Formal Semantics of Architectural Decision Models

Marcin Szlenk
Institute of Control and Computation Engineering, Warsaw University of Technology, Nowowiejska 15/19, Warszawa, 00-665, Poland
m.szlenk@elka.pw.edu.pl
http://www.ia.pw.edu.pl/~mszlenk
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Abstract

A software architecture is the result of multiple decisions made by a software architect. These decisions are called architectural decisions, as they bring solutions to architectural problems. Relations between decisions can be captured in architectural decision models. Such models are then a form of reusable knowledge for software architects. Several models have been described in the literature, introducing necessary concepts and relations. These concepts and relations were usually explained using natural language. Not much work has been done so far on their formal definitions. Specifically, such a definition of an architectural decision model is still missing. The purpose of this paper is filling this gap by providing the formal definition of an architectural decision model at both syntax and semantics levels. At the syntax level, different concepts and relations that are elements of a model have been mathematically defined. At the semantics level, the meaning of a model has been defined in a form of denotational semantics. The formalization not only allows for better understanding of architectural decision models but opens the possibility to reason on such models, e.g., checking their consistency – something that is very limited for the models proposed so far. A practical example of the semantics of an architectural decision model is also presented.

Keywords: software architecture; architectural decision; formal semantics; Alloy.

1 Introduction

A software architecture is developed as a result of numerous, sometimes strictly related, decisions. Any decision that is pertaining to a software architecture is called an architectural decision. The architecture itself, these decisions and the context of these decisions create the complete architectural documentation.

Several models of architectural decisions have been proposed in the literature by defining basic concepts and relations in an informal way [1–7]. The structural dependencies
between concepts and relations were usually shown with UML class diagrams. Even if they are presented in a form of mathematical relations with more detailed constraints [8], only the metamodel (i.e., the abstract syntax of the language) for documenting architectural decisions is defined, while the definition of the semantics of its elements is still missing. This way, properties, like semantical consistency of elements, cannot be decided. As a consequence, it reduces models’ verifiability. In this paper, the syntax and semantics of an architectural decision model is formally defined. The goal of this formalization is twofold. First, it helps in understanding the meaning of architectural decision models and relations that appear in those models. Second, it increases the verifiability of architectural decision models and can be a basis for more advanced software tools supporting architectural decision modeling.

The remaining part of the paper is organized as follows. In Section 2, the related work on modeling architectural decisions is discussed. Basic concepts that are used in architectural decision models are informally described in Section 3. Next, the formal syntax and semantics of an architectural decision model are defined respectively in Section 4 and Section 5. An example model and its semantics are presented in Section 6. The conclusions with plans for further work are outlined in Section 7.

## 2 Related Work

Various methods and tools for architectural decision modeling have been surveyed in [9,10]. In general, the role of architectural decision models can be twofold. They can be used to document decisions that have already been made and/or to ontologize the decision making process in a given domain. In the first case, decisions are usually documented in a form of textual descriptions of their attributes, sometimes accompanied with illustrating diagrams [1–6]. In the latter case, architectural decision models focus on showing possible decisions and relationships between them within the decision making process [7,8].

In [7], architectural knowledge is defined as architecture design with design decisions, assumptions, context and other factors that determine a particular solution. A design decision comprises both a design problem and its solution. The proposed classification of design decisions covers existence, non-existence, property and executive decisions. Each decision is further characterized with attributes, such as scope, rationale or state. The possible decision states are, e.g., idea, tentative, decided, approved and rejected. Allowed transitions between states are defined using the state machine. Kinds of relationships between decisions include, e.g., enables (one decision makes possible the other one), subsumes (one decision is wider than the other one) and conflicts with (two decisions are mutually exclusive), but their semantics is not formally defined.

In [8], decisions made are distinguished from decisions required from the architect. The proposed UML metamodel for capturing architectural decisions contains, among others, three core entities: ADIssue, ADAlternative and ADOutcome. An instance of ADIssue (an
architectural decision issue) informs the architect that a single architecture design problem has to be solved, whereas instances of ADAlternative (architectural decision alternatives) present possible solutions to this problem. These two entities provide reusable background information. Finally, instances of ADOutcome (architectural decision outcomes) present an actual decision made to solve the problem including its rationale. The mentioned UML metamodel is complemented with formal definitions for a rich set of relationships between alternatives, alternatives and issues, and issues alone. However, the formal definitions of their semantics are missing.

