Balancing business and technical objectives for supporting software product evolution

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Abstract

Context: Successful software systems continuously evolve to accommodate feature requests of a diverse customer-base. At some point during this evolution, the variety of customer needs and increased system complexity suggests the consideration of a software product line (SPL).

Aim: The goal of this research is to support the decision maker facing the enhancement of an evolving software system (ESS) by determining the most appropriate product line design (out of a given set of candidate SPL portfolios) to minimize the technical risk and maximize the business value.

Method: The proposed method called OPTESS is aimed at finding an evolution plan for the ESS which optimizes both the given technical and business objectives. Business analysis using a value-based pricing mechanism is applied to a set of initially proposed SPL portfolios (for enhancing the ESS) such that profit is maximized. Technical analysis is applied to the same initially proposed SPL portfolios to minimize the risk of failure of ESS due to implementation of new features. Business and technical analyses improve the performance of solutions for their respective objectives by modifying the feature sets of candidate SPL portfolios. OPTESS helps the decision maker select a plan for enhancement of an ESS by performing trade-off analysis between economic and technical objectives.

Results: The method was initially evaluated through a case study for a set of 9 new candidate features to be added to an open source text editing system called jEdit. OPTESS helped the decision maker to identify 3 non-dominated solutions judged to be the best contenders for addition when considering both technical and economic criteria.

Keywords

Software engineering decision support, cost-benefit analysis, trade-off analysis, economic analysis, software product lines, software product evolution, open source systems

1 Introduction

Successful software systems continuously evolve to accommodate features requests from customers. This system evolution increases the complexity of the architecture, thus increasing the cost of maintenance. On the other side, by increasing features the software system attracts more customers from diverse domains, making the system more successful. At a certain point during the evolution of the system, the complexity of the architecture and the variations in customers' needs triggers a software product line (SPL). A SPL is a set of software intensive systems that share a common, managed set of features satisfying the specific needs of a particular market segment or mission, and are developed from a common set of core assets in a prescribed way [1]. A number of real world software systems have evolved in this way. For example, Microsoft Windows operating system was initially launched as a single product. Due to its success, it was soon evolved into a SPL. One of the recent releases of this operating system, Windows 7, offers separate product variants for the *home* (Starter, Basic, Premium,) *business* (Professional, Enterprise) and *power users* (Ultimate) market segments, where the term product variant refers to an individual product in a SPL.

Creation of business value has always been advertised as one of the key benefits of a SPL development approach. Several case studies have been reported citing numerous business and technical benefits such as higher customer satisfaction, increase in productivity, reduction in maintenance costs, etc., [1] [2] [38]. There is, however, a lack of scientific research quantifying the economic value gained through adoption of a specific product line approach for a product. A panel discussion “How to maximize business return on SPL” was organized in the recent 13th International Software Product Line Conference (SPLC 2009) where practitioners and researchers called for more research on how to define and increase *business value* from product lines. A key conclusion was that *value* cannot be defined globally; it has to be defined for a specific product line in a given organization [35].

Despite several benefits of adopting a product line development approach (higher quality, productivity and return on investment) as reported in industrial case studies [1] [2], there is still resistance amongst practitioners towards its adoption. Several reasons have been reported for this resistance such as the loss of product ownership, high upfront investment, and the lack of scientific evidence on economic benefits and risks of adopting a product line development approach [3]. Our previous work provided decision support to transition a single software product into a product line containing product variants addressing needs of specific customers’ segments. A suitable portfolio is selected from the candidate SPL portfolios for enhancing the ESS by analyzing the customers’ preferences for product features and the impact of the features on ESS’s structure [4] [5]. The decision support for evolving a single software product in [5] can be considered as a one dimensional approach since there is no consideration for the costs and economic benefits of the candidate SPL portfolios.

Most of the existing SPL development methods do not connect the business and technical aspects for developing and evolving SPLs [6]. Our method provides a link between these two domains. The fundamental research question addressed by this paper is whether a single software product facing feature requests for upcoming release should be evolved into a software product line, recognizing that a single software product containing all the features for the upcoming release is always considered as one an alternative along with all the candidate SPL portfolios when evaluating the technical and business objectives.

We present a method called OPTESS (Optimization of Technical and Business Objectives for Evolving Software Systems) which provides comprehensive decision support for selecting an evolution plan for a single software product. In addition to the technical criterion, it also considers costs and expected revenues from candidate SPL portfolios for enhancing the ESS. The main content of the method is a trade-off analysis between technical risk and business value of candidate evolution plans for enhancing the ESS. For the purpose of our analysis, we define *technical risk* as the probability that a feature implemented in an evolving software system’s structure will cause failure of the system. The *business value* of a software product is calculated by subtracting its estimated cost of development from the projected revenue.

The specific research questions we address are:

RQ 1: From a given set of candidate SPL portfolios for enhancing an evolving software system, which ones minimize the technical risk and maximize the business value?

To address the decision problem identified in RQ1, our proposed method brings together two different but equally important criteria. The first criterion is related to the technical aspects of evolving a single software product. For this purpose, we consider the impact of implementing new features in candidate SPL portfolios. The goal is to reduce the probability of failure when features are implemented in ESS's structure. The technical aspect is addressed by the second research question.

RQ 2: How to estimate the risk of failure due to implementation of new features in the ESS's architectural structure?

The second criterion is related to the economic benefits of enhancing the single software product to a SPL. For this purpose we calculate the costs and revenues of the single product and the candidate SPL portfolios. The goal is to identify SPL portfolios which maximize the economic benefits. Third research question addresses the economic aspect.

RQ 3: How to estimate the business value of a software product when considering both the revenue and the cost associated with the SPL design?

The specific technical contributions of our work are:

(1) The decision support method OPTESS for trade-off analysis between technical risk and business value of candidate SPL portfolios.

(2) Customization of an existing technique to estimate risk of failure due to implementation of features in product variants being part of candidate SPL portfolios.

(3) Application of an economic pricing and revenue generation method to estimate the business value of each candidate SPL portfolio.

(4) A proof of concept of the method by application to an open source software system.

The remaining sections organized as follows: Section 2 presents the research work related to the solution approach. Section 3 presents background details of the techniques applied in the method OPTESS. Section 4 presents the method OPTESS. Section 5 presents an illustrative case study of the method on an open source software systems. Section 6 presents the applicability and limitation of the method. Section 7 summarizes our conclusions and future research direction.

2 Related Work

There are four main research areas that are related to the proposed method. These areas are decision support for software product evolution, risk estimation for implementing new features, product line cost models, and pricing and revenue generation for SPLs.

2.1 Decision support for software product evolution

The need for decision support arises when decisions have to be made in complex, uncertain and/or dynamic environments [7]. There are several works that address provision of decision support for various aspects of software systems development. Turban et al., suggest that decision support systems are most suitable for semi-structured and unstructured problems [8]. This is one of the key characteristics of wicked problems, i.e., they are difficult to formulate [9]. Planning releases for a single software product has been classified as a wicked problem [10]. Planning for a portfolio of products is even more challenging. This calls for greater efforts to develop methods and tools for supporting the decision making process in product line engineering. Our previous work presented a decision support method COPE+ to address the fundamental research question presented in Section 1. COPE+, however, provides a one dimensional approach to address this problem by evaluating the alignment of candidate SPL portfolios with the architecture of the ESS. OPTESS adds a second dimension to this analysis by evaluating the economic benefits of the candidate SPL portfolios. In this section we present an overview of some of the existing methods that provide decision support for software product evolution.

