Optimal Software Architecture From Initial Requirements: An End-to-End Approach

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Abstract—A software architect turns system requirements into a suitable software architecture through an architecture optimization process. However, how should the architect decide which quality improvement to prioritize, e.g., security or reliability? In software product line, should a small improvement in multiple products be preferred over a large improvement in a single product? Existing architecture optimization methods handle various steps in the process, but none of them systematically guides the architect in generating an optimal architecture from the initial requirements. In this work we present an end-to-end approach for generating an optimal software architecture for a single software product and an optimal family of architectures for a family of products. We report on a case-study of applying our approach to optimize five industry-grade products in a real-life product line architecture, where 359 possible combinations of ten different quality efforts were prioritized.

Index Terms—Software architecture, product line, software architecture evaluation, architecture optimization method

I. INTRODUCTION

A software architecture is an important property of a software system. Choosing an optimal architecture (A) early in the software production lifecycle is likely to improve design quality, reduce overall costs, and help manage risks [8]. Settling on a suboptimal architecture, on the other hand, may result in risks to the system (e.g., stability, performance, or security issues) and risks to the project (e.g., budget overrun).

A primary role of a software architect is to select an optimal software architecture that best meets the system’s initial requirements (R) [34]. To fulfill this role the architect engages in an iterative architecture optimization process (AOP) [8], depicted in Fig. 1. This process involves requirement analysis (both functional and extra-functional), taking into account the existing architecture (or lack of one), and adhering to various constraints (such as budget limits). Multiple alternative architectures are considered during the process, each with a different cost and a different level of compliance with the requirements.

The role of a software product line (SPL) architect is even more complex. A product line architecture (PLA) comprises a core architecture, architectures of shared assets, and particular architectures of specific products. The architecture optimization process effort in a SPL must balance between efforts targeted at optimizing specific products and efforts targeted at improving all the products [10].

A. Architecture Optimization Process

Fig. 2 depicts a broad overview of the flow of data in the architecture optimization process. The input to the process is the initial list of system requirements, denoted R. The process comprises three subprocesses: architecture evaluation (Proc. 1.0, Fig. 2) generation (Proc. 2.0, Fig. 2), and selection (Proc. 3.0, Fig. 2), which can be further decomposed into subsubprocesses (henceforth, activities). During the process additional data stores are produced (henceforth, byproducts). Eventually, an optimal software architecture, denoted A, is generated as the output of the process.

For each activity in the process, software architects have a plethora of architecture optimization methods (AOMs) [42] at their disposal. An architect can use, for example, formal concept analysis (FCA) to generate...
an initial architecture from requirements [20], or use scenario-based architecture reengineering (SBAR) [5] to generate alternative architectures, or use CMU’s architecture tradeoff analysis method (ATAM) [26] to evaluate the different alternatives and select the optimal architecture.

However, in spite of being a primary role of the software architect, previous studies do not cover the entire architecture optimization process. Half of the 30 AOMs listed in Table I focus solely on architecture evaluation (Proc. 1.0, Fig. 2), dealing only with activity \( a_2 \). Only two (1/15) handle initial architecture generation (activity \( a_1 \)), and only five (1/6) handle alternative architecture generation (activity \( a_3 \)). In all the rest (23/30), the architect is left to generate the initial and alternative architectures (Proc. 2.0, Fig. 2) with no supporting process.

A third of the AOMs handle architecture selection (activity \( a_4 \)). In the rest (2/3), the architect has to single out an optimal architecture (Proc. 3.0, Fig. 2) from a list of quality risks that those methods identify. Some of the AOMs do point out the need for one or more additional steps to complete the architecture optimization process. Yet, to our knowledge no method provides an end-to-end, systematic way to generate the optimal architecture from the initial requirements.

### B. Challenge

The architect cannot simply mix and match these AOMs into a complete and impartial method for carrying out the architecture optimization process.

First, many (7/15) of the AOMs are scenario-based. A common flaw of scenario-based methods is their reliance on the stakeholders’ subjective opinion on technical issues [21]. When a scenario-based model is used, there is thus a risk that the architecture optimization process will be biased by the predisposition of the organization decision-making process [24].

Second, a majority (8/15) of the AOMs apply single-parameter optimization, namely, a single quality characteristic. However, in order to find an optimal architecture, a comparison of multiple quality characteristics is often required. For example, when a single-parameter AOM, such as the scenario based architecture level usability analysis (SALUTA) [16], recommends an architecture due to it superior usability, the architect might not be able to use that recommendation in practice, as the architecture might have security, reliability, and performance issues, which the method does not analyze.