An attempt to formally define the semantics of the elements of architectural decision models is presented in [11]. It borrows the notation from [8], introducing sets of architectural decision alternatives, issues and outcomes. The proposed semantics defines the meaning of an architectural decision as a set of software systems in which this decision is implemented. Similarly, the meaning of various relationships between issues and alternatives is defined with reference to respective sets of software systems. The set of all software systems is finite [11] but unbounded, what makes the presented definitions suitable for verifications with the use of theorem proving approach, rather than model checking [14]. Another drawback of this work is the lack of definition of the semantics of the whole architectural decision model. Each element on the model is considered separately.

In Section 3, selected concepts and relationships from the architectural decision models in [8] and [11] are presented informally. They will be the starting point for further formalization of an architectural decision model.

3 Overview of Basic Concepts

A simple example of an architectural decision issue is the programming language for implementing a software system. This issue represents a design concern. The set of architectural decision alternatives for this issue comprises C, Java, Swift, etc. So the alternatives represent solutions to the issue, and making a decision on the issue means selecting one of its alternatives. Another example of an architectural decision issue can be the version of Java language. The set of alternatives for this issue comprises Java 6, Java 7, Java 8, etc.

A software architecture is the result of a decision making process. The set of issues to be resolved is not constant throughout this process. New issues can be triggered (created) by earlier decisions, in the sense that making one decision leads an architect to another problem that needs to be resolved. For example, choosing Java as the programming language triggers the Java version issue. In this case, making decision on the triggered issue describes the previous decision more precisely. Choosing a version of Java makes the general choice of Java more specific. It is worth noting that if one of the other programming languages was chosen, there wouldn’t be any reason to make a decision on the Java version issue. Choosing an alternative can trigger many issues and vice versa, an issue can be triggered by many alternatives.
Two alternatives are *compatible* if both of them can be selected as the solutions to their respective issues. In other words, such alternatives work with each other. If it does not happen, they are said to be *incompatible*. An example of two compatible alternatives are Java (programming language) and ARM (processor architecture), as there exists Java VM for ARM processors. An example of incompatible alternatives are Swift and ARM, because Swift is not officially supported on ARM processors (at least, at the moment of writing this paper). The software architecture, where the chosen programming language is Swift and the chosen processor architecture is ARM, is simply not implementable.

It has been discussed in [11], that the compatibility relation in a set of alternatives is symmetric and reflexive, but not transitive. Moreover, the relations of compatibility and incompatibility are complementary: any two alternatives are either compatible or incompatible, but not both. It is worth noting that defining two alternatives for the same issue to be compatible or not is meaningless (e.g., Java and Swift as programming languages). They are possible solutions to the same problem, so only one of them will be selected.

### 4 Architectural Decision Model

Below we formally define the abstract syntax of an architectural decision model. The definition presented clarifies the informal description from Section 3. The new concern that has not been discussed before is the *forcing* relation between alternatives [11]. This relation is defined using the relations of compatibility and incompatibility. To show the proper context for the forcing relation, it will be explained in a footnote.

**Definition 1** (Issues). With *Issue* we denote a set of all the architectural decision issues (problems).

**Definition 2** (Alternatives). With *Alternative* we denote a set of all the architectural decision alternatives (possible solutions).

**Definition 3** (Model). By an *architectural decision model* we understand a tuple

\[ M = (\text{issues}, \text{alternatives}, \text{issueFor}, \text{compatibleWith}, \text{triggeredBy}) \]  

where:

1. \( M.\text{issues} \) is a set of architectural issues:

\[ M.\text{issues} \subseteq \text{Issue}. \]

2. \( M.\text{alternatives} \) is a set of alternatives:

\[ M.\text{alternatives} \subseteq \text{Alternative}. \]
3. $M\text{.issueFor}$ is a function of an alternative’s issue. The function maps each alternative to its issue:

$$M\text{.issueFor} : M\text{.alternatives} \rightarrow M\text{.issues}. \quad (4)$$

For the model $M$, a function of issue alternatives is thus defined as:

$$M\text{.alternativesTo} : \text{def } M\text{.issues} \rightarrow \mathcal{P}(M\text{.alternatives}), \quad (5)$$

$$M\text{.alternativesTo}(i) = \text{def } \{ a \in M\text{.alternatives} : M\text{.issueFor}(a) = i \}.$$ 

4. $M\text{.compatibleWith}$ is a function of alternative’s compatibility. The function assigns to each alternative a set of alternatives that are compatible with it:

$$M\text{.compatibleWith} : M\text{.alternatives} \rightarrow \mathcal{P}(M\text{.alternatives}). \quad (6)$$

