



Optimization of rule-based systems in mHealth applications



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ARTICLE INFO

Keywords:

Rule-based systems
Ontologies
Optimization
mHealth
Reasoning

ABSTRACT

mHealth applications are becoming more and more advanced, exhibiting capabilities to deliver innovative health services for improving the individual's comfort, enhancing the quality of life, promoting wellness and healthy lifestyle, or improving the adherence to therapies of remotely monitored patients. One of the most relevant components of such applications is represented by rule-based systems able both to reproduce deductive reasoning mechanisms and to explain how their outcomes have been achieved. Unfortunately, the efficiency of rule-based systems, especially on resource-limited mobile devices, rapidly decreases depending on the amount of data satisfying their rules as well as on the size and complexity of the whole rule base. Starting from these considerations, this paper proposes an optimization approach aimed at revising the structure of ontologies and rules built on the top of them that are contained into a rule-based system, with the goal of reducing the cost of evaluation for all its rules, by operating directly at the knowledge level. A general cost model is also presented to estimate the impact of research and identification of available rule instances to execute. Such a model is used to assess impacts and benefits due to the application of the proposed approach to a case study pertaining an mHealth app devised to evaluate eating habits of users in order to take under control their lifestyles and, thus, preserve their wellness. Finally, this theoretical evaluation is also transposed in a practical scenario, where the rule-based system embedded in the considered mHealth app is evaluated on a real smartphone, in terms of memory usage and overall response time. Moreover, a further study has been arranged in order to evaluate the impact of different rule conditions on the cost of evaluation of a knowledge base, and the eventual benefits drawn by their optimization. All the evaluation results show that the proposed approach offers an innovative and efficient solution to drastically reduce the cost of the evaluation of rule instances to execute and, thus, to build mHealth apps able to meet both real-time performance and computation intensive demands.

1. Introduction

Rule-based systems are able to reproduce deductive reasoning mechanisms as well as to explain how their outcomes have been achieved, by means of logic production rules made of a conjunction of conditions to verify and a set of actions to execute. Thanks to these capabilities, they have been profitably used in medical settings for encoding the knowledge underlying therapies and/or treatments to follow and, thus, enabling the development of a new generation of healthcare applications able to continuously supporting individuals everywhere and at any time. In fact, the growing penetration of mobile devices, coupled with infrastructures for telecommunication, has deeply influenced the delivery of healthcare services (Malvey and Slovensky, 2014), and defined wider horizons for health through mobile technologies (WHO, 2011). The cheap and widespread availability of mobile phones and wearable devices has enabled the development of new mobile health (mHealth) systems, deployed on

smartphones provided to the individuals, able to deliver innovative health services for improving the individual's comfort, enhancing the quality of life (Akter et al., 2013), promoting wellness and healthy lifestyle (Knight et al., 2014), or improving the adherence to therapies of remotely monitored patients (Hamine et al., 2015).

In this context, the authors experienced the design and development of mobile rule-based components in the Italian project “Smart Health 2.0”, a research and development (R&D) project in which several mHealth applications were designed for supporting healthy users in preserving and taking under control their wellness. The final goal was to provide individuals tailored recommendations about their lifestyle with respect to the estimation of the risk to contract a disease. Several deductive health recommendations were identified in accordance with the peculiar domain of interest on which each mHealth application was focused.

In order to achieve the project goals, a hybrid approach was used to model and reason on recommendations about healthy lifestyle and

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wellness, consisting in the representation of *declarative knowledge* (i.e. the structure of the domain knowledge) in form of ontology-based models so as to facilitate data integration between heterogeneous data sources characterizing the scenario of interest, and in the representation of *procedural knowledge* (i.e. the knowledge about the decision making process) as a set of if-then rules built on the top of such models.

Unfortunately, the efficiency of rule-based systems rapidly decreases when they are deployed on resource-limited mobile devices. Indeed, since the cost of research and identification of rules to execute, which is the most computation intensive and time-consuming task of the whole reasoning process (Forgy 1979), is directly influenced by the square of the number of assertions satisfying a set of rule conditions, a large amount of data has to be handled and processed as size and complexity of the rule base grow up. Moreover, also the memory usage required to maintain the generated reasoning results increases dramatically so limiting the overall efficiency in mobile devices.

Several optimization approaches have been proposed in literature for reducing the cost of research and identification of rules to execute in rule-based systems. Most of them has been thought to desktop-oriented applications and has been based on the optimization of the pattern-matching algorithm used to repeatedly compare available assertions with the conditions of the rules. The most famous pattern-matching algorithm is RETE (Forgy, 1982), which reduces the number of comparisons to evaluate the satisfaction of a rule by maintaining a cache of intermediate results in memory. More recently, the authors have proposed a mobile pattern-matching algorithm, based on a lazy reasoning approach (Miranker 1990, Weert 2010), specifically designed to be efficiently embedded in mobile devices, by granting lower memory requirements and real-time responsiveness (Minutolo et al., 2015).