Product Line Potential Analysis (PLPA) [11] is a decision support approach (partly) addressing the research questions presented in Section 1. It is applied in a one day workshop for personnel of a business unit. The authors have developed a set of criteria which they suggest is important for answering this decision problem. These criteria are categorized as: *main criteria* (essential for product line development and have to be fulfilled), *inclusion criteria* (indicates product line already exists), *supporting criteria* (applied if a business unit has problems that product line approach addresses) and *exclusion criteria* (to rule out factors that reduce economic advantage of product line approach). Each one of these four categories has a set of fine grained criteria. The authors have prepared a questionnaire to elicit information on these criteria. The participants of the business unit are asked to fill out the questionnaire in the workshop. Their answers are then mapped to the criteria to address the decision problem. The results of this method are: *yes* (the product line approach is suitable for these products and markets), *no*, or *investigation required*. The focus of this method is to provide decision support at a higher level of abstraction without considering detailed attributes of the product portfolios. Additionally, it does not consider the cost and revenue of developing the product line.

Product Line Technical Probe (PLTP) assesses an organization's readiness to adopt product line development approach [1]. It requires an organization-wide effort in which assessors gather information through structured interviews of key stakeholders. The results are a set of findings identifying the potential benefits, risks, as well as an assessment of the organization's expertise regarding product line development approach. The risks and benefits are identified at the organizational level and not for an individual product or a product line.

Product Line Benefit and Risk Assessment method analyzes the benefits and risks for each of the technical domains associated with the product line [12]. Hence, instead of just saying *yes* or *no* to product line engineering, this method prioritizes technical domains for reuse potential. This method has been modeled on the pattern of existing process maturity assessment methods. It does not evaluate the benefits and risks at the feature level.

Almost all systems development methods perform scoping at initial product definition stage to identify what (functionality) will be part of the system and what (functionality) will not be part of the system. This activity becomes even more important in SPL development since a product line contains multiple product variants. Most frameworks and methodologies for SPL development include scoping as a distinct activity. It is used to identify products within the product line (product portfolio scoping), features of these products as well as the features that will be developed for reuse (asset scoping) [13]. PULSE-Eco v2.0 is one such approach [13]. It relies on technical details such as economic benefit analysis to define products in the SPL. It does not, however, look into the ESS's structure to analyze the impact of new features.

2.2 Risk estimation for implementing new features

The enhancement of the ESS to one of the candidate SPL solutions requires the implementation of features in the ESS's structure. Each feature impacts one or more packages in the system structure. A *package* is a composition of classes in objected oriented design and refers to an element of implementation as defined by Bass et al., in [14]. Packages represent a code-based way of considering the system structure. The purpose of risk estimation here is to compare the candidate SPL solutions with respect to their risk of failure as a result of implementation of new features. There is an extensive body of knowledge on risk management for software systems. Boehm has identified top ten software risk items after investigating several large projects [15].

One of his findings is that as the size of the requirement increases, the probability of failure also increases.

Two approaches have been proposed in literature to estimate the probability that a change (due to a bug fix or new feature implementation) in a software system will result in failure. The techniques in the first approach use product measures such as size of the file, degree of nesting, code complexity (such as McCabe's cyclomatic complexity) to predict the probability of failure. The techniques in the second approach for modeling fault rates use data from the change and defect history of the program. Both approaches are applicable for the purpose of our method; however, we are more interested in estimating the probability of failure using product measures than historical data.

Therefore, we have selected and adapted a technique by Mockus and Weiss [16] to estimate the probability of failure of the ESS. They have proposed a risk estimation model that estimates the probability of failure by using the "change measures" for the feature being implemented. These change measures capture information such as the number of packages modified for implementing the feature, the number of lines of code added or deleted, the duration for implementing the feature and experience of the developer. This model estimates the risk for one feature implementation in isolation. However, in our case, each product variant (in a given SPL portfolio) is typically developed by implementing more than one feature. Therefore, we have customized their model to estimate risk.

2.3 Product line cost models

Boehm defines economics as the, "study of how people make decisions in resource-limited situations" [17]. The investment in establishing a product line enables an organization to improve quality, capture diverse markets, eventually increasing its revenues and profits as reported in many case studies [1] [2]. Due to large upfront costs and risks of failure, industry is hesitant to adopt product line development [3] [18]. There is a large body of knowledge on cost estimation of software products [17]. Below we present an overview of the most popular cost estimation models for SPL development.

The Constructive Product Line Investment Model (COPLIMO) is based on the COCOMO II model [19]. COPLIMO determines the cost of a SPL in two components. The first reflects the cost of initial development of the SPL architecture and the second reflects the post-development extensions. This second cost component incorporates the reuse of previously developed components in products developed later in the development life cycle. The qCOPLIMO model extends the COPLIMO model by evaluating the additional benefits of higher quality in product line development [20].

Structured Intuitive Model for Product Line Economics (SIMPLE) provides a high level framework for estimating the cost of developing a SPL [21]. It provides four cost functions that can be combined in a number of ways to estimate the cost of establishing a SPL. Boeckle et al., present seven scenarios that cover several possibilities of evolving and instantiating a SPL. As opposed to COPLIMO, SIMPLE does not look into the costs and revenues from future extensions of the product line. As we are only considering the cost of evolving the ESS into a SPL in one release, we selected SIMPLE to estimate the cost of the SPL in our method.

The application of SIMPLE requires effort estimates for the features. Effort estimation methods for software systems fall into three main categories: expert judgment, estimation by analogy, and algorithmic cost estimation [22]. Expert judgment relies on the experience of experts, and the accuracy of expert-based prediction is low. Algorithmic estimation involves the application of mathematical models such as in COPLIMO [19]. The idea of analogy-based estimation is to determine the effort of the target feature (or project) as a function of the known effort from similar historical features (or projects). Compared with the other two categories, estimation by analogy performed best in 60% of the published case studies [23]. Existing analogy-based effort estimation methods have several limitations. For example, the CATREG method proposed by Angelis et al., can only work with data sets containing categorical (or qualitative) attributes [24]. Many of the existing analogy-based effort estimation techniques can only work data sets without any missing values [25]. Method AQUA proposed by Li and Ruhe in [25] supports multiple data types by defining similarity measures for these data types. It is also able to tolerate missing values in the data set. AQUA has performed better than other analogy-based effort estimation techniques using publicly available data sets. We have selected AQUA to implement cost functions of SIMPLE.

2.4 Pricing and revenue generation for SPLs

Pricing and revenue generation for SPLs have been broadly explored in the economic and marketing literatures. The major purpose of SPL design is to meet the requirements of customers in different market segments to maximize profit. Pricing of a SPL is normally determined through a value-based pricing mechanism, which is to set prices for different product variants according to customers' valuations [26].

Moorthy [27] proposed a customer self-selection model to evaluate the product line design strategies of a monopolist. He argued that customers should be able to choose their preferred products freely and the optimal product line design strategies should address this in order to maximize the overall profits of the product line. In order to make customer self-selection work for SPL design, the individual rationality (IR) and incentive compatibility (IC) constraints are normally imposed on pricing of a SPL [28]. The IR constraint ensures that a consumer gets non-negative surplus from purchasing their chosen product variant and the IC constraint indicates that the consumer prefers the product variant that maximizes her surplus.

Product variants in a SPL can be either horizontally or vertically differentiated. For vertical differentiation, a product variant includes all the features of another product variant and more, while for horizontal differentiation; different product variants include some special features of their own although they usually share some common features. Wei and Nault [29] proposed analytical models to develop product line design strategies under both situations when a monopolist chooses to offer different products to meet the special requirements of different groups of customers to maximize its overall profit. In our method, we follow Wei and Nault [29] to calculate revenues generated from a product line in order to estimate its business value.

3 Technical background for method OPTESS

SPL development aims at maximizing profit. This includes two parts: (i) cost of establishing a SPL and (ii) revenue generated from the product line. To estimate costs of establishing a SPL, we adopt the SIMPLE model [21]. To maximize revenues from a SPL, we follow pricing strategies of information goods developed in information systems economics based on economics and marketing research, and adjust them to the purposes of this research. To estimate the risk of failure by implementing new features in the ESS, we customize an existing risk estimation method. In the following subsections, we present an overview of these techniques.