The relation of compatibility is symmetric and reflexive [11]. Formally:

$$\forall a, a' \in M\text{.alternatives} : \quad a \in M\text{.compatibleWith}(a') \Rightarrow a' \in M\text{.compatibleWith}(a),$$

$$\forall a \in M\text{.alternatives} : a \in M\text{.compatibleWith}(a). \quad (8)$$

For the model $M$, a function of alternative’s incompatibility is thus defined as:

$$M\text{.incompatibleWith} : \text{def } M\text{.alternatives} \rightarrow \mathcal{P}(M\text{.alternatives}), \quad (9)$$

$$M\text{.incompatibleWith}(a) = \text{def } M\text{.alternatives} \setminus M\text{.compatibleWith}(a)$$

and a function of forced alternatives as:

$$M\text{.forcedBy} : \text{def } M\text{.alternatives} \rightarrow \mathcal{P}(M\text{.alternatives}), \quad (10)$$

$$M\text{.forcedBy}(a) = \text{def } \{ a' \in M\text{.compatibleWith}(a) : \quad M\text{.issueFor}(a') \neq M\text{.issueFor}(a) \land$$

$$M\text{.alternativesTo}(M\text{.issueFor}(a')) \setminus \{ a' \} \subseteq M\text{.incompatibleWith}(a) \}.$$ 

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1. For a set $A$, $\mathcal{P}(A)$ denotes the set of all the subsets of $A$.
2. As it was stated earlier, the relations of compatibility and incompatibility are complementary. The relation of incompatibility is here a derived relation that can be computed from the relation of compatibility.
3. The definition presented is based on [11]. Let $a$ be an alternative for issue $i$ and $a'$ be an alternative for issue $i'$ ($i \neq i'$). The alternative $a$ forces $a'$ if $a$ is compatible with $a'$ and is incompatible with any other alternative for $i'$. Such as the incompatibility relation, the relation of forcing is a derived one, i.e., it can be computed from other elements of the model.
5. $M.\text{triggeredBy}$ is a function of triggered issues. The function maps each alternative to a set of new issues created by it:

$$M.\text{triggeredBy}: M.\text{alternatives} \rightarrow \mathcal{P}(M.\text{issues}).$$  \hspace{1cm} (11)

An alternative cannot create its own issue:

$$\forall a \in M.\text{alternatives} \cdot M.\text{issueFor}(a) \notin M.\text{triggeredBy}(a).$$ \hspace{1cm} (12)

**Definition 4** (Models). With *Model* we denote a set of all the architectural decision models as in definition 3.

Our past experience with the formalization of UML models \[12,13\] has shown that it is highly difficult to avoid any flaws in such definitions. The kinds of problems we were struggling with can be summarized with following informal questions: are all formulas correct? Are they all required formulas? Are all formulas required? In the current work, to cope with these problems, the above mathematical definition of an architectural decision model has been worked out together with its specification in the Alloy language \[14,15\]. The specification is presented in Appendix A. The model expressed in Alloy was being verified with the Alloy Analyzer tool through model *simulations*, i.e., finding model instances. A number of instances of the architectural decision model have been generated and analyzed to assure that all the necessary constraints have been finally captured and properly expressed. The subject is, however, too broad to be deeply addressed in this paper. An example instance of the model, that was obtained with the Alloy Analyzer, is presented in Fig. 1.

5 Semantics of Architectural Decision Model

Designing a software architecture comprises a set of architectural decisions. This process can be driven by an architectural decision model that represents architectural knowledge for a specific technical domain. Such a model carries information about architectural issues that need to be solved and their possible solutions (alternatives). It also shows, through the triggering relation, that some decisions should result from others, and through the compatibility relation, that some solutions may work or may not work with each other. Following the information from an architectural decision model, a software architect decides among alternatives of subsequent issues. Those decisions (i.e., selected alternatives) constitute the design of a software architecture. Below, the concepts of a design and its conformity to an architectural decision model are formally defined.

**Definition 5** (Design). A *design* is a partial function

$$d: Issue \rightarrow Alternative.$$ \hspace{1cm} (13)

The function maps issues to their solutions, i.e., it defines alternatives that are selected for architectural decision issues.
Figure 1: An instance of the Alloy model from Appendix A.

