Incremental Development of RBAC-controlled E-marking System Using the B Method

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Abstract—**Role Based Access Control (RBAC) models are access policies that associates access rights to roles of subjects on objects. The incremental development of software by adding new features and the insertion of new access rules potential render the model inconsistent and creates security flaws. This paper proposes modeling RBAC models using B language such that it is possible to reevaluate the consistency of the model following changes to the model. It shows the mechanism of formalizing RBAC policies of an Electronic Marking System (EMS) using B specifications and illustrates the verification of the consistency of the RBAC specification, using model checking and proof obligations.**

I. INTRODUCTION

Security is now becoming a very important aspect when it comes to the development of modern systems. Many critical systems, especially those which handle commercial transactions, enforce different security policies to their systems in order to ensure that existing data and information flow are enough secure to preserve confidentiality. If there is any defect in applying any security policy to a particular system, as if specifying ambiguous properties or defining inconsistent model, then the system might lack reliability. Hence, formal methods are widely used to verify the correctness and consistency of most of security models, including Role Based Access Control (RBAC) policies, as they rely on mathematical logic and set theory [3].

RBAC model is regarded as a successful alternative to discretionary and mandatory access control models. Efficiently, RBAC can be more suitable for commercial systems, since it depends essentially on assigning different users to particular roles [4]. However, RBAC policy is not restricted to business systems only, but also to any critical system that needs to determine whether a given subject (user) is allowed to access a certain object (resource). This paper discusses a study case: Electronic Marking System (EMS) in Oman Secondary Schools, where RBAC security policy needs to be applied to. EMS aims to provide a consolidated environment, where each member within a school has the right to access the system within the powers (authorizations) given to him/her. For example, teachers can access the system for the purpose of adding, editing or deleting marks. Whereas, students have the authorization to submit reports and view their grades.

II. RBAC SECURITY POLICY

Role Based Access Control (RBAC) is one of the most efficient models of access control policies [1]. Began in 1970s with multi-user and multi-application, and has rapidly evolved in the last three decades as a technology for applying a high level security in large-scale systems. The pivotal idea behind RBAC model is that permissions are associated with roles, and users are administratively assigned to proper roles [9]. This mechanism ensures that only authorized users can perform some functions on some data/resources [4]. Generally, RBAC model consists of some basic elements, such as Users, Roles, Permissions, User Assignment (UA), Permissions Assignment (PA) and Constraints (see Figure 1):
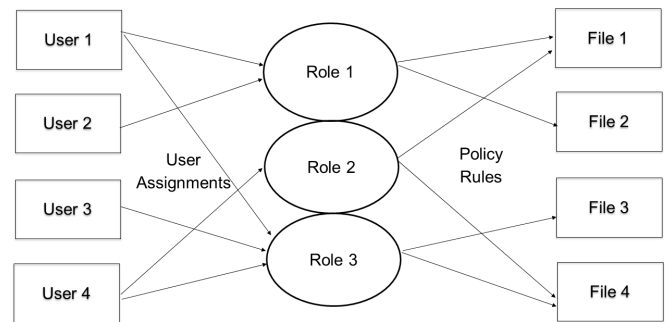

Fig. 1. The concept of RBAC security policy.

It is clear that users are not mapped directly into permissions of accessing some resources, but to specific roles which have to be previously assigned to those permissions [8]. For example, in medical systems, nurses are authorized to access specific resources (e.g. files) which certainly differ from those in which physicians are allowed to. Therefore, each role in the system (i.e. nurse and physician) is being mapped into the corresponding permissions. If Alice, for instance, is a nurse, then she has to be assigned to the role nurse [3]. In RBAC model, states that there are some relevant terms and concepts, which define the different models elements [7] (see Figure 2). However, not all of them are necessary to represent an RBAC security policy, where there are some models that describe only certain needs for a particular system.