3.1 SIMPLE

SIMPLE proposed by Boeckle et al., provides a framework to estimate the cost of developing a SPL [21]. We selected SIMPLE to estimate the costs of candidate SPL portfolios for the reasons discussed in Section 2.3. The model has four cost functions, each of which represents a separate idea and can be implemented through a variety of approaches. Below we provide an overview of the four cost functions:

Definition 1 (C_{unique}()): This function, given the relevant parameters, returns the cost to develop unique software that is not based on a product line platform. Usually, this will be a small portion of the product but in the extreme it could be a complete product. We apply the method AQUA [25] to estimate the effort (in person months) for implementing each unique feature.

Definition 2 (C_{cab}()): This function returns the cost to develop the shared features for a SPL portfolio. The shared features cost more than unique features because of the variability required to support multiple product variants. We include this additional effort by considering the packages in ESS's structure impacted by the shared features and correspondingly adjust the effort estimates suggested by AQUA [25].

Definition 3 (C_{reuse}()): This function returns the cost to reuse the shared features in multiple product variants. It includes the cost of tailoring it (by applying appropriate variability mechanisms) for use in the intended product variant and performing the extra integration tests. We follow the recommendations by experts [37] to estimate the cost of reusing shared features across multiple product variants in a SPL.

Definition 4 (C_{org}()): This function returns the cost for an organization to adopt a product line development approach for its products. Such costs can include reorganization, process improvement, training and other organizational remedies as necessary.

With these functions, however implemented, the cost of developing the *i*-th SPL portfolio can be expressed as:

$$\text{Cost}(i) = C_{unique}(i) + C_{cab}(i) + C_{reuse}(i) + C_{org}(i) \qquad (1)$$

These cost functions form the basis for a number of different scenarios of instituting or evolving a SPL [21]. One such scenario will be considered in details in Section 5.3.2.

3.2 Pricing and Revenue Generation Applied to SPL

After a SPL portfolio has been designed, pricing strategies are implemented to maximize revenue. We assume customer self-selection [27] where a customer selects the product variant to maximize their surplus which equals to the value the they receive from the product variant less price of the product variant. Customer self-selection has been widely adopted in research on the pricing of product variants in SPL portfolios [28] [29].

In our method, we follow Wei and Nault [29] to calculate the overall revenue generated from a SPL to lay an economic basis for the estimation of the business value of the SPL design. Revenue generated from the SPL is the sum of revenues from all the market segments. The total revenue generated from a SPL portfolio depends on the price of each product variant and number of customers who purchase the product variant. To specify the revenue generation of a SPL portfolio, we define the following variables:

Definition 5 (Revenue R(p(i,j))): The revenue generated from the *j*-th product variant in the *i*-th SPL portfolio, and equals to the price of the product variant times the number of customers that select this product variant.

Definition 6 (Price of each product variant P(p(i,j))): The price of the *j*-th product variant in the *i*-th SPL portfolio, which is the same for all customers that select it.

Definition 7 (Customer's valuation V_k(p(i,j))): Customer k's valuation for the product variant p(i,j). In our model, the customer's valuation of a product variant is determined through the feature voting scores.

In order to make customer self-selection work, two classical constraints must be satisfied: the IR constraint and the IC constraint. As discussed earlier, the IR constraint indicates that a customer always gets non-negative surplus from purchasing a certain product variant. If the price for a certain product variant p(i,j) is higher than the value the customer can get from it, the customer would choose not to purchase. Thus the IR constraint can be expressed as:

$$V_k(p(i,j)) - P(p(i,j)) \geqq 0, \text{ for all } p(i,j) \qquad (2)$$

In order to maximize revenue, some consumers with low valuation may not purchase any product variant if prices of all product variants are set higher than their valuation, in other words, not all customers are necessarily served with a product variant.

The IC constraint indicates that when there are many product variants for the customer to select from, the one selected maximizes their surplus. It means the customer k gets greater surplus from purchasing product variant p(i,j) than any other product variant p(i,l). The IC constraint can be expressed as:

$$V_k(p(i,j)) - P(p(i,j)) \geqq V_k(p(i,l)) - P(p(i,l)), \text{ for all } p(i,j) \text{ and } p(i,l) \qquad (3)$$

The IC and IR constraints determine the price relationship of different product variants in a SPL portfolio. More details will be discussed in the cost-benefit analysis in Section 4.2.2.

Definition 8 (Q(p(i,j))): The quantity of a product variant p(i,j). For a specified product variant p(i,j), the number of customers depends on the price of the product variant and the valuation of each customer.

The total revenue generated from the *i*th SPL portfolio is the sum of revenues generated from each product variant. Thus, we express the total revenue as:

$$R(i) = \sum_j (P(p(i,j)) * Q(p(i,j))) \qquad (4)$$

The combination of revenue generated from a SPL portfolio and relevant costs associated with the product line development determines the business value of that portfolio.

3.3 Estimating Risk of Software Change

Mockus and Weiss have proposed a model for estimating risk of implementing a maintenance request in a software system [16]. They consider the implementation of each maintenance request (MR) in isolation. For the purpose of this work, we assume that multiple MRs (or product features) are implemented sequentially to develop a product variant in any given SPL portfolio. Correspondingly, we have replaced the *diffusion* (DF) metric from the model by Mockus and Weiss with another metric, which we call as *adjusted diffusion* (ADF) to reflect this assumption.

Definition 9 (Maintenance request): We will assume that an MR is the request to implement one new feature in the ESS.

Mockus and Weiss's model uses the following five metrics to estimate the probability that a change implemented as a result of an MR will cause failure in the software system:

Definition 10 (Diffusion): Diffusion (DF) is the number of distinct subsystems modified in the ESS's structure to implement the change.

Definition 11 (Delta): Delta is an atomic change to the source code recorded by a version control system. Each MR may require changes to several source code files. A file may be changed several times. Each change to a file is called a delta. The model uses the total number of deltas (ND) for an MR to predict the probability of failure.

Definition 12 (Interval): Interval (INT) is the time between the last and first delta.

Definition 13 (Experience): Average experience (EXPR) of the developer implementing the change.

Definition 14 (Lines of Code Added): Lines of code added (LA) to represent the size of the change to implement the MR.

Definition 15 (Adjusted Diffusion): Adjusted diffusion (ADF) is the number of distinct subsystems modified in the ESS to implement all the MRs (features) for a product variant in a given SPL portfolio.

The above criteria are combined in the following model to estimate the probability of failure (P) as shown in Equation 5. α_i represents the estimated coefficients for the five parameters.

