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RESEARCH ARTICLE

Programming Models for Determining Optimal R&D Arrangement in Mobile Application Development Process

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ABSTRACT The R&D (Research & Development) process of mobile application can be regarded as a complex system engineering that needs to take into account a variety of influencing elements, such as customer's demands, engineering measures and business goals etc., as well as their interplay. A novel decision support platform is proposed to assist project managers in determining the optimal technical measures with implementation degrees and resource allocation scheme. Specially, the HDQ (House of Development Quality) is designed to collect essential data and information as well as reflect correlations among elements, which can effectively connect isolated information islands. Through the transform of HDQ, a multi-objective programming model is constructed to meet customers' overall demands and specific requirements. A combination of specified technical measures and resource allocation can be obtained under ideal conditions. Additionally, the extended model considering resource substitution is designed to realize further improvement by effectively utilizing the surplus resource in the above optimal condition, demonstrating the advantage of proper managerial arrangement and resource deployment. Finally, the R&D case of family financial management application is conducted to illustrate the effectiveness of the suggested method, which offers a new perspective on mobile application R&D project management.

INDEX TERMS Mobile application development, house of development quality, programming model, resource allocation.

I. INTRODUCTION

In the 5G era, the mobile devices with various utilitarian, user-friendly and accessible applications have become the most popular and indispensable expediencies for satisfying human essential requirements in the past few years [1]. To maintain a leading position in marketing competence, an application with competitive functions, should be released precisely on time [2], [3]. However, in realistic application development process, development team may meet many situations that influence the development quality and delay the launch date of the applications, such as unclear requirements, lack of technical ability, limited resource, etc. Different from complicated pc software should widely satisfy the customers' requirements, the goal of the mobile application strategy is that the mobile application can meet the needs of users, help users to ‘‘do something'' quickly and effectively. Lack of users' participation and neglect to demand driven have been regarded as the main causes for failure of software project [4]. Hence, it is crucial to recognize and meet explicit functional demands and implicit non-functional requirements in mobile application customers.

Compared to PC software, mobile application development has more advanced features, such as potential interaction with other applications, information transformation among local and cloud databases, security management and user interface for touchable screen, etc. [5], which brings more challenges to the development process [6], [7]. Agile development was proposed to generate new process for the application development by effectively controlling unexpected risks in

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the lifecycle, which is regarded as a natural fit by many researchers [1], [8]. Alsabi and Dahanayake [9] proposed a novel lightweight Mobile Application Development Method following SMART (simple, meaningful, adequate, realistic, and tractable) principle, which can improve the development efficiency and reduce project timelines. Martinez et al. [10] established Mobile Ilites development framework using agile and Scrum methodologies. Pandey et al. [11] introduced the agile development strategy decision-making method, which employed fuzzy AHP(Analytical Hierarchy Process) method to determine the indicator weights. Agile development methodologies make customers' needs be delivered on time during the development cycle, enable the development life cycle to adapt changes more quickly and the development and testing are not considered separate phases as in traditional software development, thus in agile environment, user requirement and the project resources allocation should be systematically considered more seriously.

As the input of agile development, various resources should be organized and invested to ensure the desired development effect [12], [13]. It can be regarded as the optimization problems, which includes project objectives and resource constraints such as human, finance and time, etc. [13]. Chen and Zhang [14] employed ant colony optimization algorithm and event-based scheduler to consider both task scheduling and employee allocation, which can enable the modeling of resource conflict and preserve the flexibility in human resource allocation related to task preemption. Silva and Costa [15] explored a dynamic programming model to confirm optimal HR (human resource) allocation, which can match software project tasks with suitable developers with different personal skills and experience. Chiang and Lin [16] proposed an integer programming model for allocating human resource for pursuing optimal project efficiency under labor and budget constraint. Previous studies mostly focused on individual competence, expertise, and other personal factors in HR assignment challenges in software development. However, there is lack of systematic and thorough considerations that should match customers' core requirements and project implementation with essential resource allocation to avoid serious R&D delay and waste.