Third, most (4/3) of the AOMs are cost-agnostic. When the cost of each architecture alternative is not taken into consideration, the selection becomes biased towards the architecture with the highest quality improvement, even though it might be too expensive to implement or provide a too small a return on investment.

Fourth, the vast majority (13/15) of the AOMs on our list assume a monolithic system and thus apply a single-objective optimization. However, in the case of a SPL, modifications to a PLA can be made to either one of the core, shared, or particular architectures [15]. The architect needs to analyze these options simultaneously in order to optimize the PLA [15].

Last, the various AOMs are practically incompatible [7]. They do not agree on the type of input/output, let alone on the quality model used. For example, some AOMs generate a textual output, while others assume as input a metric representation. Some AOMs do not define a quality model. Others define their own unique model. Therefore, the architect cannot easily combined them to create a full method for carrying out the architecture optimization process.

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1The list of AOMs in Table I was compiled from several surveys that were conducted over the years: 4 from 2004 [2], 7 from 2006 [36], 8 from 2008 [44], 2 from 2012 [4, 46], 7 from 2014 [1, 17], and 2 from 2020 [14, 33].

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### TABLE I  ARCHITECTURE OPTIMIZATION METHODS

| Method | Activities | Properties |
|--------|------------|------------|
| ABAS   | ✔          | ✔          | ✔          |
| AISAM  | ✔          | ✔          | ✔          |
| ALMA   | ✔          | ✔          | ✔          |
| ARGUS  | ✔          | ✔          | ✔          |
| ASAAM  | ✔          | ✔          | ✔          |
| ATAM   | ✔          | ✔          | ✔          |
| ATRIUM | ✔          | ✔          | ✔          |
| CaliPro| ✔          | ✔          | ✔          |
| CBAM   | ✔          | ✔          | ✔          |
| CBAMAF | ✔          | ✔          | ✔          |
| DoSAM  | ✔          | ✔          | ✔          |
| D-SAM  | ✔          | ✔          | ✔          |
| EATAM  | ✔          | ✔          | ✔          |
| EBAE   | ✔          | ✔          | ✔          |
| ESAAMI | ✔          | ✔          | ✔          |
| FAAM   | ✔          | ✔          | ✔          |
| FCA    | ✔          | ✔          | ✔          |
| HoPLA2 | ✔          | ✔          | ✔          |
| LQN    | ✔          | ✔          | ✔          |
| PASA   | ✔          | ✔          | ✔          |
| QuaDAl | ✔          | ✔          | ✔          |
| RARE   | ✔          | ✔          | ✔          |
| SAAM   | ✔          | ✔          | ✔          |
| SAAMC2 | ✔          | ✔          | ✔          |
| SAEM   | ✔          | ✔          | ✔          |
| SALUTA | ✔          | ✔          | ✔          |
| SAM    | ✔          | ✔          | ✔          |
| SBAH   | ✔          | ✔          | ✔          |
| SPE    | ✔          | ✔          | ✔          |
| SOME   | ✔          | ✔          | ✔          |

\( a_1 \) Initial architecture generation  
\( a_2 \) Architecture evaluation  
\( a_3 \) Alternative architectures generation  
\( a_4 \) Optimal architecture selection  
\( t_1 \) Metrics-based assessment  
\( t_2 \) Multi-parameter, multi-feature optimization  
\( t_3 \) Cost-aware optimization  
\( t_4 \) Multi-objective, multi-product optimization
C. Contribution

This work contributes a systematic, end-to-end approach to the architecture optimization process. In Sect. III we present a novel AOM, named OFIR (Optimal Architecture from Initial Requirements) that implements our approach. OFIR includes all the activities $a_1$, $a_2$, $a_3$, and $a_4$ listed in Table I, as well as all the properties $\tau_1$, $\tau_2$, $\tau_3$, and $\tau_4$ listed here:

- **Metrics-based** (property $\tau_1$): Suitability and quality gaps are rated in OFIR on a numerical scale. The rating is done with a separation of business decisions from technical decisions. Business stakeholders prioritize quality characteristics while the technical stakeholders calculate the impact of quality features on each quality characteristic (like the impact of fault tolerance on reliability).
- **Multi-parameter** (property $\tau_2$): OFIR uses a quality model containing all extra-functional quality parameters from ISO/IEC 25010 [22], simultaneously optimizing many quality features, while balancing, possibly conflicting, requirements.
- **Cost-aware** (property $\tau_3$): The architecture optimization process in OFIR takes into account the cost of each modification to the architecture, and optimizes the quality gain with a cost ratio or limit.
- **Multi-objective** (property $\tau_4$): OFIR performs a metric comparison of the quality of different products in a SPL, allowing the architect to identify cross-product weaknesses, generate both product-specific and cross-product-line solutions, and reuse one product’s effective solution across the SPL.