**Definition 6 (Designs).** With Design we denote a set of all the designs as in definition 5.

**Definition 7 (Conformity).** Let \( d \in \text{Design} \) and \( M \in \text{Model} \). The design \( d \) conforms to the model \( M \) and we write

\[
\text{conforms}(d, M),
\]

if and only if:

1. All resolved issues are defined in \( M \):

\[
\text{dom}(d) \subseteq M.\text{issues}.
\]

2. A solution to a given issue is one of the alternatives to that issue:

\[
\forall i \in \text{dom}(d) \cdot d(i) \in M.\text{alternativesTo}(i).
\]

3. Any two solutions are compatible with each other:

\[
\forall i, i' \in \text{dom}(d) \cdot d(i') \in M.\text{compatibleWith}(d(i)).
\]

\footnote{For a function \( d \), \( \text{dom}(d) \) and \( \text{rng}(d) \) denote, respectively, the domain and the range of \( d \).}
4. All the top level issues in $\mathcal{M}$ (i.e., not triggered ones) are resolved, whereas the lower level issues (i.e., triggered ones) are resolved if, and only if, the triggering alternative was selected:

$$\forall i \in \mathcal{M}.issues \cdot i \in \text{dom}(d) \iff ((\exists a \in \mathcal{M}.alternatives \cdot i \in \mathcal{M}.triggeredBy(a)) \lor (\exists a \in \text{rng}(d) \cdot i \in \mathcal{M}.triggeredBy(a))).$$

As it has been mentioned before, an architectural decision model can represent architectural knowledge for a specific domain. Basing on this knowledge, one can design the software architecture. All the designs that conform to this knowledge (i.e., which use given concepts and respect constraints from a model) can be treated as a meaning of an architectural decision model.

**Definition 8** (Model’s meaning). Let $\mathcal{M} \in \text{Model}$ and $\text{meaningOf} : \text{Model} \rightarrow \mathcal{P}(\text{Design})$ be the function which is defined as:

$$\text{meaningOf}(\mathcal{M}) = \{ d \in \text{Design} : \text{conforms}(d, \mathcal{M}) \}.$$  

The value $\text{meaningOf}(\mathcal{M})$ refers to the meaning of $\mathcal{M}$.

It may happen that there are no designs conforming to a given model. In such a situation, the model can be interpreted as inconsistent in a sense that it describes a domain in which one cannot construct an implementable architecture. A typical example of inconsistency would be a model forcing an architect to select two incompatible alternatives. However, due to limited space, that subject will not be elaborated more here.

**Definition 9** (Model’s consistency). Let $\mathcal{M} \in \text{Model}$. The architectural decision model $\mathcal{M}$ is consistent, if and only if:

$$\text{meaningOf}(\mathcal{M}) \neq \emptyset.$$  

6 Example

As an example of the semantics of an architectural decision model we will consider architectural decisions that are being made when building a robot application in the RAPP system [16][17]. RAPP is an open-source software platform for developers to create and deliver robotic applications dedicated to social inclusion of elderly people. It is the result of a 3-year research project (2013–2016) funded by the European Commission.

The overall architecture of the RAPP system is composed of two layers: a RAPP platform and Robot platform. The RAPP platform is located in the cloud and provides

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5 In [8], such issues are called architectural decision entry points.
computing-intensive services to robots, such as machine learning or data mining. It also contains a RAPP store, which holds RAPP applications (provided by developers) that can be downloaded and executed on robots. The Robot platform is located on each robot and allows them to connect to the RAPP platform. It is responsible for downloading and starting RAPP applications, calling services provided by the RAPP platform and also offers some robot-specific services, such as movement control, sound recording or image capturing.

The simplest RAPP applications are the ones using only robot-specific services of the Robot platform, i.e., not requiring the RAPP platform. If a developer decides to use services offered by the latter, he or she can use the global instance of the RAPP platform (being maintained as part of the RAPP research project) or configure and use a local instance. At the moment of writing this paper, three robot types are supported by RAPP: ANG, NAO and Electron, but the connection to the RAPP platform is fully implemented only for NAO and Electron. As for holding RAPP applications in the RAPP store, they can be submitted by developers in one of three forms: as a ROS (Robot Operating System) package with C++ or Python code, pure JavaScript code, or pure C++ code. These possible submission forms are further restricted by the robot type for which the given RAPP application has been created. The described architectural decisions are presented on the model in Fig. 2.

Table 1 shows all twenty two of designs (i.e., mappings of issues to their solutions) that conform to the architectural decision model presented in Fig. 2. Under definition 8 they are the meaning of this model. These conforming designs have been automatically generated with the Alloy Analyzer, based on the formal definitions proposed in this paper. The Alloy specification of a design and its conformity is shown in Appendix B. Under definition 9 the model considered is certainly consistent.