QFD (Quality Function Development) was introduced by Yoji Akao and Shigeru Mizuno in 1966, which can help developers to translate client opinions into prospective engineering solutions in R&D process [17], [18], [19]. As the bridge connecting customer and R&D staff, QFD demonstrated many advantages, including systematic improvement during the entire product and development process [20], specific recognition on customers' core need and effective improvement of customers' satisfaction [20], [21], which was widely conducted in the domain of software project [22]. Sun and Liu [23] employed QFD in software process improvement framework to estimate the importance priority of alternative process optimization actions. Li et al. [24] utilized QFD method to assess the overall quality of software, which was related to the weight of the customers' requirements. Anang et al. [25] used QFD to calculate the volatility degree of software function, which may be considered as the predictive response to customer demands. However, the existing research mainly focused on the necessity of evaluating customer's voice and solutions, and was not comprehensively related to market objective and resource constraints.

Looking over the relevant research in recent years, one can find that the existing research about the software development management are mostly addressed from a single perspective, such as development strategy selection, user requirements identification or project resource allocation. However, mobile application development is a complex process, in which various interactive factors and R&D actions such as development strategy, market competition, attractive functions, detailed arrangements and resource allocation, should be systematically considered. What's more important, the complicated correlations and potential resource conflicts among the proposed R&D actions are easily omitted and will impact the actual development effect and efficiency. The research concerning the above issue has not produced a mature and complete methodology from a systematic perspective. Hence, this paper designs a decision support system for the app development process, which can help project managers to determine which technical measures with implementation degree to be taken and how to allocate resources. First, a systematic analysis framework is built to assist in collecting information that covers users' core requirements, the implementation of technical measures, R&D objectives and constraints as well as their interactive relationships. Then, the multi-objective programming with R&D objectives and constraints is constructed to identify the optimal implementation degree of technical measures. Additionally, according to the result of multi-objective programming, the project resource is distributed related to technical measures ensuring that R&D activities are carried out effectively. Finally, in order to get further optimization and improve the utilization efficiency of the surplus project resource, the extended models are constructed.

The rest of paper is organized as follows. In section 2, a novel HDQ is designed to comprehensively consider vital R&D factors and their complicated relationships. In section 3, a multi-objective programming model was developed with market competition, requirement improvement and resource consumption objectives, in which optimal implementation of technical measures and allocation scheme can be obtained. In section 4, extended models that takes the resource substitution into account was built based on deviation results from multi-objective programming model. In section 5, a development case of a family financial management application is presented, which can be used to demonstrate the scientific validity and feasibility of above explorations.

II. FRAMEWORK OF HDQ AND ITS MODULES

In order to conveniently exhibit various groups of data and their connections, an effective analysis framework should be built to aid people in collecting necessary information.

A novel framework called HDQ for mobile application, is constructed to conduct data preparation and technical measure display as shown in Fig. 1, which can directly provide decision-making support for allocating optimal resource. HDQ consists of six main modules: left wall, ceiling, roof, right wall, room and basement, which can be presented as follows.

A. LEFT WALL (CUSTOMER ORIENTED COMPONENT, CO)

The left wall is utilized to describe the information covering customers' requirements with influential weights. The initial information on customers' demands can be collected by distributing questionnaires or interviews, and hence need to summarize under a certain principle. According to ISO 9126 standard [26], software customers' demands mainly include six parts: aesthetically pleasant interface, desired functionality, data security, accessible usability, responsive efficiency and high reliability. Aesthetically pleasant interface is one in which visual layout follows a suitable selection of font, color, icon, layout etc., to lessen users' visual confusion. Desired functionality is the most appealing feature when compared to similar products. Data security guarantees users' information security. Accessible usability indicates the users' operational convenience. Responsive efficiency denotes the response time to users' operations, as measured by the system resources used to operate the required functionality. High reliability presents the software's ability to run stably. Additionally, in order to determine the requirement weights, AHP [27], [28], [29], analytical network process(ANP) [30], fuzzy AHP [31], [32], [33], [34], fuzzy ANP [35], fuzzy cognitive network process method [36] can be employed to deal with dual comparison appraisal data.

B. CEILING (TECHNICAL IMPLEMENTATION COMPONENT, TI)

Technical measures recommended by development teams are included in the ceiling. According to the agile software development lifecycle [37] and the actual development practices, the technical measures include the engineering and management actions such as user interface designation, functional implementation, data encryption, system testing and system maintenance, which can be divided into sub-process related to the specific circumstances. If alternative technical measures are collected, the implementation degree and resource arrangement are determined, which can be regarded as optimization issues with objectives and constraints.