To validate our approach, in Sect. IV we report on a case study of applying OFIR to optimize a real-life, industry-grade product line architecture.

II. BACKGROUND

A. Architecture Optimization

Let $Q(A, R) \in \mathbb{R}$ denote the overall quality adherence of an architecture $A \in \mathcal{A}$ to the system’s quality requirements $R \in \mathcal{R}$, where $Q$ is a real-valued function from $\mathcal{A} \times \mathcal{R}$ to $\mathbb{R}$ and higher values mean better adherence. Let $\mathcal{M} = \{\mu_i \in \mathcal{A} \mapsto \mathcal{A}\}_{i \in I}$ denote a set of architecture modification options indexed by $I$.

Given a cost estimation function, $\text{cost} : \mathcal{M} \to \mathbb{R}$, and a cost limit, $\xi \in \mathbb{R}$, set by the stakeholders for architecture optimization, the goal of the software architect is to systematically find a subset of modifications $\psi(\mathcal{M}) \supseteq \mathcal{M}_K = \{\mu_{i_k} \in \mathcal{M}\}_{i_k \in K}, K \subseteq I$, that satisfies the cost constraint

$$\xi \geq \sum_{i_k \in K} \text{cost}(\mu_{i_k})$$

and maximizes $Q(A', R)$, where

$$A' = \mu_{i_1} (\cdots \mu_{i_k} (\mu_{i_1} (A)) \cdots)$$

is the architecture obtained by applying all the modifications indexed by $K$ to $A$.

For example, for $\mathcal{M} = \{\mu_1, \mu_2, \mu_3, \mu_4\}$ and the modification costs depicted in Fig. 3, the set of modifications $\mathcal{M}_{3,4}$ is optimal for $\xi = 8$, but $\mathcal{M}_{2,3} = \{\mu_2, \mu_3\}$ is optimal for $\xi = 6$.

Alternatively, the stakeholders may decide not to set $\xi$. Instead, a parameter $\gamma$ is set, which represents the importance of $Q(A, R)$ to the stakeholders with respect to implementation costs. A higher $\gamma$ means willingness on their part to accept a higher cost in return to a more significant quality improvement. In such a case, the goal is to maximize:

$$\frac{(Q(A', R))^\gamma}{\sum_{i_k \in K} \text{cost}(\mu_{i_k})}$$

where $K$ is not empty.

In the example shown in Fig. 3, for each $\gamma$ the optimum is different: $\mathcal{M}_2$ is optimal for $\gamma = 0.7$; $\mathcal{M}_3$ for $\gamma = 1$; $\mathcal{M}_{3,4}$ for $\gamma = 1.2$; and $\mathcal{M}_{1,2,3,4}$ is optimal for $\gamma = 1.6$.

B. Optimization Methods

An essential part of every AOM is architecture evaluation (Proc. 1.0, Fig. 2). An AOM helps assessing the degree to which a software architecture fulfills the system’s requirements, especially extra-functional requirements [8]. There are many kinds of AOMs [44], including: scenario-based, mathematical model-based, experience-based, simulation-based, metrics-based, tool-based, and controlled experiments.

While AOMs vary in nature, they share a common structure [31]. In every AOM, some knowledge about the evaluated architecture(s) and the desired system’s quality value(s) is processed, and the perceived suitability of the evaluated architecture(s) to the desired quality value(s) is produced as output. Additional byproducts include prioritization of quality attributes, identification of architectural patterns used to compose the software architecture(s), and correlation between the architectural...
patterns in use to the quality attributes. These byproducts are intermediate results in some AOMs. Other AOMs define them either as a expected input or as provided output.

While the majority of AOMs are contented with just architecture evaluation, the architecture optimization process is far from over for the architect. The software architect now needs to thoughtfully address the reported quality gaps of each architecture. Specifically, the architect must decide whether or not to: send the recommended, most-suitable architecture to implementation; apply some modifications to the architecture(s) to receive better results; or take business actions in face of intolerable quality-risks. Should the software architect decide to refine the architecture, a subset of the quality gaps is selected for minimization.

During architecture generation (Proc. 2.0, Fig. 2), the software architect identifies a list of changes to the former evaluated architecture that addresses some or all of the quality gaps. Since multiple quality gaps can be addressed in more than one way, multiple possible change lists exist. For a single software system, the software architect can either make a specific change to the architecture for each quality gap, or make changes that address multiple quality gaps at once.