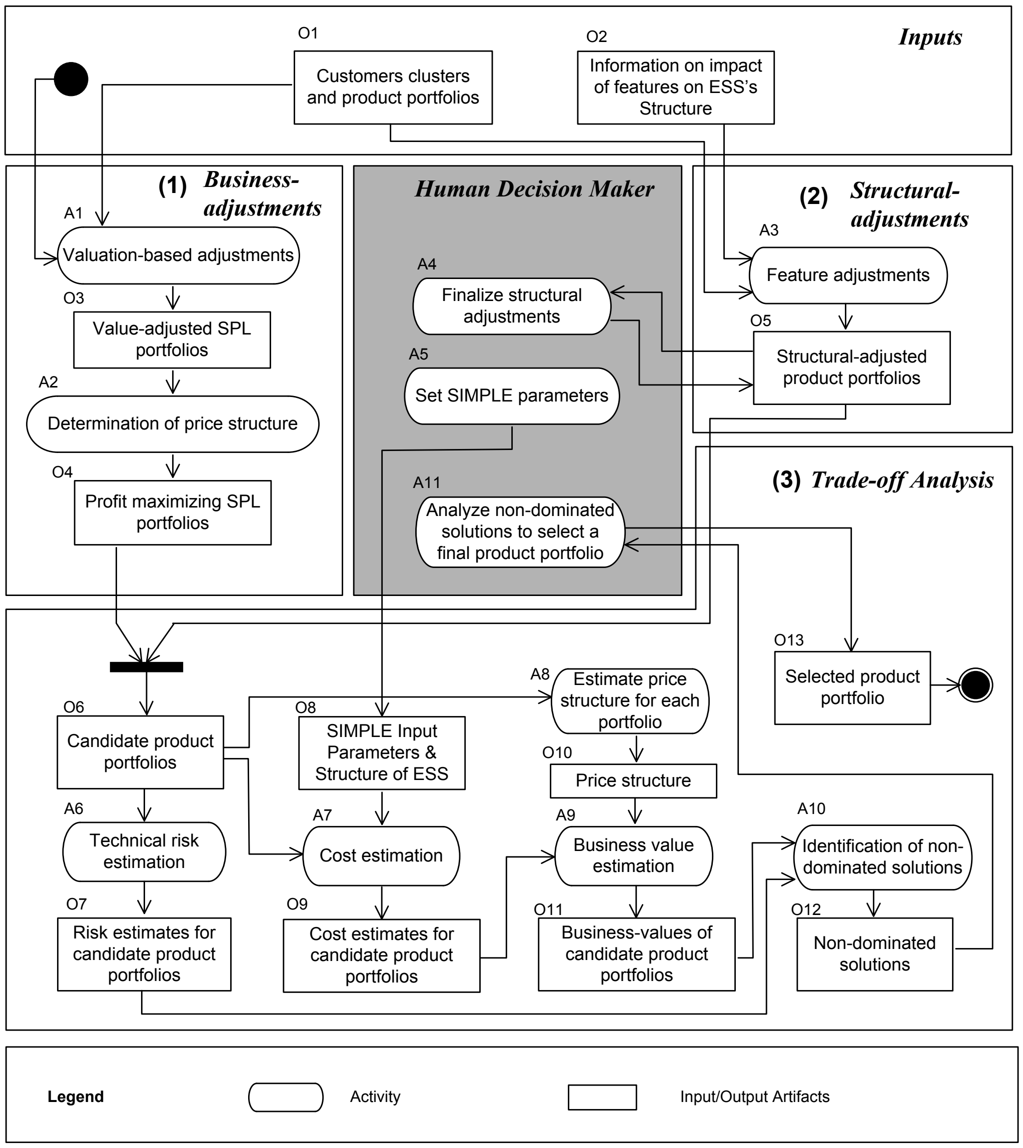
$$P = \frac{e^{\alpha_1 \bullet ADF + \alpha_2 \bullet ND + \alpha_3 \bullet INT + \alpha_4 \bullet EXPR + \alpha_5 \bullet (LA+1)}}{1 + e^{\alpha_1 \bullet ADF + \alpha_2 \bullet ND + \alpha_3 \bullet INT + \alpha_4 \bullet EXP + \alpha_5 \bullet (LA+1)}} \qquad (5)$$

4 Method OPTESS

4.1 Overview

The idea of offering decision support arises when decisions have to be made in complex, uncertain and/or dynamic environments. In software development and evolution, many decisions have to be made concerning processes, products, tools, methods and techniques. From a decision-making perspective, all these questions are confronted by different objectives, constraints, and a huge number of variables under dynamically changing requirements. Very often, this is combined with incomplete, fuzzy or inconsistent information about all the involved artifacts, as well as with difficulties regarding the decision space and environment [7].

The method OPTESS has three modules as shown in Figure 1. The method requires that segments of customers and their corresponding products be available as input. This input is generated by our previous work [4] [30]. Another input is related to the impact of new features on ESS's architectural structure. Feature impact analysis techniques and tools are available to generate this information. The interested reader is referred to [5] for a discussion on such techniques. Figure 1 shows the workflow of COPE+ illustrated as a UML activity diagram. Elements with identifiers *Ai* are the activities which take one or more input artifacts (data) identified as *Oi*. An activity manipulates input artifacts to produce at least one output artifact. These activities are arranged in three modules. The human decision maker is involved at various stages of the decision support to analyze and update the data and results. A brief overview of the modules is presented below.



Inputs
O1
Customers clusters and product portfolios
O2
Information on impact of features on ESS's Structure
(1) Business-adjustments
A1
Valuation-based adjustments
O3
Value-adjusted SPL portfolios
A2
Determination of price structure
O4
Profit maximizing SPL portfolios
Human Decision Maker
A4
Finalize structural adjustments
A5
Set SIMPLE parameters
A11
Analyze non-dominated solutions to select a final product portfolio
(2) Structural-adjustments
A3
Feature adjustments
O5
Structural-adjusted product portfolios
(3) Trade-off Analysis
O13
Selected product portfolio
O6
Candidate product portfolios
O8
SIMPLE Input Parameters & Structure of ESS
A8
Estimate price structure for each portfolio
O10
Price structure
A6
Technical risk estimation
A7
Cost estimation
A9
Business value estimation
A10
Identification of non-dominated solutions
O7
Risk estimates for candidate product portfolios
O9
Cost estimates for candidate product portfolios
O11
Business-values of candidate product portfolios
O12
Non-dominated solutions
Legend
Activity
Input/Output Artifacts

Figure 1 Workflow of OPTESS illustrated as a UML Activity diagram

Starting with an initial set of SPL portfolios, the first module of OPTESS called *Business-adjustments* modifies the feature sets (by adding or removing features) of the product variants to increase the business value of the portfolios. The output of module 1 is a set of business-adjusted SPL portfolios.

The second module called S*tructural-adjustments* modifies the feature sets of the product portfolios (by adding or removing features) using the information on how these features impact the ESS's structure. A human decision maker is involved in this process to finalize the changes to the feature sets. Selecting features in product variants that impact a cohesive set of subsystems in ESS's structure reduces the probability of failure of the system when these features are implemented.

The first two modules generate SPL portfolios that are optimized either on the business objective or the technical objective. The purpose of module 3 called *Trade-off-analysis* is to allow the decision maker to perform trade-offs between technical and business objectives. This module takes the business-adjusted portfolios (from module 1) and structural-adjusted portfolios (from module 2) and combines them in a set of candidate SPL portfolios. A customized risk estimation technique is applied to determine the risk of implementing new features for all candidate product portfolios. A product line cost estimation model is applied to determine the cost of developing the candidate SPL portfolios. Our previous work from software versioning is applied to determine the pricing structure, revenues and business value for each candidate SPL portfolio. A trade-off analysis between the technical risk and business value of the candidate product portfolios identifies the non-dominated solutions. The decision maker analyzes these suggested solutions and selects a final solution.

4.2 Module 1: Business-adjustments

4.2.1 Valuation-based adjustment

After the initial SPL solutions are generated from our clustering method [30], we explore the possible adjustment of the SPL solutions to find the profit-maximizing portfolios.

In the valuation-based adjustment, whether a feature should be included in certain product variant of a SPL is adjusted according to the customer's valuation. In our model, the customer's valuation of certain features is measured by their initial voting scores. The adjustment is done according to the following three rules:

Rule 1: If customers and features can be determined by the clustering method, then features included in each product variant correspond to the clustering results.

Rule 2: If features associated with certain customer segment are not the result of the application of the clustering method, then features with a majority of the customer segment whose initial votes are above a pre-defined threshold are included in the product variant.

Rule 3: Product variants which cannot satisfy the IC and IR conditions are removed from the SPL.

In order to maximize revenue from the SPL portfolio, some product variants may be combined together to better satisfy the IC and IR conditions for optimal software pricing. In our model, we measure all possible combinations of clusters of customers to generate various possible SPL portfolios. In Section 5, we illustrate this process through an example case study.

4.2.2 Analyze profit-maximizing portfolios

For each possible SPL portfolio, we apply the IR and IC conditions to set the optimal prices for each product variant. The revenue generated is a sum of revenues from all product variants in a product line.

Because the prices are set according to customers' valuation of features and the costs are measured in person months, we introduce a conversion factor β to convert cost into dollar value.