C. ROOF (MEASURE INTERACTIVE MATRIX, MIM)

Because one technical measure implementation may have impact on others, the roof is employed to represent the mutual internal correlations among the technical measures, which helps the application development team to make systematic arrangement. For example, improvements in system testing can directly be contributed to completed function design. Moreover, in order to characterize the above connections, various symbols can be employed while quantitative and relative values can be assigned. For example, one can use •, ⋆, +, ×, ◯, ◇, and – to represent strongly positive, generally positive, weakly positive, irrelevant, strongly negative, generally negative, weakly negative, respectively.

D. ROOM (DEMAND GRATIFICATION MATRIX, DGM)

The room refers to demand gratification matrix, which indicates the connection between the CO and TI. For example, interface design can greatly satisfy the customers' requirement of aesthetically pleasant interface which is less influenced by data encryption. According to the relationship between the CO and TI, the development team can be driven by enhancing user satisfaction, which can translate into better technical measures in the mobile application development process. Similarly, symbols and given values can be used to depict the interplay in the room as well.

E. RIGHT WALL (COMPETITION APPRAISAL COMPONENT, CA)

The right wall is utilized to define development goals by comparing the performance between current app and that of its competitors. Development objectives can be reflected as complete improvement rate with specific branches related to each CO, which can be considered as the customers' requirement satisfaction improvement goals.

F. BASEMENT (MEASURE OUTPUT COMPONENT, MO)

The basement is employed to define technical measures, such as the effect indicator, present effect, predicted effect, and resource consumption, from the project management perspective. One can confirm technical measures priorities and provide support for making an optimal development decision based on the information detailed in the basement.

III. MULTI-OBJECTIVE PROGRAMMING FOR DETERMINING MEASURES IMPROVEMENT AND RESOURCE ALLOCATION SCHEME

Based on the data collection and the displayed information listed in the HDQ, a multi-objective programming of mobile application development can be developed to assist decision-makers in identifying the optimal technical measures improvement and resource allocation. The optimal objectives include satisfying the customers' requirements and realizing market competitive goals.

A. INDEPENDENT AND COMPREHENSIVE IMPLEMENTATION EFFECTS OF TECHNICAL MEASURES

Assume that there are $m$customers' demands, $D = \{d_1, d_2, \cdots, d_m\}$, listed in the left wall, whose weights are $W = (w_1, w_2, \cdots, w_m)$. According to market competitive analysis result as in the right wall, the performance of present version and expected version are $S^0 = \left(s_1^0, s_2^0, \cdots, s_m^0\right)^T$ and $S^1 = \left(s_1^1, s_2^1, \cdots, s_m^1\right)^T$, respectively. Hence, the desired performance improvement rate related to customers' requirements can be expressed as $H = |S^1 - S^0|/S^0$.