TABLE I
TITLE FOR THE TABLE.

| Code	Description
Users (U)	persons who interact with a system.
Roles (R)	prescribed behaviours, which describe particular positions or functions within an organization.
Permissions (P)	descriptions of the type of interactions that a user can have with an object.
Object	a passive entity that has some information, and can receive new information.
User Assignment (UA)	a many-to-many relationship between users and roles.
Permission Assignment (PA)	a many-to-many relationship between permissions and roles.
User Assignment (UA)	a many-to-many relationship between users and roles.
Permission Assignment (PA)	a many-to-many relationship between permissions and roles.
Session (S)	a mapping between a user and any activated role/s that the user is assigned to.
Role Hierarchy (RH)	a partial order relationship on roles.
Constraints	restrictions on any of the above relationships/assignments.
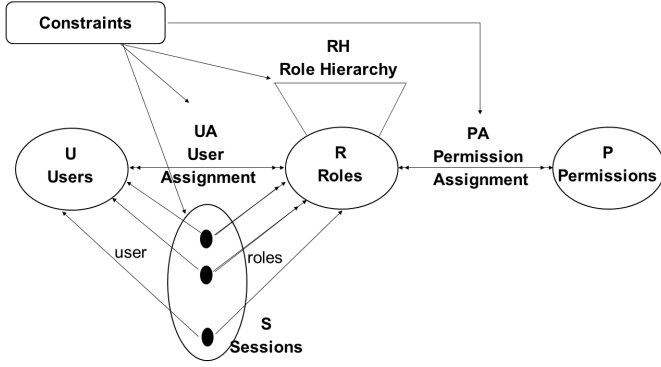
Fig. 2. Elements of RBAC security policy.
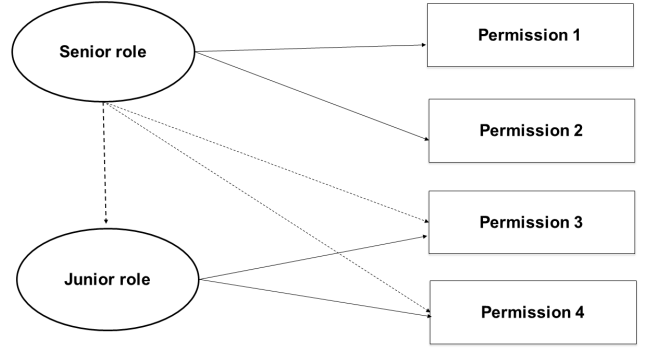
Fig. 3. Role Hierarchy.

III. RBAC MODELS

There is a family of four conceptual models for RBAC security policy, which define the various dimensions of it [6]. $RBAC_0$ is considered as the basic model, which has the minimum requirements for a system. Whereas, $RBAC_1$, $RBAC_2$ and $RBAC_3$ are more advanced models. However, the latter models are based on the basic one, $RBAC_0$, as some elements are common for all types of models [1].

$RBAC_0$ contains some basic elements of RBAC policies, where cannot define any RBAC policy without specifying those elements. Usually, components of $RBAC_0$ are Users (U), Roles (R), Permissions (P), Sessions (S) as well as relationships between them. In addition to the components of $RBAC_0$, $RBAC_1$ model supports the concept of Role Hierarchy (RH). Hierarchical of roles describe the gradualism of authorizations and responsibilities in an organization. In other words, RH is about defining what are called senior roles (more powerful roles) and junior roles (less powerful roles), where senior roles may inherit permissions that are assigned to junior roles.