Definition 16 (Conversion factor β): The conversion factor β indicates the conversion rate between person-months and dollars.

We assume there is no variable cost associated for creation and distribution of any additional copy of a product variant. The profit of a SPL portfolio is defined as:

Definition 17 (Estimated profit of a portfolio): Profit from the *i*-th SPL portfolio is measured by revenue generated from the product line less the cost associated with creation of the SPL.

The estimated profit of the *i*-th SPL portfolio is measured as:

$$\text{Profit}(i) = R(i) - \beta * \text{Cost}(i) \tag{6}$$

4.3 Module 2: Structural-adjustments

The product portfolios given as input to the method OPTESS are generated using customers' preference structure on product features. Each one of the new features in these product portfolios impacts a subset of packages in the ESS's structure. To analyze the impact of features on ESS's structure, we identify sub-systems in ESS's structure. A sub-system is a cohesive group of packages that implement a group of features. A human decision maker adds or removes features from the product variants of initially proposed SPL portfolios according to the following rules:

Rule 1: If all the features implemented in a subsystem in ESS's structure are present in a product variant, then none of them is removed from the product variant.

We define θ_{adj} as the percentage of features implemented in a subsystem in the ESS's structure that are present in a product variant.

Rule 2: If greater than or equal to θ_{adj} of the features implemented in a subsystem in ESS's structure are present in a product variant, then remaining features corresponding to the same subsystem are included in the feature set of that product variant.

Rule 3: If less than θ_{adj} of the features implemented in a subsystem in ESS's structure are present in a product variant then they are removed from the feature set of that product variant.

The parameter θ_{adj} is set by the human decision-maker based on the time and resources available for the release. For a resource constrained scenario, θ_{adj} can be set high which reduces the impact of features on ESS's structure, consequently reducing the effort required to complete the release. The structural adjustments decrease the diffusion of the features of product variants (in any given SPL portfolio) consequently reducing the risk of failure. A human expert finalizes the structural adjustments by considering other constraints, such as pre-assignment and coupling. This activity is illustrated in Section 5.2.

4.4 Module 3: Trade-off analysis

The business-adjusted solutions from module 1 and the structural-adjusted solutions from module 2 are combined to form a set of candidate SPL portfolios. Module 3 allows the decision maker to perform trade-off analysis for candidate SPL portfolios.

4.4.1 Technical risk estimation

The technical risk of developing a product variant in any given SPL portfolio is calculated using the model presented in Equation (5). In Section 5.3.1, we present an example to illustrate the computation of the technical risk for implementing new features in an open source software system. This activity of module 3 addresses RQ2.

4.4.2 Cost estimation

To estimate the cost of developing a candidate SPL portfolio, we apply Equation (1) of the SIMPLE model. Out of the four cost functions of SIMPLE, we do not include the organizational and process related costs, calculated by the function Corg(). Assuming that Corg(), is constant for all the candidate SPL portfolios, there is no impact on the trade-off analysis. In Section 5.3.2, we illustrate the cost estimation by evaluating the cost functions of SIMPLE for the example software system.

4.4.3 Price estimation

The prices of each product variant are set to maximize revenue from the SPL. In order to segment customers effectively through self-selection, we impose the IR and IC constraints in Equations (2) and (3).

In the price estimation process, we start by setting price for the product variant with least number of features. With the IR constraint, the initial price of the product variant is set to maximize revenue of this market segment only. When more market segments are included, the IC constraint is imposed to ensure customers self-select their preferred product variants.

To maximize revenue from a SPL, the price of each product variant may be higher than valuation of some customers in the market. That means all customers are not necessarily served.

4.4.4 Business value estimation

Business value is estimated through balancing revenue and costs associated with the SPL using Equation (6). The revenue is calculated according to Equation (4) and costs are measured in Equation (1). This activity of module 2 addresses RQ3.

4.4.5 Identification of non-dominated solutions

In the final activity of module 3, the non-dominated SPL portfolios are identified using the business value and technical risk estimates. Given a bi-objective optimization problem F(x), x^* is said to be a *Pareto-optimal* solution (or a non-dominated solution) of the bi-objective problem if $x^* \in X$ and there does not exist any other solution x which dominates x^* when the values of both the objectives are considered together.

The bi-objective optimization problems typically present a set of compromise optimal values, and these optimal values are called *Pareto-optimal* solutions if there are no other solutions that are superior to them when the two objectives are considered. These set of solutions are referred to as non-dominated. Multiple Pareto-optimal solutions allow trade-offs between the technical risk and business values of the candidate SPL portfolios. The human decision maker analyzes the non-dominated solutions and ultimately selects one of them as the strategy for enhancing the ESS. In Section 5.3.4, this is explained through application of OPTESS on an open source text editing software system. This activity addresses RQ1.

5 Illustrative Case Study

5.1 Overview and context

We designed an illustrative case study to show how business and technical objectives are integrated to determine the desired SPL. Our method is initially evaluated (in the sense of "proof-of-concept") using an open source software project. jEdit (www.jedit.org) is a popular open-source text editing software system. Its user-base is steadily increasing with frequent feedback and feature requests on the project website [31]. Observing the increasing user-base and continuous evolution of the jEdit system, we selected it to evaluate method OPTESS. The results are based on the jEdit version 4.0. A total of nine feature requests as shown in Table 1 are used for the illustrative case study [31].

Table 1 jEdit features

Feature Name	Functionality	Effort Estimate (person-months)
DC	Domain Concepts	22
UI	User Interface	12
RE	Regular Expressions	8
TB	Text Buffers	7
DW	Dockable Windows	4
BS	Beanshell Scripting	6
XR	XML Reader	2
BA	Bytecode Assembler	1
TZ	Tar and Zip Archives	3

Using the preferences of ten hypothetical customers on these features, a clustering algorithm generated seven SPL portfolios as shown in Table 2 below. The details of the cluster analysis for this case study are available on the first author's website [32]. Note that P(0) represents the single product option for the next release.

Table 2 Initial product portfolios

Portfolios	Product Variants	Feature Sets
P(0)	-	All 9 features
P(1)	p(1,1)	DC, UI, DW, BS, XR, BA
	p(1,2)	All 9 features
P(2)	p(2,1)	DC, UI, DW, BS, XR, BA
	p(2,2)	DC, UI, RE, DW, BA
	p(2,3)	All 9 features
P(3)	p(3,1)	DC, UI, DW, BS, XR, BA,TZ
	p(3,2)	DC, UI, TB, XR
	p(3,3)	DC, UI, RE, DW, BA
	p(3,4)	All 9 features
P(4)	p(4,1)	DC, UI, BS, TZ
	p(4,2)	DC, UI, XR
	p(4,3)	DC, UI, RE, DW, BA
	p(4,4)	All 9 features
P(5)	p(5,1)	DC, UI, BS, TZ
	p(5,2)	DC, UI, XR
	p(5,3)	DC, UI, RE, DW, BA
P(6)	p(6,1)	DC, UI, BS, BA, TZ
	p(6,2)	DC, UI, XR
	p(6,3)	DC, UI, RE, DW, BA
P(7)	p(7,1)	DC, UI

5.2 Module 1: Business-adjustments

In this module, we apply the three rules in Section 4.2.1 for the adjustment of the initial SPL solutions. For the features that are not the result of the application of the clustering method, we include features with no less than 50 percent of customers whose valuation is above the threshold (6 in our case) in the product variant for the specified SPL portfolio. Any product variants that contradict with the IC and IR conditions are removed from the SPL. The adjusted product portfolios are shown in Table 3 below:

Table 3 Business adjustments to initial product portfolios

Portfolios	Product Variants	Feature Sets	Feature Removals and Additions
P(8)	p(8,1)	DC, UI, DW, BS, BA, TZ	Combine p(3,1) with p(3,3)
	p(8,2)	All 9 features	Combine p(3,2) and p(3,4)
P(9)	p(9,1)	DC, UI, DW, BS, XR, BA,TZ	Same as p(3,1)
	p(9,2)	DC, UI, TB, DW, BS, XR, BA	Combine p(3,2) with p(3,3)
	p(9,3)	All 9 features	Same as p(3,4)
P(10)	p(10,1)	DC, UI, TB, DW, BS, XR, BA	Combine p(4,2) with p(4,3)
	p(10,2)	DC, UI, DW, BS, XR, BA,TZ	Combine p(4,1) with p(4,4)
P(11)	p(11,1)	DC, UI, BS, TZ	Same as p(4,1)
	p(11,2)	DC, UI, TB, DW, BS, XR, BA	Combine p(4,2) with p(4,3)
	p(11,3)	All 9 features	Same as p(4,4)
P(12)	p(12,1)	DC, UI, TB, DW, BS, XR, BA	p(6,2) plus TB, DW, BS, BA
	p(12,2)	DC, UI, RE, TB, DW, BS, BA, TZ	Combine p(6,1) with p(6,3)

5.3 Module 2: Structural-adjustments

In this module, the human decision maker gains information related to the impact of the new features on ESS's structure. jEdit v4.0 has thirty source code packages [31] [32]. Domain experts have identified four subsystems in jEdit's structure [32]. Each subsystem consists of a group of packages and implements a subset of features. Table 4 lists the features that are implemented in each subsystem. The decision maker updates the feature sets of the product variants in the seven initially proposed SPL portfolios such that each product variants contains all the features corresponding to a given subsystem.

Table 4 Subsystems in jEdit's system structure

Subsystem	Corresponding Features
1	DC
2	UI, XR, TB
3	RE, TZ, DW
4	BS, BA

Table 5 shows the updates in the feature set of each product variant using the value of θ_{adj} equal to 50%. For example, for product variant p(1,1) of portfolio P(1), feature DW was removed because the other features (TZ and RE) implemented by the subsystem 3 were not present in the feature set of p(1,1) (Section 4.3, Rule 3). TB was included in p(1,1) to complete the feature group corresponding to subsystem 2 (Section 4.3, Rule 2). The finalized structural-adjusted portfolios are P(13) to P(18) as shown in the Table A.1 (Appendix A) and Table B.1 (Appendix B).

Table 5 Structural adjustments to initial product portfolios

Portfolios	Product Variants	Feature Sets	Feature Removals and Additions
P(0)	-	All 9 features	-
P(1)	p(1,1)	DC, UI, ~~DW~~, BS, XR, BA, TB	Removed DW and included TB
	p(1,2)	All 9 features	-
P(2)	p(2,1)	DC, UI, ~~DW~~, BS, XR, BA, TB	Removed DW and included TB
	p(2,2)	DC, ~~UI~~, RE, DW, ~~BA~~, TZ	Removed UI, BA and included TZ
	p(2,3)	All 9 features	-

Portfolios	Product Variants	Feature Sets	Feature Removals and Additions
P(3)	p(3,1)	DC, UI, DW, BS, XR, BA,TZ, TB, RE	Included TB, RE
	p(3,2)	DC, UI, TB, XR	-
	p(3,3)	DC, ~~UI~~, RE, DW, ~~BA,~~ TZ	Removed UI, BA and included TZ
	p(3,4)	All 9 features	-
P(4)	p(4,1)	DC, ~~UI~~, BS, ~~TZ,~~ BA	Removed UI, TZ and included BA
	p(4,2)	DC, UI, XR, TB	Included TB
	p(4,3)	DC, ~~UI~~, RE, DW, ~~BA~~, TZ	Removed UI, BA and included TZ
	p(4,4)	All 9 features	-
P(5)	p(5,1)	DC, ~~UI~~, BS, ~~TZ,~~, BA	Removed UI, TZ and included BA
	p(5,2)	DC, UI, XR, TB	Included TB
	p(5,3)	DC, ~~UI~~, RE, DW, ~~BA~~, TZ	Removed UI, BA and included TZ
P(6)	p(6,1)	DC, ~~UI~~, BS, BA, ~~TZ~~	Removed UI, TZ
	p(6,2)	DC, UI, XR, TB	Included TB
	p(6,3)	DC, ~~UI~~, RE, DW, ~~BA~~, TZ	Removed UI, BA and included TZ
P(7)	p(7,1)	DC, ~~UI~~	Removed UI

5.4 Module 3: Trade-off analysis

The third module of OPTESS performs a trade-off analysis for all the candidate SPL portfolios. The candidate SPL portfolios include the initially proposed SPL portfolios given as input to OPTESS, the business-adjusted SPL portfolios, the technical adjusted SPL portfolios and the single software product. The trade-off is performed between two objectives: (i) minimizing the technical risk of failure due to implementation of features and (ii) maximizing the business values of the SPL portfolio.

5.4.1 Technical risk estimation

The technical risk of failure is calculated using Equation (5). The results are shown in Table A.1 as probability of failure of the system when features are implemented in the ESS's structure. For the jEdit case study we have access to data for only one of the parameters i.e. adjusted diffusion (ADF). The other four parameters in Equation (5) were ignored due to non-availability of data. Because of this, we are not able to generate the values for the coefficients α_i. Therefore, for this illustration we have applied the value of the coefficient α_1 equal to 0.41 as suggested in [16]. It can be seen that the higher the number of subsystems impacted in the ESS's structure (reflecting higher diffusion), the higher the probability of failure. This activity of module 3, addresses RQ 2.

5.4.2 Cost estimation

The SIMPLE cost estimation model is applied (as explained in Section 3.1) to calculate the cost of developing the candidate SPL portfolios. The cost to develop the unique part of each candidate SPL portfolio is estimated by identifying the features that are offered by only one of the product variants. These features are not developed for reuse, and consequently the cost to implement them is less than for features that are shared by multiple product variants. The SIMPLE model does not provide details on how a particular cost function is estimated. As explained in Sections 2.3 and 3.1, we have applied an analogy-based effort estimation technique (AQUA) to estimate the function $C_{unique}()$. The effort estimate for implementing each feature of the jEdit software system is given in Table 1.

The development of shared features (determined by the Ccab() function), requires more effort. The reason is that these features are shared by multiple product variants requiring implementation of variability mechanisms. The higher the level of variability amongst the product variants, the higher is the level of effort to develop them. If a feature is shared across all the product variants in a SPL portfolio, the effort estimate by AQUA is adjusted. This adjustment is based on the number of product variants that are sharing this feature and the number of packages being impacted by the feature in the ESS's structure. The interested reader is referred to [33] for detailed effort estimation results for shared features of each candidate SPL portfolio.

Adaptation of a shared feature for use in a specific product variant requires additional effort. This effort is reflected in the results of the function Creuse(). The actual value of the function Creuse() depends on how many product variants reuse the shared feature. Results for the function Creuse() for each candidate SPL portfolio in the jEdit case study are presented in [33]. The final cost estimates by application of the SIMPLE model for the single product and 18 candidate SPL portfolios are listed in Table B.1 (Appendix B). As mentioned earlier, $C_{org}()$ cost function of SIMPLE is not applied in this case study.

5.4.3 Price and business value estimation

Prices are determined using the IR and IC constraints in Equations (2) and (3). The customer's valuation of a product variant is calculated as the sum of all the feature voting scores that are no less than the threshold (6 in our case). Prices are set so that customers self-select their favorite product variants. Revenue is calculated by Equation (4) and business value is measured by Equation (6). To simplify the calculation of business value, we set the conversion factor β as 1.