However, the optimization of the pattern-matching algorithm cannot be enough for enabling an efficient reasoning procedure on mobile devices, in particular when complex and highly structured knowledge bases are involved. In this respect, in the project “Smart Health 2.0”, the authors experienced that also the way the knowledge was formalized affected the cost of research and identification of rules to execute and, accordingly, computational resources and memory consumption. In fact, formalizing known assertions with ontology-models leads to a structured knowledge base describing many and rich semantic relations among data. Production rules built on the top of such models can contain many conditions in order to increase the rule interpretability, i.e. by mentioning and evaluating the different properties characterizing the semantic data of interest. But, more a rule becomes intelligible with many conditions describing the existing relations among assertions of interest, more the cost required for processing and evaluating the rule increases. Moreover, since ontology-models are usually composed of classes and properties hierarchically structured, when rule conditions operate on the roots of such hierarchies, the assertions satisfying them can rapidly grow up. For instance, when a rule condition is aimed at verifying that a generic individual is an instance of a class, it will be satisfied by all individuals being instance of that class and, eventually, by all individuals being instance of its inherited classes.

Thus, rule interpretability may often lead to a lessening of the efficiency of their evaluation, since little restrictive conditions produce an increase of both the number of results matching them and the number of intermediate results to process when reasoning tests are evaluated. For this reason, when the focus is the optimization of performance, the interpretability of rules should be traded with more efficient rules for reducing the number of reasoning tests to evaluate at each reasoning cycle, and, thus, the amount of required computational and memory resources.

Starting from these considerations, this paper proposes an optimization approach aimed at revising the structure of the knowledge base of a rule-based system, with the goal of reducing the cost of evaluation for all its rules.

In detail, a set of optimization procedures has been defined in order to operate in a pre-processing phase and revise the way ontology-models and production rules are formalized. Since the way the knowledge is formalized can drastically change the cost of research and identification of rules to execute, these procedures have been devised to reduce the data involved in rules' evaluation and manage intermediate reasoning results directly at the knowledge level, without introducing an excessive overhead due to ad-hoc and complex memory structures.

Even if this need of optimizing the way the knowledge is formalized has been generated by operating in mHealth scenarios, they have been formulated with a general basis in order to be also applied to all the scenarios characterized by complex production rules built on the top of highly structured ontology-models. Indeed, these procedures are based on three wide-ranging criteria: (i) diminishing the portion of knowledge base on which rules operate can highly reduce the amount of data involved in the research and identification of rules to execute; (ii) maintaining intermediate results matching pairs of conditions, when a relation exists among them, can avoid to re-inspect combinations of data already classified as invalid for a given pair; (iii) changing the evaluation order of the rule conditions can highly influence the cost of the research and identification of rules to execute.

A general cost model has been also proposed to estimate the impact of research and identification of available rule instances to execute. Such a model has been used to evaluate impacts and benefits due to the application of the proposed optimization procedures to a case study pertaining an mHealth app developed in the context of the Italian project “Smart Health 2.0” and devised to evaluate eating habits of users in order to take under control their lifestyles and, thus, preserve their wellness. Finally, this theoretical evaluation has been also transposed in a practical scenario, where the rule-based system embedded in the considered mHealth app has been evaluated on a real smartphone, in terms of memory usage and overall response time.

The remainder of the paper is structured as follows. Section 2 introduces some preliminary notions about rule-based systems, reports an overview of the state-of-the-art solutions for their optimization and introduces a general cost model to estimate the impact of research and identification of available rule instances to execute. Section 3 presents the proposed optimization approach. Section 4 describes a theoretical and practical evaluation of the approach on a case study represented by an mHealth app devised to evaluate eating habits of users. Section 5 reports a further performance evaluation arranged according to the Taguchi's experimental design to investigate the general applicability of the proposed approach. Finally, Section 6 concludes the work.

2. Background and preliminaries

Rule-based systems are typically based on a rule engine in charge of repeatedly comparing the conditions of the rules with a set of assertions (known *facts*), stored in the Working Memory (WM), which provides a description of the current state of the system during the reasoning process. The flow of execution of a rule-based system consists in the research (**match phase**), identification (**select phase**) and execution (**act phase**) of available rule instances, also referred as *rule activations* (Forgy 1982, Miranker 1987). Each rule activation consists into a pair made of a rule and the set of available WM elements (WMEs), representing the current system state, which satisfies the conditions of that rule (Brant et al., 1993). When a rule activation is identified, the corresponding actions of the considered rule are produced, the WM is consequently updated, and the rule engine is restarted.

More formally, denoted with $\mathbf{R}$ the set of all production rules stored in a rule base (RB), a rule $r \in \mathbf{R}$ is defined as the pair $r = (\text{LHS}_r, \text{RHS}_r)$, where LHS_r and RHS_r are respectively the left-hand side and the right-hand side of the rule. Both LHS_r and RHS_r are lists of rule atoms, interconnected among them by means of logical operators.

Three types of rule atoms are commonly admitted as conditions in

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