifies security objectives, intended environments, and assumed threats. Moreover, software developers understand how this RBAC extension model overlaps with other access control models when more than two access control models are integrated into a single system. A survey [6] shows that over 50% of users at organizations with more than 500 employees are given some of their permissions to access resources based on RBAC. To adopt RBAC into a system, organizations often use hybrid approaches, which combine RBAC and access control lists because specific user types, systems, and workflow may not be effective to manage access based on roles. Therefore, when RBAC is extended and combined with other access control models, software developers can provide a formal representation which can serve as support for proof of the model. Then, software developers implement RBAC extension models based on NIST standard of RBAC implementation. Especially, software developers understand intended use of RBAC extension models to meet a new system requirement. For example, for a spatial RBAC model, software developers incorporate additional spatial constraints, which can be either static or dynamic, in practice into the RBAC model.

11. Conclusion

The RBAC extension models were revealed to fall into a number of categories with Const, Org, Priv, Task, Spatio-Temporal, Spatial, and Temporal falling under the general category of context. The categories each had properties specific to their implementation, but were seen to generalize to being specialized instances of context tailored to the entities or actions the categories covered. A number of domains were identified as being the motivations behind needing extensions to the RBAC Reference model. The domains, such as healthcare, presenting new challenges the previous models were not required to design for. Our literature review showed that the state of RBAC extension model evaluation needs focused from the research community given most model evaluations seen within the papers were based on hypothetical situations with little to no case studies or implementations in practice.

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13. Appendix

Table 6: Primary sources by classification and properties (Implementation Type / Domain / Evaluation Type(s))

Context			[19] A flexible content and context-based access control model for multimedia medical image database systems, 2001 (None / Medical / Scenario)
			[23] A Context-Aware Role-Based Access Control Model for Web Services, 2005 (None / Web Applications / None)
			[14] A context-sensitive access control model and prototype implementation, 2000 (Prototype / Enterprise Workflow / Scenarios)
			[15] A Context, Rule and Role-Based Access Control Model In Enterprise Pervasive Computing Environment, 2006 (Prototype / Pervasive Computing / Scenarios)
			[11] A contextual role-based access control authorization model for electronic patient record Motta, 2003 (Enterprise / Medical / Case Study)
			[16] A Role and Context Based Access Control Model with UML, 2008 (Prototype / Enterprise Workflow / Complexity, Comparison to Standard, Scenarios)
			[10] An extended RBAC model based on granular logic, 2008 (None / None / Scenarios)
			[20] Designing an agent-based RBAC system for dynamic security policy, 2004 (None / Organizations / Scenarios)
			[21] Leveraging Access Control Mechanism of Android Smartphone Using Context-Related Role-Based Access Control Model, 2011 (None / Mobile Computing / Scenarios)
			[22] CRBAC: Imposing multi-grained constraints on the RBAC model in the multi-application environment, 2009 (None / Mobile Computing / None)
	Const		[18] A constraint based role based access control in the SECTET a model-driven approach, 2006 (None / Medical / Scenarios)
	Org		[24] ROBAC: Scalable Role and Organization Based Access Control Models, 2006 (None / Enterprise Workflows / Complexity Analysis)
	Priv		[8] Privacy-aware role-based access control, 2007 (None / Medical / Time-based Performance)
			[25] PuRBAC: Purpose-Aware Role-Based Access Control, 2008 (None / Web Applications / None)
	Task		[13] A Task-Role Based Access Control Model with Multi-Constraints, 2008 (Enterprise / Organizations / Scenarios)
			[17] Team and Task Based RBAC Access Control Model, 2009 (Prototype / Medical / Scenarios)
			[34] Task-role-based access control model, 2003 (None / Enterprise Workflows / Scenarios)
	Spatio-Temporal		[29] STARBAC: Spatiotemporal role based access control, 2007 (None / None / Mathematical Modeling)
			[30] On spatio-temporal constraints and inheritance in role-based access control, 2008 (None / Pervasive Computing / Mathematical Modeling)
			[31] A framework for specification and verification of generalized spatio-temporal role based access control model, 2007 (None / Medical / Scenarios)
			[32] LoT-RBAC: A Location and Time-Based RBAC Model, 2005 (None / Mobile / None)
			[33] A Spatio-temporal Role-Based Access Control Model, 2007 (None / Pervasive / Scenarios, Comparison to Standard)
			[12] Role Based Access Control with Spatiotemporal Context for Mobile Applications, 2009 (Enterprise / Medical, Mobile / Complexity Analysis, Time-based performance)
		Spatial	[26] GEO-RBAC: a spatially aware RBAC, 2005 (None / Medical / Mathematical Modeling)
			[27] LRBAC: A location-aware role-based access control model, 2006 (None / Mobile / None)
			[28] Spatial role-based access control model for wireless networks, 2003 (None / Medical / Mathematical Modeling)
		Temp	[35] A generalized temporal role-based access control model, 2005 (None / Enterprise Workflows / Scenarios)