Here we take P(1) as an example to show how the business value of a specified SPL is calculated. Firstly, from the clustering results, we get that p(1,1) is designed for customers 1, 2, 3, 4, 5, 8, 9 and 10. Each customer's valuation of p(1,1) is calculated as 29, 37, 44, 35, 40, 20, 32 and 32. To maximize revenue generated from p(1,1), we set price as 29. Because customer 8's valuation for p(1,1) is 20, which is less than 29, according to the IR constraints, customer 8 will not purchase p(1,1). Accordingly, p(1,2) is designed for customers 6 and 7 with valuation 69 and 70. In order to encourage customers 6 and 7 to self-select p(1,2) instead of p(1,1), the IC constraints are applied so that the price of p(1,2) is set as 53. With this price schedule, customers 1, 2, 3, 4, 5, 9 and 10 purchase p(1,1) at price 29 and customers 7 and 7 purchase p(1,2) at price 53. Customer 8 does not purchase any product variant. The total revenue generated is 309. Using equation (1), we get the total cost associated with P(1) is 58.6. Thus, the total business value for P(1) is calculated as 250.4. Table B.1 (Appendix B) lists the revenues and business values of all the candidate SPL portfolios.

5.4.4 Identification of non-dominated solutions

The decision maker is presented the business values and technical risk estimates for all the candidate product portfolios. Using this information, the non-dominated solutions can be identified. For the jEdit example, the portfolios P(4), P(11) and P(16) are the non-dominated solutions as identified in Figure 2. The decision maker analyzes the non-dominated solutions and selects the one of them.

Product portfolio P(4) is one of the initial product portfolios generated by cluster analysis using customers' preferences on product features. This product portfolio does not have the highest business value amongst all the solutions nor the lowest technical risk. However, when both the objectives are considered together, it performs better than all the candidate product portfolios. The other two non-dominated solutions are the optimized solutions. Portfolio P(11) was optimized by performing business related adjustments; consequently it has the highest business value. Portfolio P(16) is optimized on technical objectives and thus has the lowest technical risk amongst all the candidate product portfolios.

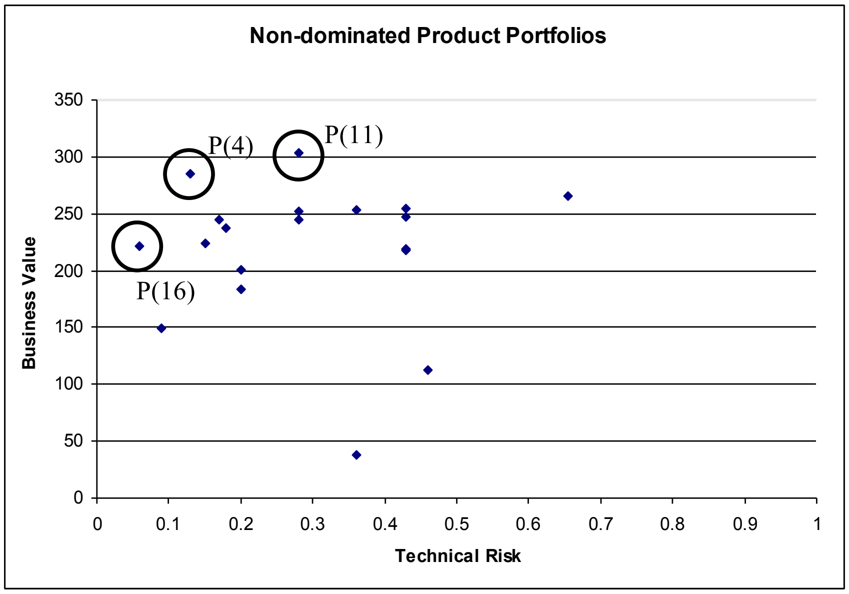


Figure 2 Non-dominated product portfolios maximizing the business value objective and minimizing the technical risk objective

6 Applicability and Limitations

6.1 Applicability

Method OPTESS addresses the complex problem of evolving a software product facing feature demands of a diverse customer-base. The goal of OPTESS is to propose a portfolio of non-dominated solutions to the decision maker. These solutions can become a starting point for initiating discussions amongst project stakeholders.

In our previous work, we proposed methods that can be applied for this decision problem of enhancing a single software product into a product line with different levels of data availability. In [30], we proposed method COPE (Customer Oriented Product Evolution) which requires information on customers' preference structure on product features to determine segments of customers and suggests candidate SPL portfolios. A human decision maker evaluates the candidate SPL portfolios using her expert judgment and selects a suitable portfolio for enhancing the ESS. The decision maker can also initiate further iterations of COPE by changing model settings to generate more solutions.

Method COPE+ [5] extends COPE by including impact analysis of the features on the ESS's architecture. The decision maker is given information on the level of impact of candidate SPL portfolios on the ESS's architectural components. COPE+ also performs behavioral comparisons of candidate SPL portfolios and the ESS to rank the candidate solutions.

Method OPTESS brings in economic considerations to rank the candidate SPL portfolios using the technical and business objectives. This, however, requires more sophisticated data related to the impact of features on system structure, and effort estimates for the implementation of features and pricing structure. Given such data requirements, we recommend the application of OPTESS for organizations being at least at CMMI level 3 where measurement and analysis practices are followed [34]. Tool support for the method OPTESS is also planned to automate some of the activities.

6.2 Assumptions and Threats to Validity

The assumptions and threats to validity of the work presented here are listed below:

(1) The risk estimates for the candidate SPL portfolios are calculated using data for only one of the parameters in the Mockus and Weiss's model [16]. This is a threat to the validity of the conclusions.

(2) Real customers were not involved for eliciting preferences on features of jEdit. Therefore, no feedback is available to determine the level of acceptance for the results generated by OPTESS.

(3) For the jEdit system, we used feature impact analysis results from [32] which can be a threat to the validity of conclusions.

(4) For revenue estimation, we assumed that each customer purchases only one product. It may not always be true.

(5) SPLs are a long term investment. Therefore, the return on investment should include analysis over a longer period of time to determine costs and benefits. In this work we analyzed the return on investment for a single release. This is a limitation of our method.

7 Conclusions and Future Work

Method OPTESS brings together the concepts and techniques from economics and software engineering to evaluate SPL portfolios for a given evolution scenario. The goal is to provide a decision support framework rather than focus on specific technical and economic techniques. The cost estimation model, risk estimation model and customer valuation technique applied in this work are examples that show how trade-off analysis can be performed for selecting a candidate SPL portfolio.

In this work we highlight the interplay between economic and technical aspects of the SPL design. From the economic side, we apply the widely adopted value-based pricing mechanism to estimate price and revenue in a self-selection market. The SIMPLE cost model is applied to estimate the effort for developing candidate SPL portfolios. On the technical side, a risk estimation technique is applied to determine the probability of failure of the system when new features are implemented. To balance both the economic and technical objectives, three non-dominated product portfolios were proposed out of eighteen candidate SPL portfolios.

Ahmed et al., have investigated how business factors influence success of SPLs [36]. They argued that strategic planning is one of the key factors in business performance of a SPL. An important component of strategic planning is market orientation i.e., identification of customer segments and a plan to target them. There are other factors that are equally important e.g., competitors in each segment, order of entry in the market etc. OPTESS addresses a part of this strategic planning. Other techniques such as those from marketing can be applied to bring in additional criteria for evaluation of the candidate SPL portfolios.

This research presents initial results of our method on an open source text editing software system. In the future, we plan to conduct a sensitivity analysis to identify the degree of influence of technical and economic factors on the results generated by OPTESS. Further case studies are planned with real customers to determine the level of acceptance of the results.