In order to provide a powerful protection to the RBAC-based systems, $RBAC_3$ (constraints model) is defined to be the main drive of RBAC security policies. That is $RBAC_3$ uses a mechanism to force restrictions and form a high level security pol-icy. Constraints can be applied to any relationship/assignment that has been defined in the two previous models, such as UA, PA, Sessions and Role Hierarchy (RH) (see Figure ??). There are many types of applicable constraints, in particular those which deal with exclusiveness of roles (Separation of Duties) and cardinality constraints.
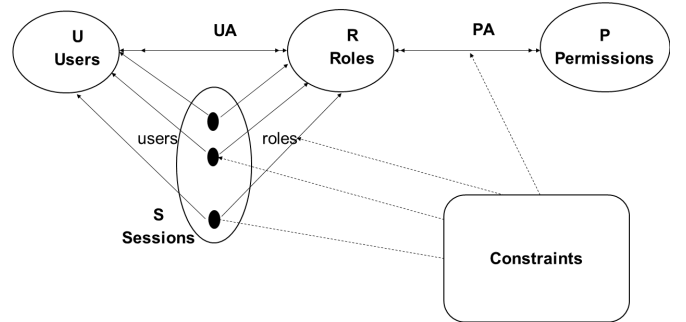

Fig. 4. RBAC Model Constraints.

Mutual exclusiveness of roles is one of the most common constraints for an RBAC model. Usually, it is defined as Separation of Duties (SoD), where the same user cannot be

assigned to two conflicted roles at the same time [4]. For example, for two roles R1 and R2 belonging to mutually exclusive sets of roles, then if a user U is assigned to R1, this implies that U cannot be assigned to R2, and vice versa. This is expressed formally as:

$$If(U \times R1) \in UA \Rightarrow (U \times R2) \notin UA; and$$
$$If(U \times R2) \in UA \Rightarrow (U \times R1) \notin UA$$

Cardinality constraints define the maximum number of users that can be assigned to a particular role. Likewise, cardinality constraints can be used to specify the number of roles that can be related to a particular user. In addition to that, they can be applied to Permission Assignment (PA) for the purpose of restricting the number of permissions that a particular role should be assigned to [7].

IV. THE EMS SYSTEM AND IT'S ENTITIES

The Electronic Marking System (EMS) allows students, teachers, headmasters and guardians to access students marks of their units. Each user is able to benefit from the system according to the powers/authorizations given to him/her. For example, students can electronically submit papers (reports) for a particular unit to be marked by the units teacher. Teachers, on the other hand, have the right to establish, edit and delete marks of their students. In addition, headmasters and guardians can also access the system for the purpose of viewing marks and signing final reports.
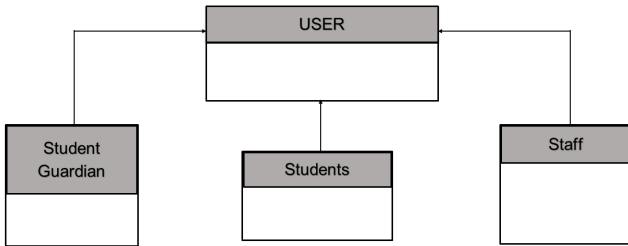

Fig. 5. Entities of the EMS's users.

Generally, the EMS system can be accessed by different users: the system admin (who controls and manages the different entities and resources of the system), students, teachers, headmasters and guardians. Hence, users can be classified into three main entities (tables): staff, students, and guardians, where staff entity represents teachers and headmasters as well as the system admin.

There are also relationships between those entities, which can be briefly stated as:

Therefore, the final mark of each student for a particular unit is being calculated as follows:

$$Final mark = total of submissions marks +$$
$$total of exams marks + inclass mark$$

V. APPLICATION OF THE RBAC TO THE EMS

In order to apply an RBAC security policy to the EMS system, we need to define the different components of RBAC models (i.e. $RBAC_0$, $RBAC_1$ and $RBAC_2$). For $RBAC_0$, it is essential to specify the sets of USERS, ROLES, and PERMISSIONS.