For example, consider the architecture of a system’s web service that is diagnosed with quality gaps in four quality parameters: maturity, availability, modularity, and co-existence with external services. After analyzing the risks and possible solutions, the software architect has several options:

1) Fixing each one of the 4 quality gaps separately, by adding metrics to the web service’s availability, creating a stand-by service instance, separating the service discovery code from the business logic, and adding a throttling mechanism.

2) Hosting the web service on public cloud virtual servers to rectify both maturity and availability risks, with the other quality risks handled as in item 1. This reduces the number of changes from 4 to 3 and has different consequences.

3) Installing an API gateway in front of the web service to tackle all of the quality risks together.

To proceed, another iteration of the architecture optimization process is conducted in order to evaluate the suitability of the new architecture(s) in addressing selected quality gaps. In each iteration, the output of the architecture optimization process is used to create an updated input for another iteration of the process, until the stakeholders decide to stop refining and proceed with the latest or best result.

Note that some changes might cause new quality gaps to appear while solving others. Each change list has its own cost, too. The cost is based on the progress of implementation of the current architecture (as changing an implemented system costs more than changing architecture diagrams), and the effort needed to implement the changes themselves. Different change lists will leave the architecture with different lists of quality gaps. The challenge is finding the list of changes which maximizes the quality while minimizing the implementation cost.

III. AN END-TO-END METHOD

In this section, we introduce our AOM named Optimal architecture from initial Requirements (OfIR). The method has 6 steps (Fig. 4): Scope (Sect. III-A); Prioritization (Sect. III-B); Construction (Sect. III-C); Evaluation (Sect. III-D); Generation (Sect. III-E); and Selection (Sect. III-F).

A. Scope

The first step in OfIR sets the appropriate quality model for the architecture optimization process. The architect identifies quality characteristics that are relevant to all the software products being evaluated (Sect. III-A1), and selects significant features to be considered in their evaluation (Sect. III-A2).

1) Characteristic Selection: The architect starts with the quality model found in ISO/IEC 25010 [22], which partitions the notion of software quality into eight quality characteristics: Functional suitability, Efficiency, Compatibility,
Usability, Reliability, Security, Maintainability, Portability. Each characteristic is composed of several correlated quality properties. To possess a quality characteristic, an architecture has to adhere to the quality properties it is composed of.

The ISO/IEC 25010 model is then narrowed down by eliminating characteristics irrelevant to software architecture or irrelevant to the system. For example, when the goal is evaluation of both functional and extra-functional aspects of the system, all characteristics may be deemed relevant. However, in the context of an architecture optimization process the enterprise management and software architects may find the evaluation of extra-functional aspects to be more meaningful, in which case some of the characteristics may be eliminated from the quality model.

First, Functional suitability can be ignored, because deciding on an architecture is mostly the result of balancing trade-offs between extra-functional requirements. Functional characteristics do not compete with extra-functional over which architecture to choose the same way different extra-functional characteristics do.

Second, Usability can also be ignored. Most of the properties of Usability are functional, or otherwise not related to the software architecture. The only two extra-functional properties of Usability are User error-protection, which is covered by the Fault tolerance property of Reliability, and Learnability of code and structure, which is covered by the Analyzability property of Maintainability.

Third, Compatibility can be merged into the other characteristic. We find its Interoperability property inseparable from Maintainability, regarding consequences of changes in integrating components, and its Co-existence property directly related to Efficiency.

For the rest of this paper we shall assume that the five selected quality characteristics for extra-functional quality evaluation, and their associated properties, are those listed and numbered in Table II.

2) Feature Selection: The properties, as defined in ISO/IEC 25010, can be evaluated in different ways. In order to share the results among products, which is the main goal of OFIR, all the products of the SPL need to be evaluated with the same criteria and metrics [6]. To this end, key features which implement or compose each of the properties are identified and defined in terms of the organization’s common architectural patterns.

For each such feature, the architect forms one or more yes-no survey questions. These questions should be articulated in such a way that answering yes on all the questions related to a given property implies full compliance with that property, while answering no on all of them implies total neglect.

For example, the Fault tolerance property of Reliability may be broken down into five distinct features: protection from logical exceptions, wrong user actions, faults in external services, hardware failures, and full site failures; in which case the following questions will be formed:

- Fault tolerance (exec): Does the product protect its activity from logical exceptions?
- Fault tolerance (user): Does the product protect its activity from wrong user actions?
- Fault tolerance (ext): Does the product protect its activity from faults in external services?
- Fault tolerance (hw): Does the product protect its activity from hardware failures?
- Fault tolerance (site): Does the product protect its activity from full site failures?