7 Conclusions

In the paper we have proposed a concise formalization of an architectural decision model. The main application of the presented model is to support a decision making process through capturing reusable information about problems to be solved and their potential solutions. The set of all designs of the architecture that a software architect would create using this information is considered here as the meaning of a given architectural decision model. As can be seen from the example presented, the semantics defined is relatively easy to be computed (however, we have not considered the problem of computational complexity in the paper). Thanks to this feature, it can be useful not only for the theory of architectural decision models but also used practically in software tools for modeling architectural decisions.

The formalization presented helps in understanding the meaning of architectural decision models and relations that appear in those models. It opens possibility to reason on such models in a way similar to the one proposed for UML models in [12],[13]. However, an issue related to reasoning about consistency of an architectural decision model has only
Figure 2: Architectural decision model for RAPP. Architectural issues are grouped into the problems related to: RAPP platform, Robot platform, and RAPP store. For readability, the compatibility relation is not shown (it is complementary to the incompatibility relation).

been briefly touched upon here. Together with the problem of semantical equivalence of two models, it is an interesting direction of further theoretical research.

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A Architectural Decision Model in Alloy

sig Issue {}  
sig Alternative {}
Table 1: The meaning of architectural decision model for RAPP. Each row presents one design, i.e., the alternatives that are selected for respective issues (none means undefined value).

| RAPP app. type | RAPP platform | Robot type | Submission form | ROS language |
|----------------|---------------|------------|-----------------|--------------|
| Platform based | Local         | NAO        | ROS package     | C++          |
| Platform based | Local         | NAO        | ROS package     | Python       |
| Platform based | Local         | NAO        | Pure JavaScript | none         |
| Platform based | Local         | NAO        | Pure C++        | none         |
| Platform based | Local         | Electron   | ROS package     | C++          |
| Platform based | Local         | Electron   | ROS package     | Python       |
| Platform based | Local         | Electron   | Pure C++        | none         |
| Platform based | Global        | NAO        | ROS package     | C++          |
| Platform based | Global        | NAO        | Pure JavaScript | none         |
| Platform based | Global        | NAO        | Pure C++        | none         |
| Platform based | Global        | Electron   | ROS package     | C++          |
| Platform based | Global        | Electron   | ROS package     | Python       |
| Platform based | Global        | Electron   | Pure C++        | none         |
| Stand-alone    | none          | ANG        | Pure JavaScript | none         |
| Stand-alone    | none          | NAO        | ROS package     | C++          |
| Stand-alone    | none          | NAO        | ROS package     | Python       |
| Stand-alone    | none          | NAO        | Pure JavaScript | none         |
| Stand-alone    | none          | NAO        | Pure C++        | none         |
| Stand-alone    | none          | Electron   | ROS package     | C++          |
| Stand-alone    | none          | Electron   | ROS package     | Python       |
| Stand-alone    | none          | Electron   | Pure C++        | none         |

one sig M {
    issues: set Issue,
    alternatives: set Alternative,
    issueFor: alternatives -> one issues,
    compatibleWith: alternatives -> alternatives,
    triggeredBy: alternatives -> issues,
    alternativesTo: issues -> alternatives,
    incompatibleWith: alternatives -> alternatives,
    forcedBy: alternatives -> alternatives
}

all i: issues | alternativesTo[i] =
\[
\{ \text{a: alternatives | issueFor[a] = i} \}
\]
all a, a’: alternatives |
\[ \text{a in compatibleWith[a']} \text{ implies a’ in compatibleWith[a]} \]
all a: alternatives | a in compatibleWith[a] =
alternatives - compatibleWith[a]
all a: alternatives | incompatibleWith[a] =
\{ \text{a': compatibleWith[a] | issueFor[a'] != issueFor[a] and} \text{alternativesTo[issueFor[a']]} - a’ \text{ in incompatibleWith[a]} \}
all a: alternatives | issueFor[a] not in triggeredBy[a]

\section*{B Design and Conformity in Alloy}

sig Issue { d: lone Alternative }
sig Alternative {}
one sig M { ... }
fun dom[f: Issue -> Alternative]: set Issue {
\[ f.\text{Alternative} \]
}
fun rng[f: Issue -> Alternative]: set Alternative {
\[ \text{Issue.f} \]
}
pred conformity {
\[ \text{dom[d] in M.issues} \]
all i: dom[d] | d[i] in M.alternativesTo[i]
all i, i’: dom[d] | d[i’] in M.compatibleWith[d[i]]
all i: M.issues | i in dom[d] iff
  \[ \text{(no a: M.alternatives | i in M.triggeredBy[a]) or} \]
  \[ \text{(some a: rng[d] | i in M.triggeredBy[a])} \]
}

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