A. RBAC0- Basic model

Since the system has three main types of users (i.e. staff, students, studentsguardains), each user represents an element in the USER set (U). Regarding ROLES (R), there are six basic roles, which describe the main functionality for users in the Electronic Marking System (EMS). These roles would be stored into the ROLES entity of the database. Therefore, contents of this entity can be defined as follows:

$$ROLES = \{admin, student, teacher, headteacher,$$
$$headmaster, student\_guardian\}$$

Permissions (P) are pairs of (operations, objects) in which users are allowed to perform.. For example, a student wants to store a report (operation) into SUBMISSION table (object) in order for the report to be considered submitted. This process means that the student is permitted to add submission. The EMS system allows each type of users to perform only specific permissions.
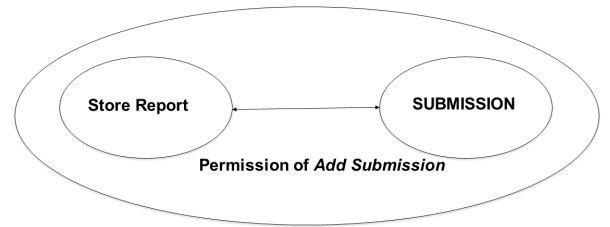

Fig. 6. "Add Submission" permission for students.

B. User Assignment (UA) and Permission Assignment (PA)

User Assignment (UA) is a many-to-many relationship between the systems users U and the roles R. For example, students take the role student, while teachers are assigned to role teacher. In some cases, it is possible to assign a user to two different roles if a given situation requires that. For instance, in case of absence of a headmaster, any teacher can be authorized to perform the headmaster permissions, and that would be done

Code	Description
UNIT	to represent all units taught at secondary schools.
SUBMISSION	to store submitted reports by students.
FINAL_REPORT	which contains final reports for all students.
MARK	its contents are natural numbers, which represent students marks.
ROLES	this entity is set up for the purpose of applying RBAC model. Hence, it represents the different roles in the EMS system (i.e. admin, teacher, student, etc.).

TABLE III
ENTITIES OF THE EMS SYSTEM.

Code	Description
studies	represents a relation between a student and a unit; where each student studies more than one unit; and that unit can be registered for many students.
taughtBy	a relation between a unit and a teacher; where each unit must be taught by at least one teacher; and that teacher can be registered to more than one unit.
hisGuardian	a relation between a student and a guardian. A student can have more than one guardian in order to facilitate the process of following up the students level. In addition, the guardian can be registered for more than one student
submits	a relation between a student and a submission; where any student can submit any number of reports (depending on the unit and the academic level that a student is studying at); however, any report cannot represent a submission for more than one student.
reportFor	a relation between a submitted report and a unit. Therefore, all submitted reports are for particular units, and each unit may have more than one report.
submissionMark	a relation between a submitted report and a mark (which is a natural number). However, cannot find any report mapped into two different marks (axiomatically!), but we can find that a given mark represents the grade of more than one report.
InClassMark	a relation between a unit and a mark (i.e. natural number) to specify a students mark for his/her participations and activities inside the class during the year.
examMark	a relation between a unit and a mark to specify the students mark/s (depending on how many exams for that unit).
studentReport	a relation between a student and a final report; where each student must have a final report for each unit, which shows his/her final mark. However, cannot find two final reports are related to the same student.
hasTheRole	maps a user (i.e. a student, a teacher, etc.) into a set of roles (e.g. student, teacher, headmaster, student guardian); where each user would be linked to only one role (unless there were some circumstances made otherwise, e.g. in case of absence of the school manager, any teacher can be assigned to play the role of headmaster; and this assignment falls under the responsibility of the systems admin).

through giving the role headmaster to the teacher, in addition to his/her own role.

Permission Assignment (PA) is also a many-to-many relationships, in which roles are mapped into permissions (functions). There are specific functions for each role, where can only be performed by user(s) who is/are assigned to those roles. The following diagram shows an example of Admin assignment:

C. RBAC1- Role Hierarchy (RH)

In the EMS system, there is only one instance of role hierarchy. Head teachers are, in fact, teachers, although they have special tasks for organizing and monitoring roles assigned to teachers, such as reviewing records. When a head teacher is assigned to role headteacher, this means that the head teacher is allowed to perform functions of the headteacher role, and inherit permissions from the role teacher.