The collection of questions make up a quality compliance questionnaire (like the one presented in Table III). Not all properties may be relevant to every organization or to every product — only relevant properties should be measured. However, when a characteristic is relevant to some but not all of the organization’s products, it should nevertheless be included, and skipped when irrelevant. We discuss several approaches to dealing with irrelevant characteristics in Sect. III-B1. In cases where the solution is mediocre or when the answer differs between several parts the evaluated architecture, the answers may also be somewhere in between yes and no.

B. Prioritization

The second step in OFIR is prioritization. Let \( \mathcal{F} = \{ \phi_1, \phi_2, \ldots, \phi_n \} \) be the set of features selected in Sect. III-A, and let \( \mathcal{C} = \{ \kappa_1, \kappa_2, \ldots, \kappa_l \} \) be the partition of \( \mathcal{F} \) into characteristics. Each characteristic \( \kappa \in \mathcal{C} \) is assigned a normalized weight \( w_C(\kappa) \in [0,1] \), such that

\[
1 = \sum_{\kappa \in \mathcal{C}} w_C(\kappa),
\]

and each feature \( \phi \in \mathcal{F} \) is assigned a normalized weight \( w_F(\phi) \in [0,1] \), such that for all \( \kappa \in \mathcal{C} \),

\[
1 = \sum_{\phi \in \mathcal{F}} w_F(\phi).
\]

Giving due weighting to quality char-
TABLE III

| Feature | Question | Weight |
|---------|----------|--------|
| 1.1 | Maturity | Is the reliability of the product monitored? | .14 |
| 1.2 | Availability | Can the product be upgraded without downtime? | .10 |
| 1.3.1 | Fault tolerance (exec) | Does the product protect its activity from logical exceptions? | .14 |
| 1.3.2 | Fault tolerance (user) | Does the product protect its activity from wrong user actions? | .14 |
| 1.3.3 | Fault tolerance (ext) | Does the product protect its activity from faults in external services? | .14 |
| 1.3.4 | Fault tolerance (hw) | Does the product protect its activity from hardware failures? | .14 |
| 1.3.5 | Fault tolerance (site) | Does the product protect its activity from full site failures? | .06 |
| 1.4 | Recoverability | Does the product have a verified data backup and recovery ability? | .14 |
| 2.1.1 | Time behavior (req) | Does the product meet its latency and throughput requirements? | .15 |
| 2.1.2 | Time behavior (mon) | Are the latency and throughput of the product’s activity monitored? | .15 |
| 2.2.1 | Resource utilization (req) | Does the product meet its resource utilization requirements? | .15 |
| 2.2.2 | Resource utilization (mon) | Is the resource utilization of the product’s activity monitored? | .15 |
| 2.3 | Capacity | Is the product’s activity load actively shared amongst its resources? | .20 |
| 2.4 | Co-existence | Does the product prevent external load from harming its performance? | .20 |
| 3.1 | Modularity | Does a change impact only one component of the product? | .20 |
| 3.2 | Reusability | Are external data and logic re-used (rather than re-implemented)? | .14 |
| 3.3 | Analyzability | Is the architecture kept clear by adhering to common patterns? | .14 |
| 3.4 | Modifiability | Do all product’s services implement forward/backward-compatibility? | .14 |
| 3.5 | Testability | Is the product continuously tested to supply confidence in changes? | .19 |
| 3.6 | Interoperability | Are the inter-communication protocols loosely-coupled? | .19 |
| 4.1 | Adaptability | Can the product be scaled for higher usage by merely adding resources? | .28 |
| 4.2 | Installability | Can the product be installed in different environments? | .28 |
| 4.3.1 | Replaceability (lang) | Can the product’s components be developed in different programming languages? | .16 |
| 4.3.2 | Replaceability (inst) | Can the product be used without installing specific technologies? | .28 |
| 5.1 | Confidentiality | Does the product use common authorization mechanisms? | .15 |
| 5.2 | Integrity | Do the product’s components prevent unauthorized access? | .25 |
| 5.3 | Non-repudiation | Does the product permanently audit all user actions? | .25 |
| 5.4 | Accountability | Does the product enforces use of personal users? | .15 |
| 5.5 | Authenticity | Does the product fully-separate simulated data from real data? | .20 |

Characteristics in C is a business decision, while weighting features in F is an engineering decision.