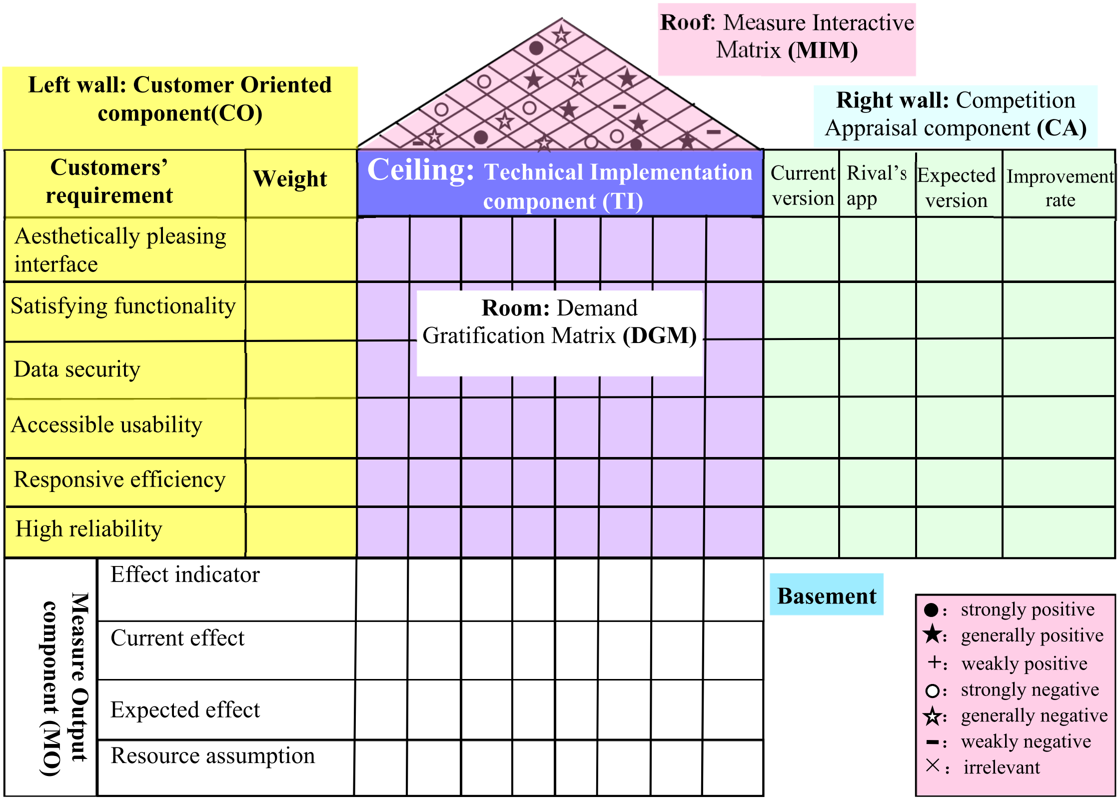

FIGURE 1. House of development quality.

Additionally, there exist n kinds of technical measures, $T = \{t_1, t_2, \cdots, t_n\}$, whose current and expected implementation effects are $\overline{E} = (\overline{e}_1, \overline{e}_2, \cdots, \overline{e}_n)^T$ and $\tilde{E} = (\tilde{e}_1, \tilde{e}_2, \cdots, \tilde{e}_n)^T$. Taking into account the interrelations of the technical measures, the independent and the comprehensive implementation effects of technical measures can be defined as below.

Definition 1: The independent implementation effect, x_i, of technical measures t_i refers to the rate of change in an indicator induced solely by technical measures t_i only, without taking into account the effects of additional technical measures. The independent improvement rates of the technical measures, $X = (x_1, x_2, \cdots, x_n)^T$, can be presented as follows:

$$X = |\tilde{E} - \overline{E}|/\overline{E} \tag{1}$$

Definition 2: The comprehensive implementation effect, $y_i$of technical measure t_i means the overall change effect that is influenced by both its own and others' indicator of all the technical measures.

Proposition 1: Assume that the independent implementation effect and the comprehensive implementation rates are $X = (x_1, x_2, \cdots, x_n)^T$ and $Y = (y_1, y_2, \cdots, y_n)^T$, respectively.

According to the information in the roof, MIM can be expressed as a liner matrix, $C = \{c_{ij}\}_{n\times n}$, in which $c_{ij}$is the correlation coefficient between technical measure t_i and t_j acquired through statistical methods. Hence, X and Y satisfy the following equation:

$$Y = CX \tag{2}$$

Proof: As $c_{ij} = c_{ji}$, MIM can be regarded as a real symmetric matrix, $C = C^T$. The comprehensive implementation effect, y_i, of technical measure t_i comes from both its own improvement and the influence of others' change, which can be calculated as follows.

$$y_i = 1 \times x_i + \sum_{\substack{j=1 \\ j\neq i}}^{n} c_{ij}x_j = \left(1 + \sum_{\substack{j=1 \\ j\neq i}}^{n} c_{ij}\right) x_i = \sum_{k=1}^{n} c_{ik}x_k$$

Hence, it can be written using a matrix expression as $Y = CX$.

B. OPTIMAL OBJECTIVES OF MOBILE APPLICATION DEVELOPMENT

1) OBJECTIVE 1: OVERALL SATISFACTION IMPROVEMENT OF CUSTOMER'S DEMANDS

Suppose that DGM, which is determined by the information in the room of HDQ, is $R = \{r_{ij}\}_{m\times n}$, The information can be acquired from the proposal of actual development team and reflect as the predicted improvement effects of the projects on customer's demands. Influenced by technical measures, the actual satisfaction improvement rate of demand d_i can be evaluated as α_i. The parameter in DGM, r_{ij}, which describes the correlation coefficient between α_i and y_i, can be represented by $r_{ij} = \alpha_i / y_i$, and the matrix form can be written as $\delta = RY$.

Proposition 2: The overall performance improvement of the customers' requirement, Δ, the independent improvement rates of technical measures, X, should satisfy the following equation.

$$\Delta = V^T X \tag{3}$$

in which $V = CR^T W^T$.