D. RBAC2- Constraints

For the EMS system, there are two types of constraints that can be defined: cardinality constraints and mutual ex-
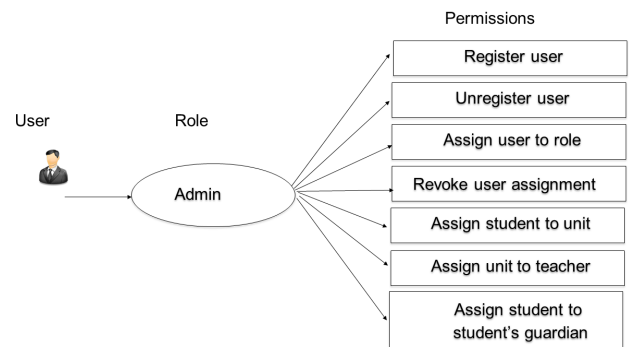

Fig. 7. "Admin" role in the EMS System.

clusiveness of roles. Usually, cardinality constraints represent the number of users who should be assigned to a particular role. In our system, it doesnt matter how many students to be assigned to student role, or how many teachers to be mapped

into teacher role, as that depends on the number of students and teachers inside a certain school. However, there must be only one user who should take the role headmaster. Thus, the cardinality constraint for role headmaster is expressed as:

$$UA \subseteq U \times R \text{ where}$$
$$\mathbf{card}(U(schoolmanager)) \times \mathbf{card}(R(headmaster)) = 1$$

Mutual exclusiveness of roles (Separation of Duties) define the conflicted sets of roles, which must not be related to the same user/s. For example, if there are two roles R1 and R2 belonging to two conflicted sets of roles S1 and S2, respectively, then: If a user U has been assigned to a role in S1, this implies that U is not assigned to any role in S2, and vice versa.

In the Electronic Marking System (EMS), there are two conflicted classes (sets) of roles:

$$SoD1 = \{teacher, headteacher, headmaster\}, and$$
$$SoD2 = \{student, student\_guardian\}$$

VI. Modeling the RBAC policy using the B language

Analyzing RBAC models using a formal method, such as the B method or Event-B may assist system developers to obtain a correct and consistent specification. By knowing RBAC constraints, formal specifications can play a significant role to examine security policies, and determine whether a particular system is secure at every point of time. The B method is one of the abstract formal languages that uses a special language named Abstract Machine Notation (AMN). The idea is to use mathematical notations (relying on mathematical logic and set theory) to formalize specifications for the purpose of formally verifying correctness and consistency of a specification.

A. Modeling the Basic RBAC Components

To formalize the basic RBAC elements, it is essential to define the sets of USER and ROLES as well as UA and PA assignments. In the EMS system, USER set contains subsets of students, guardians and staff. The latter itself contains subsets of teachers and headmasters. Therefore, these subsets must be declared as variables in the AMN:

$$staff, students, studentGuarian, teachers, manager$$

Now, we can declare, within INVARIANT clause, that each of those variables is a subset of USER set, and some are also subsets of staff subset, provided that no element of each subset can be found into two different subsets. For example, if a student has been registered into students subset, then that student cannot be found as a member of staff subset (i.e. students staff =). This can be expressed using the B specification as follows:

$$students \subseteq USER \wedge$$
$$staff \subseteq USER \wedge$$
$$students \cap staff = \{\} \wedge$$
$$studentGuardian \subseteq USER \wedge$$
$$studentGuardian \cap students = \{\} \wedge$$
$$studentGuardian \cap staff = \{\} \wedge$$
$$manager \subseteq staff \wedge$$
$$teachers \subseteq staff \wedge$$
$$manager \cap teachers = \{\}$$

To model the User Assignment (UA), which assigns each user to a particular role, we need to define a relation between USER set and ROLES set. This relation is, in fact, a set of elements, where each element is a pair of user and role. For example, if a user u has been assigned to a role r, then there is an element for the relation can be defined as: (u, r.