1) Weighting Characteristics: By assigning weights to the different characteristics, the organization management expresses which quality characteristic is of higher business priority, e.g., the management may choose to prioritize security over performance [47]. Through updates to these priorities management can direct the organization towards the desired results [39].

By default, every characteristic $\kappa \in C$ is assigned the weight $1/|C|$ (1/5 in Table II). An architecture optimization process based on these default weights produces balanced quality scores for the various products. Later, these weights can be changed according to business prioritization, and the revised evaluation scores would indicate which architectural changes can make the biggest impact.

2) Weighting Features: Feature weighting, on the other hand, is of a more technical nature, prioritizing elements of a desired product architecture. These weights are much less likely to change during the architecture optimization process, unless a major cross-product technological change occurs, because they are based more on advances in the state-of-the-art than on human decisions.

The weight of each feature reflects the quality gained to the relevant characteristic by implementing the feature (or lost by not implementing it). In weighting the different features the architect should consult professional studies and veteran architects. For all $\kappa \in C$, for all $\varphi \in \kappa \subset F$, we define the overall weight of feature $\varphi$ to be:

$$w(\varphi) \triangleq 100 \ast w_C(\varphi) \ast w_F(\varphi)$$

where $w_C(\varphi) \equiv w_C(\kappa)$ is the weight assigned to the characteristic $\kappa$ to which $\varphi$ belongs.

C. Construction

To begin the architecture optimization process, an initial architecture is needed. In the case of an SPL, several products are chosen to present their initial architectures. Note that selecting a subset of an SPL’s products can be sufficient for identifying common quality flaws across the product line [12].

If an initial architecture does not exist, one has to be generated. A naive approach is to use appropriate design patterns for all the requirements, based on the quality compliance questionnaire from Sect. III-A2. This could produce a perfect or near-perfect architecture, but not necessarily a feasible one. Applying all desired modifications might not adhere to the budget constraints. It will be hard to backstep from the perfect architecture to an optimal feasible architecture.

Instead, in OFIR the most basic design patterns are applied to create a minimal initial architecture, with only those patterns that are necessary to fulfill the functional requirements. The quality gaps in this initial architecture
will be identified downstream, and a set of modifications will be applied to achieve the optimal architecture.

D. Evaluation

In the fourth step of Ofir, the specific architecture of each product is assessed by asking its architect in an interview the questions found in the quality compliance questionnaire (Sect. III-A2). Let \( \mathcal{P} = \{\pi_1, \pi_2, \ldots, \pi_m\} \) be a set of \( m \) products of the SPL being evaluated. During the interviews, every feature \( \varphi \in \mathcal{F} \) in every product \( \pi \in \mathcal{P} \) is assigned a numeric value \( u(\varphi, \pi) \in \mathbb{Q} \cap [0, 1] \) that reflects \( \pi \)'s degree of compliance with \( \varphi \).

When a certain feature \( \varphi \) is irrelevant with respect to a specific product \( \pi \), its weight \( w_{\mathcal{F}}(\varphi) \) can either be divided among the other features in the same characteristic or retained. If retained, \( u(\varphi, \pi) \) can be assigned either a perfect value, \( u(\varphi, \pi) = 1 \), indicating that there is no flaw in the architecture with respect to this feature, or an empty value, \( u(\varphi, \pi) = 0 \), indicating that the architecture does not handle that feature. The last option is usually for a feature for which it is inherently difficult to find an architectural solution. This way, products that are not concerned with that feature will not stand out as those who do handle it successfully.

For all \( \varphi \in \mathcal{F}, \pi \in \mathcal{P} \), the weighted score for feature \( \varphi \) in product \( \pi \) is defined to be:

\[
\text{score}(\varphi, \pi) \equiv w_{\mathcal{F}}(\varphi) \times u(\varphi, \pi)
\]  

(4)

To detect exceptional scores, for each feature \( \varphi \in \mathcal{F} \) we compute the mean score \( \mu_\varphi = \frac{1}{|\mathcal{P}|} \sum_{\pi \in \mathcal{P}} \text{score}(\varphi, \pi) \) across products, and its standard deviation, \( \sigma_\varphi \). The quality gap of \( \varphi \) is defined to be: \( \Delta_\varphi \equiv w_{\mathcal{F}}(\varphi) - \mu_\varphi \).

Features with a quality gap \( \Delta_\varphi > \mu_\varphi + \sigma_\varphi \) have the highest impact over the quality of the product line. Features with \( \text{score}(\varphi, \pi) < \mu_\varphi - \sigma_\varphi \) have a major quality gap in a specific product \( \pi \).