Proof: The overall performance improvement of customer' s requirement is the weighted sum of the actual each improvement of customer's requirement, which can be expressed as

$$\Delta = W\varphi = W(RY) = W(RCX) = (WRC)X \tag{4}$$

As C is a real symmetric matrix, $C = C^T$, (4) can be reformulated as

$$\Delta = \left[(RC)^T \mathrm{W}^\mathrm{T}\right]^T = X = (CR^T W^\mathrm{T})^\mathrm{T} X \tag{5}$$

When comparing (3) and (5), it can be observed that the satisfaction contribution of the technical measures are $V = CR^T W^T$ and $\Delta = V^T X$. □

The overall satisfaction improvement is expected to surpass the performance improvement of mobile application given as the right column in the right wall in Fig. 1. Hence, the overall satisfaction improvement objective can be expressed as

$$\Delta = (CR^T W^\mathrm{T})^\mathrm{T} X \geq WH \tag{6}$$

2) OBJECTIVE 2: INDEPENDENT SATISFACTION IMPROVEMENT OF CUSTOMER'S EACH DEMANDS

The mobile application development process is concerned with not only improving overall product satisfaction but also improving each customer's individual need. As a consequence, the actual satisfaction improvement of customer's individual demand should not be less than the target improvement rate given in the right wall, which can be written as

$$R(CX) \geq H \tag{7}$$

3) OBJECTIVE 3: RESOURCE CONSUMPTION CONTROL

In order to achieve expected satisfaction improvement, the development of mobile application requires a variety of resources, such as human, financial, time and equipment resources to ensure project implementation. Hence, resource investment should not exceed the budgets, which can be considered as a resource consumption objective. Assume there are k kinds of resources whose budgets are $B = (b_1, b_2, \cdots, b_k)^T$ and weights are $\Phi = (\phi_1, \phi_2, \cdots, \phi_k)$, and the resource consumption of technical measures implementation, which can be evaluated by the development team and are reflected in the basement, are $G = \{g_{ij}\}_{k \times m}$ (fourth row from the bottom in the basement). The resource consumption objective can be expressed as

$$GX \leq B \tag{8}$$

C. CONSTRAINTS OF MEASURE EXPECTED IMPLEMENTATION EFFECT

As an improvement project, each measure has the optimal implementation effect or maximum target. The constraints of expected improvement effect represent that the change range of actual implementation effect should be less than the most expected target. If the maximum improvement effects of the technical measures are $\hat{E} = (\widehat{e}_1, \widehat{e}_2, \cdots, \widehat{e}_n)^T$, the measures-effect constraint can be represented as follows

$$0 \leq X \leq |\hat{E} - \overline{E}|/\overline{E} \tag{9}$$

D. MULTI-OBJECTIVE PROGRAMMING AND ITS OPTIMAL SOLUTIONS

Because there are various objectives for mobile application development management, it is necessary to assign priorities to the objectives so that the higher priority will be implemented. Suppose that $P_{obj(i)} \succ P_{obj(j)}$ means Objective i has a higher priority to Objective j. Hence, the multi-objective programing model that uses the information in HDQ, can be built as follows.

$$\min Z = P_{obj(1)} d_1^- + P_{obj(2)} W D_2^- + P_{obj(3)} \phi D_3^+$$
$$s.t \begin{cases} (CR^T W^\mathrm{T})^\mathrm{T} X + d_1^- - d_1^+ = WH \\ R(CX) + D_2^- - D_2^+ = H \\ GX + D_3^- - D_3^+ = B \\ 0 \leq X \leq |\hat{E} - \overline{E}|/\overline{E} \\ d_1^-, d_1^+, D_2^-, D_2^+, D_3^-, D_3^+ \geq 0 \end{cases} \tag{10}$$

In Programming (10), $D_2^\bullet = \left(d_{2,1}^\bullet, d_{2,2}^\bullet, \cdots, d_{2,m}^\bullet\right)^T$, $D_3^\bullet = \left(d_{3,1}^\bullet, d_{3,2}^\bullet, \cdots, d_{3,k}^\bullet\right)^T$; $d_\bullet^-$ and $d_\bullet^+$ represent the negative and positive deviations, respectively. It is clear that the program is a bounded domain, in which there are m kinds of customers' requirements and k sorts of resources. Hence the number of the independent variables in multi-objective program is $m + k + 1$. Based on the polynomial algorithm introduced by Khanchiian [38], suppose that the scale of the program is L. Since all the matrices in the multi-objective program are liner matrices, the computational complexity of multi-objective program can be expressed as $O\left((m + k + 1)^4 L^2\right)$. Solving multi-objective program, one can obtain the optimal improvement effects of technical measures as $X^* = \left(x_1^*, x_2^*, \cdots, x_n^*\right)^T$, which can ensure the optimal objective realization. Additionally, the resource allocation scheme for distributing development resources to technical measures t_i is $O_i^* = \left\{x_i^* g_{\bullet i}\right\}$, which guarantee that the specialized developing task has the desired effect.