Since elements of the relation between USER and ROLES are subject to change (i.e. assigning new users to roles, or revoking existing assignments), we represent this relation as a variable, and we give it the name: hasTheRole. The declaration of that within the INVARIANT clause would be as:

$$hasTheRole \in USER \leftrightarrow ROLES$$

To model the Permissions Assignments (PA), we do not need to define a new set for permissions, or a direct relation (as in the UA assignment) between ROLES and those permissions. Since any permission is actually a pair of operation and object, we will be specifying (within preconditions of each operation (function)) in the system, that this operation is only performed by users who have been given a particular role.

For example, users who can add a submission are only students. Therefore, we say, as a precondition of the operation, that who has the role of student, can perform this operation. This is expressed by the B specification as in Figure 8:

B. Modeling the RBAC Constraints

We begin with mutual exclusiveness of roles (Separation of Duties). As has been mentioned earlier, there are two conflicted sets of roles in the EMS system. Since roles are previously known and defined for the system, the two conflicted sets of roles should be initialized within the INITIALIZATION clause as:

$$sod1 = \{teacher, headteacher, headmaster\},$$
$$sod2 = \{student, student_guardian\}$$

Each of sod1 and sod2 is a subset of ROLES set, and the intersection between them is equal to an empty set. Therefore,

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Algorithm 1 Assigning "add a submission" permission to "student" role

PRE

  hasTheRole[{s}] = {student}$\wedge$

  $report \in SUBMISSION \wedge$

  $report \notin reports \wedge$

  $u \in studies[\{s\}] \wedge$

  $card(submit[\{s\}] \cap reportFor[\{u\}]$

  $< maxSubmissions$

THEN

  $report \leftarrow reports \cup \{report\} \; \|$

  $submits \leftarrow submits \cup \{s \mapsto report\} \; \|$

  $reportFor \leftarrow reportFpr \cup \{report \mapsto u\}$

END

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this must be declared within INVARIANT clause:

$$sod1 \subseteq ROLES \wedge$$
$$sod2 \subseteq ROLES \wedge$$
$$sod1 \cap sod2 = \{\}$$

Now, we can formulate the condition of Separation of Duties (SoD) using the B specification, as follows:

$$\forall(u, role_1, role_2).(u \in USER \wedge role_1 \in sod_1$$
$$\wedge role_2 \in sod_2 \wedge role_1 \in hasTheRole[\{u\}]$$
$$\Rightarrow \neg(role_2 \in hasTheRole[\{u\}])$$
$$\wedge$$

$$\forall(u, role1, role2).(u \in USER \wedge role1 \in sod1$$
$$\wedge role2 \in sod2 \wedge role2 \in hasTheRole[\{u\}]$$
$$\Rightarrow \neg(role1 \in hasTheRole[\{u\}])$$

The above two predicates mean, respectively, that for every user u and two given roles role1 and role2, where u USER and role1 sod1 and role2 sod2 and that role1 belongs to the set of roles given to the user u, then the role2 must not belong to the roles of the user u. Likewise, for every user u and two given roles role1 and role2, where u USER and role1 sod1 and role2 sod2 and that role2 belongs to the set of roles given to the user u, then the role1 must not belong to the roles of the user u The second type of constraints is cardinality constraints. In the EMS system, the number of users who will be assigned to headmaster role must not be greater than 1.

Hence, the cardinality of users who have the role headmaster must be less than or equal to 1. This is expressed as:

$$\forall(headmaster).(headmaster \in sod1 \Rightarrow$$
$$card(hasTheRole^1[\{headmaster\}] \leq 1)$$

C. Modeling the Role Hierarchy (RH)

Head teachers have their own permissions, such as reviewing records. However, they still teachers, and, therefore, can perform operations that are given to teachers. We need to formulate a predicate that satisfies the concept of inheritance, where head teachers can inherit permissions from teacher role. In the B specification, this is expressed as:

$$\forall(u, headteacher).(headteacher \in sod1 \wedge$$
$$u \mapsto headteacher \in hasTheRole$$
$$\Rightarrow headteacher \in hasTheRole[\{u\}]$$
$$\wedge teacher \in hasTheRole[\{u\}])$$

Which means that for every user u and headteacher role, where headteacher sod1 and that user has been assigned to the role headteacher, then the user u would become have the role teacher in addition to the role headteacher.