E. Generation

The fifth step in Ofir is to generate the set of architecture modification options, \( \mathcal{M} \) (recall Sect. II), that if applied to the existing architecture may address the quality gaps.

1) Product Line Level Modifications: For each high-impact feature, one or more modifications are generated, using as guide the questions formed in Sect. III-A2. In principle these modifications should achieve full adherence to those quality features, i.e., \( \forall \pi \in \mathcal{P}, u(\varphi, \pi) = 1 \).

In practice, however, sometimes a modification only achieves a partial improvement. Moreover, a modification can have a positive or negative impact on other quality features \(^4\).

There are different types of modifications in a SPL. Each modification incurs a total cost, which may include a shared cost for the SPL level effort and particular costs for each product level effort. Similarly, each modification also has its own total quality gain, which includes the sum of quality improvements in all quality feature in all of the products.

2) Product Level Modifications: For each feature with a major quality gap, one or more modifications are generated, using the questions formed in Sect. III-A2. As opposed to Sect. III-E1, only product-specific modifications are analyzed at this step. Still, a modification may have an impact on more than one quality feature.

Finally, each subset of these modifications is assigned its total quality adherence gain and total cost. The full list of modifications is used in the final step of Ofir.

F. Selection

The final step of Ofir provides the software architect with a subset of modifications, \( M_k \subset \mathcal{M} \), that produce the optimal architecture, where \( \mathcal{M} \) is the list of modifications derived in Sect. III-E.

In principle, there are \( 2^{|\mathcal{M}|} \) subsets in \( \varphi(\mathcal{M}) \) to consider. In practice, the number is much lower because some of the modifications may be mutually exclusive. The subset with the highest overall quality that adheres to the total cost restriction \( \xi \) (Eq. 1, Sect. II) is selected. Alternatively, if \( \xi \) is not set, the subset which maximizes the \( \gamma \) function (Eq. 2, Sect. II) is selected. Applying the selected subset of modifications to the existing architecture produces the optimal architecture.

IV. Evaluation

Ofir was applied to an industrial software product line comprising dozens of products. Five products, code-named A, B, C, D, and E, were randomly chosen for the architecture optimization process. These five products had different requirements, constraints, and architectures, and varied in their “nature” (Table V), e.g., in the number of users (ranging from few to thousands), in the rate of transactions (ranging from hundreds per hour to thousands a second), and in the number of interoperable systems (ranging from several to dozens of interfaces).

Three expert architects were consulted for the selection of features, assigning weights representing the normalized impact that each feature has over its quality characteristic (left-hand section in Table IV). The resulted quality compliance questionnaire is the one presented in Table III. For each of the quality features, they also defined one or more architectural patterns that can be used to achieve the desired quality.

A 5-hour interview was held with each of the architects of the individual products, in order to understand the product’s architectures in depth and fill out, for each product, the quality compliance questionnaire. The structure of the interviews was based on common architecture review practices. The collected data is displayed in the

\(^4\) We consider Coexistence and Interoperability as properties of Performance Efficiency and Maintainability, respectively, although ISO/IEC 25010 places them in a separate category named Compatibility.
middle section of Table IV, and the weighted scores are listed in the right-hand section of that table. Exceptional values that are more than one standard deviation away from the mean are marked in red and in green to emphasize low and high quality results, respectively.

### A. Results

The data revealed that the product line suffers major risks in features 2.1.2, 2.2.2, 3.1, 3.6, 4.2, 5.2, and 5.3, as they have very low values across the product line ($\Delta_g > 2.7$). Fixing these features should achieve the highest quality improvement for the product line.

Table VI lists the 10 possible architecture modifications that were independently proposed by the expert architects for addressing these specific low-valued features. These modifications are known to achieve perfect answers to the questions in Table III, i.e., modifications that could potentially bring about full adherence to these quality features.

The total cost, in workdays, of each modification is the cost estimation for applying the change to the core architecture or for producing a shared asset, plus the cost estimation for applying the change to each of the affected products separately. The total gain of each modification is the sum of quality improvements in each quality feature in each of the affected products.

For example, the cost of $M_8$ is estimated as 15 workdays to create the shared access control asset plus 2 days to implement it in each of the 5 products, for a total of 25 workdays. The gain is 2.5 for $A$, 0 for $B$, 5 for $C$, 2.5 for $D$, and 5 for $E$, for a total of 15.