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Appendix A

Table A.1 Probability of failure estimates for the candidate SPL portfolios

Portfolios	Product Variants	Feature Sets	Subsystems Impacted	Probability of Failure of Product Variants	Probability of Failure of Product Portfolios
P(0)	-	All 9 features	4	-	0.6548
P(1)	p(1,1)	DC, UI, DW, BS, XR, BA	4	0.65	0.43
	p(1,2)	All 9 features	4	0.65	
P(2)	p(2,1)	DC, UI, DW, BS, XR, BA	4	0.65	0.28
	p(2,2)	DC, UI, RE, DW, BA	4	0.65	
	p(2,3)	All 9 features	4	0.65	
P(3)	p(3,1)	DC, UI, DW, BS, XR, BA,TZ	4	0.65	0.18
	p(3,2)	DC, UI, TB, XR	4	0.65	
	p(3,3)	DC, UI, RE, DW, BA	4	0.65	
	p(3,4)	All 9 features	4	0.65	
P(4)	p(4,1)	DC, UI, BS, TZ	4	0.65	0.13
	p(4,2)	DC, UI, XR	2	0.46	
	p(4,3)	DC, UI, RE, DW, BA	4	0.65	
	p(4,4)	All 9 features	4	0.65	
P(5)	p(5,1)	DC, UI, BS, TZ	4	0.65	0.20
	p(5,2)	DC, UI, XR	2	0.46	
	p(5,3)	DC, UI, RE, DW, BA	4	0.65	
P(6)	p(6,1)	DC, UI, BS, BA, TZ	4	0.65	0.20
	p(6,2)	DC, UI, XR	2	0.46	
	p(6,3)	DC, UI, RE, DW, BA	4	0.65	
P(7)	p(7,1)	DC, UI	2	0.46	0.46
P(8)	p(8,1)	DC, UI, DW, BS, BA, TZ	4	0.65	0.43
	p(8,2)	All 9 features	4	0.65	
P(9)	p(9,1)	DC, UI, DW, BS, XR, BA,TZ	4	0.65	0.28
	p(9,2)	DC, UI, TB, DW, BS, XR, BA	4	0.65	
	p(9,3)	All 9 features	4	0.65	
P(10)	p(10,1)	DC, UI, TB, DW, BS, XR, BA	4	0.65	0.43
	p(10,2)	DC, UI, DW, BS, XR, BA, TZ	4	0.65	

Portfolios	Product Variants	Feature Sets	Subsystems Impacted	Probability of Failure of Product Variants	Probability of Failure of Product Portfolios
P(11)	p(11,1)	DC, UI, BS, TZ	4	0.65	0.28
	p(11,2)	DC, UI, TB, DW, BS, XR, BA	4	0.65	
	p(11,3)	All 9 features	4	0.65	
P(12)	p(12,1)	DC, UI, TB, DW, BS, XR, BA	4	0.65	0.43
	p(12,2)	DC, UI, RE, TB, DW, BS, BA, TZ	4	0.65	
P(13)	p(13,1)	DC, UI, BS, XR, BA, TB	3	0.56	0.36
	p(13,2)	All 9 features	4	0.65	
P(14)	p(14,1)	DC, UI, BS, XR, BA, TB	3	0.56	0.17
	p(14,2)	DC, RE, DW, TZ	2	0.46	
	p(14,3)	All 9 features	4	0.65	
P(15)	p(15,1)	DC, UI, TB, XR	2	0.46	0.14
	p(15,2)	DC, RE, DW, TZ	2	0.46	
	p(15,3)	All 9 features	4	0.65	
P(16)	p(16,1)	DC, BS, BA	2	0.46	0.06
	p(16,2)	DC, UI, XR, TB	2	0.46	
	p(16,3)	DC, RE, DW, TZ	2	0.46	
	p(16,4)	All 9 features	4	0.65	
P(17)	p(17,1)	DC, BS, BA	2	0.46	0.09
	p(17,2)	DC, UI, XR, TB	2	0.46	
	p(17,3)	DC, RE, DW, TZ	2	0.46	
P(18)	p(17,1)	DC	1	-	0.36

Appendix B

Table B.1 Cost, price, revenue and business value estimates for the candidate SPL portfolios

Portfolios	Product Variants	Feature Sets	Cost	Price	Revenue per product variant	Revenue per portfolio	Business value
P(0)	-	All 9 features	30	37	37*8	296	266
P(1)	p(1,1)	DC, UI, DW, BS, XR, BA	62.4	29	29*7=203	309	246.6
	p(1,2)	All 9 features		53	53*2=106		
P(2)	p(2,1)	DC, UI, DW, BS, XR, BA	61.2	29	29*5=145	313	251.8
	p(2,2)	DC, UI, RE, DW, BA		31	31*2=62		
	p(2,3)	All 9 features		53	53*2=106		
P(3)	p(3,1)	DC, UI, DW, BS, XR, BA,TZ	62.2	28	28*4=112	300	237.8
	p(3,2)	DC, UI, TB, XR		21	21*2=42		
	p(3,3)	DC, UI, RE, DW, BA		30	30*2=60		
	p(3,4)	All 9 features		43	43*2=86		
P(4)	p(4,1)	DC, UI, BS, TZ	62.2	25	25*3=75	347	284.8
	p(4,2)	DC, UI, XR		22	22*3=66		
	p(4,3)	DC, UI, RE, DW, BA		41	41*2=82		
	p(4,4)	All 9 features		62	62*2=124		
P(5)	p(5,1)	DC, UI, BS, TZ	59.9	25	25*3=75	261	201.1
	p(5,2)	DC, UI, XR		22	22*3=66		
	p(5,3)	DC, UI, RE, DW, BA		30	30*4=120		
P(6)	p(6,1)	DC, UI, BS, BA, TZ	59.9	28	28*2=56	244	184.1
	p(6,2)	DC, UI, XR		21	21*4=84		
	p(6,3)	DC, UI, RE, DW, BA		26	26*4=104		
P(7)	p(7,1)	DC, UI	23	15	15*9=135	135	112
P(8)	p(8,1)	DC, UI, DW, BS, BA, TZ	61.2	28	28*6=168	316	254.8
	p(8,2)	All 9 features		37	37*4=148		

Portfolios	Product Variants	Feature Sets	Cost	Price	Revenue per product variant	Revenue per portfolio	Business value
P(9)	p(9,1)	DC, UI, DW, BS, XR, BA,TZ	65.1	28	28*4=112	310	244.9
	p(9,2)	DC, UI, TB, DW, BS, XR, BA		28	28*4=112		
	p(9,3)	All 9 features		43	43*2=86		
P(10)	p(10,1)	DC, UI, TB, DW, BS, XR, BA	62.4	28	28*5=140	280	217.6
	p(10,2)	DC, UI, DW, BS, XR, BA, TZ		28	28*5=140		
P(11)	p(11,1)	DC, UI, BS, TZ	62.5	25	25*3=75	366	303.6
	p(11,2)	DC, UI, TB, DW, BS, XR, BA		37	37*5=185		
	p(11,3)	All 9 features		53	53*2=106		
P(12)	p(12,1)	DC, UI, TB, DW, BS, XR, BA	57.5	37	21*4=84	276	218.5
	p(12,2)	DC, UI, RE, TB, DW, BS, BA, TZ		48	48*4=192		
P(13)	p(13,1)	DC, UI, BS, XR, BA, TB	64.8	30	30*7=210	318	253.2
	p(13,2)	All 9 features		54	54*2=108		
P(14)	p(14,1)	DC, UI, BS, XR, BA, TB	58.6	30	29*5=145	303	244.4
	p(14,2)	DC, RE, DW, TZ		25	25*2=50		
	p(14,3)	All 9 features		54	54*2=108		
P(15)	p(15,1)	DC, UI, TB, XR	58.6	28	28*2=56	282	223.4
	p(15,2)	DC, RE, DW, TZ		25	25*2=50		
	p(15,3)	All 9 features		44	44*4=176		
P(16)	p(16,1)	DC, BS, BA	60.8	14	14*3=42	282	221.2
	p(16,2)	DC, UI, XR, TB		22	22*3=66		
	p(16,3)	DC, RE, DW, TZ		25	25*2=50		
	p(16,4)	All 9 features		62	62*2=124		
P(17)	p(17,1)	DC, BS, BA	58.6	14	14*3=42	208	149.4
	p(17,2)	DC, UI, XR, TB		22	22*3=66		
	p(17,3)	DC, RE, DW, TZ		25	25*4=100		
P(18)	p(17,1)	DC	22	6	6*10=135	60	38