VII. FORMAL VERIFICATION

Perhaps the most important aspect in using formal methods in software development is that specifications can be analyzed and verified using mathematical techniques and tools. There are two approaches for formal verification: model checking and theorem proving (e.g. proof obligations).

A. Model Checking (the proB tool)

Model checking is an automated approach that used to verify correctness and consistency of a model. The proB tool is one of the B machines-supported tools that test automatically the consistency of the B specification. The main idea of model checking is that all machines nodes (states) are visited to examine whether there exist any potential bugs [5].

The proB tool showed that our RBAC specification is correct regarding the system states (nodes). There was no violation with the system properties and invariant when it comes to the performance of operations.

B. Theorem Proving (Proof Obligations)

The main purpose of theorem proving is to construct a mathematical proof for a mathematical statement to be true [2]. Since formal proofs do not use natural languages, they are expressed in a symbolic language, usually called a proof language. For abstract machines to be correct and consistent, there are many proof obligations that need to be proven. Theses proof obligations are for the four main clauses of an abstract machine: PROPERTIES, INVARIANT, INITIALISATION and OPERATIONS, where there is a separate proof obligation for each operation in the machine [5].

Since our RBAC model doesnt have properties clause, proof obligations would be for the clauses of INVARIANT, INITIALISATION and OPERATIONS. Proof obligation for invariant clause is expressed as:

$$Prp \Rightarrow \exists \quad v. \quad I$$

Which means that under the assumption that Prp (PROPERTIES clause, if found) is true, then: the invariant I is satisfied by at least one of the machines variables v To discharge this obligation, we need to show that there exist values for:

- *sod1* and *sod2*, which are subsets of *ROLES*; where the intersection between them is an empty set.
- *hasTheRole*, which is a relation between *USER* and *ROLES*; where:
  - for any user and two conflicted roles, the concept of SoD is applied;
  - for any user has the role headteacher, the concept of Role Hierarchy is applied; and
  - cardinality of users who take the role headmaster is less than or equal to 1.
- *staff, teachers, manager, students* and *studentGuardian*, which are subsets of *USER*; where:
  - teachers and manager are subsets of staff; and
  - the intersection between any two subsets is an empty set.
- *hisGuardain*, which is a partial surjective function between students and studentGuardain.

Perhaps the easiest way to demonstrate that is to apply the current values of variables in the INITIALISATION clause (i.e. all variables are equal to , except the sets of sod1 and sod2).

The proof obligation for INITIALIZATION takes the following predicate:

$$Prp \Rightarrow [Init]I$$

Which means that under the assumption that Prp (PROPERTIES clause, if found) is true, then: the initialisation clause Init must establish the invariant I. To demonstrate this obligation, we apply the current values in the INITIALISATION clause to their corresponding variables in the INVARIANT clause.

For each operation in the machine, there must be a separate proof obligation. Hence, there will be proof obligations for assignUserToRole and revokeUserAssignment operations. However, we will discuss only the proof obligation for assignUserToRole operation. This takes the following predicate:

$$I \wedge P \Rightarrow [S]I$$

Which means that under the assumption that invariant I is true and the preconditions P of the operation is true as well, then: the statement of the operation S (i.e. the operations body) must preserve the invariant I.

VIII. Conclusion

RBAC security policy is considered as one of the most effective security models to different critical systems, such as business systems. Formal specification is now widely used to verify security constraints/properties of RBAC models in different ways and several languages. This paper discussed the use of the B method to develop a consistent specification for the RBAC security policy of the Electronic Marking System (EMS). There was the use of two approaches for formal verification: model checking and proof obligations. Model checking was represented by the application of proB tool, while proof obligations constructed a mathematical statement/proof for the RBAC model to be true. Both mechanisms proved that our RBAC specification is correct and consistent regarding the implementation of the system operations.

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