A set of 10 possible modification spans a search space of size $2^{10} - 1$ for the optimal architecture. Note, however, that some of the modifications in Table VI are mutually incompatible. For example, different approaches to achieving the very same quality adherence cannot be implemented together. Three out of eight combination of $\{\mu_1, $\mu_2, $H_3\}$ are incompatible, and one out of four combinations is incompatible for each of the pairs $\{\mu_7, \mu_8\}$
The SPL management accepted the recommendations from our case study, putting effort and budget to implement the suggested modifications. This is further indication of the validity of OFIR and relevance to industry.

B. Discussion and Threats to Validity

This case study is a preliminary indication of the validity of OFIR. Obviously, more experiments with OFIR on different SPLs are needed to increase the method’s validity. Still, the SPL on which OFIR was evaluated is a standard SPL. The method did not rely on any special attributes, such as a specific domain. Therefore, one can expect OFIR to work on other SPLs.

Quality scores (Fig. 6) were nicely distributed, with some features having repeatedly low scores, some features with repeatedly high scores, and some features having varying scores. This made the selection step (Sect. III-F) challenging (no trivial optimal architecture), demonstrating the strength of OFIR. Selecting just five systems from the full SPL succeeded in identifying quality gaps at the SPL level in a timely manner, without needing to evaluate each and every product [12]. However, after matching the results with other products in the SPL, another recurring quality gap was identified. Therefore, finding the optimal number of products to analyze in a SPL should be further researched.

The SPL management accepted the recommendations from our case study, putting effort and budget to implement the suggested modifications. This is further indication of the validity of OFIR and relevance to industry.
V. RELATED WORK

A. Single Product Evaluation Methods

Domain-specific software architecture comparison model (DoSAM) [6] is an AOM that uses a metric comparison (τ₁), in multiple quality features (τ₂), and is cost-aware (τ₃). Weights of each quality feature are calculated mathematically. Overall, this method enables a systematic evaluation of a single product.

However, DoSAM depends on the alternative architectures to be given as input. If the optimal architecture is not in the input alternatives, it will not be found. Also, it does not easily scale to the full list of quality features, as it demands a specific analysis of the impact of each architectural element on each of the quality features.

B. Product Line Evaluation Methods

Several related works extend their AOM to target PLA evaluation [13], including: holistic product line architecture assessment (HoPLAA) [41], distributed scenario-based architecture analysis method (D-SAAM) [19], extended architecture tradeoff analysis method (EATAM) [27], and calidad del producto y del proceso software (CaLiPro) [12].

These AOMs apply a single product evaluation method, similar to that of SAAM [25] and ATAM [26], but in two phases: first to the SPL’s core architecture, and then to each of the different products. They identify suitability and quality gaps of the whole SPL (τ₄) with multiple quality features (τ₂). However, they have to be expanded with quantitative metric techniques (τ₁) in order to be used in the architecture optimization process of product line architectures [41]. Moreover, these methods do not support generation of alternative architectures, which is a task far from trivial in a product line.

Quality-driven product architecture derivation and improvement (QuaDAI) [18] is an AOM for a SPL. The SPL architect identifies the existing product architecture and its relations with the quality requirements, and measures adherence to those requirements using external metric methods. The SPL architect has to come up with a set of possible modifications. Then, a domain expert ranks each possible modification on a scale of 1 to 9. Iteratively, each modification is applied to the product architecture in an effort to meeting all the quality requirements.

While QuaDAI is designed for a SPL, its steps are focused on a single product. However, it does not consider trade-offs between single product modifications and shared assets or changes to the core architecture. Therefore, it cannot find an optimal PLA, but rather a local optimization for each product.

VI. CONCLUSION

In this paper we introduced Ofir, an end-to-end method for the architecture optimization process. Instead of using incompatible AOMs for each step, Ofir takes the architect from the initial requirements all the way to the optimal architecture.

Using Ofir, the architect analyzes multiple quality characteristics, selected from ISO/IEC 25010. The method is fitted to the SPL by defining features and assigning weights. Ofir also supports the identification of cross-SPL weaknesses, the generation of respective cross-SPL solutions, and the reuse of one product’s effective solution across the SPL. The significance of the various quality characteristics to the organization, as declared by the stakeholders, is kept separate from the effect of the various feature, as identified by technical means, while both influence the selection of the optimal architecture.

We presented a case study where Ofir was applied to a production SPL in an industrial setting. Weaknesses of the SPL and its specific systems were identified, a list of potential modifications was generated, and an optimal PLA was produced.

Once the architecture optimization process is formulated with the discretion of stakeholders being an input to the process rather than part of it, it might be possible to automate the process. Ofir thus lays the foundation for an industry-level automatic generation of software architectures and product line architectures—a topic left for future work.

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