IV. EXTENDED MODEL CONSIDERING RESOURCE SUBSTITUTION

If the optimal solution of Programming (10) is obtained as $X^* = \left(x_1^*, x_2^*, \cdots, x_n^*\right)^T$, there may be a bottle-neck resource, such as human, financial, time or equipment resources, which constrains the entire optimization. To improve optimization effect, some resources can be consumed and transferred to the additional amount of bottle-neck resource. For example, if human resource is the current bottle-neck resource for a development project, the surplus finance resources are available and can be used to employ extra staff to increase the amount of human resource. Additionally, increased resource utilization can improve the implementation efficiency of a project, which can be comparatively regarded as the increase of total resource amount. For example, more human resource could cut the project time in half, resulting in the double total requirement of time from the perspective of schedule management. In order to make full use of surplus resource and realize additional improvement, extended models considering the resource substitution can be constructed, which will be divided in to several situations with varied deviation results $d_{\bullet}^{-(+)}$ from Programming (10).

A. CONSTRUCTION OF THE EXTENDED MODEL IN DIFFERENT DEVIATIONS

1) SITUATION 1: $d_1^- < 0$

If $d_1^- < 0$, the objective 1 as overall satisfaction is failed to meet customers' demand. One can't obtain the optimal solution of Programming (10). There is no feasible solution for the extended model as well.

2) SITUATION 2: $d_1^- \geq 0, \forall d_{2,i}^- \geq 0, \forall d_{3,j}^+ \leq 0$

If $d_1^- \geq 0$, $\forall d_{2,i}^- \geq 0$ and $\forall d_{3,j}^+ \leq 0$, the objective 1 as overall satisfaction and Objective 2 as specific satisfaction exceeds relevant demands, and resources are sufficient. According to the optimal solution of Programming (10), the optimal improvement effect of technical measures is $X^* = \left(x_1^*, x_2^*, \cdots, x_n^*\right)^T$ and the original consumption of resources is $Q = GX^*$. If the additional resource consumption is $L = (l_1, l_2, \cdots, l_k)^T$, it will be less than the amount of surplus resource, $0 \leq L \leq B - Q(X^*)$. If the resource substituted relationship matrix is $A = \left\{a_{ij}\right\}_{k \times k}$ and the independent implementation effect considering resource substitution is $X' = \left(x_1', x_2', \cdots, x_n'\right)^T$, the updated resource budget can be regarded as the sum of consumed resource, $Q = GX^*$, and the amount of additional resources after substitution, AL, which can be expressed as

$$GX' \leq Q + AL \tag{11}$$

In order to achieve the better implementation effect concerning resource substitution, the maximum improvement of overall satisfaction can be designed as $\max Z_1 = \left(CR^T W^{\mathrm{T}}\right)^{\mathrm{T}} (X' - X^*)$.

Hence, extended model with resource substitution can be expressed as

$$\max\ Z_1 = \left(CR^T W^{\mathrm{T}}\right)^{\mathrm{T}} (X' - X^*)$$
$$s.t.\ \begin{cases} R\left(CX'\right) \geq H & (C1) \\ GX' \leq Q\left(X^*\right) + AL & (C2) \\ 0 \leq L \leq B - Q\left(X^*\right) & (C3) \\ 0 \leq X' \leq |\hat{E} - \overline{E}|/\overline{E} & (C4) \end{cases} \tag{12}$$

in which $C1$ means the specific satisfaction improvement rate ranges, $C2$ refers the new constraints of resource budgets, $C3$ denotes the additional resource consumption range, $C4$represents the range of actual measure implementation effect.

3) SITUATION 3: $d_1^- \geq 0, \forall d_{2,\cdot}^- \geq 0, \exists d_{3,i}^+ > 0$

If $d_1^- \geq 0, \forall d_{2,\cdot}^- \geq 0$ and $\exists d_{3,i}^+ > 0$, $i = 1, 2, \cdots, k$, both overall and independent satisfaction improvement of customers' demand objectives are achieved, but the amount of ith resource, b_i, is not insufficient, which plays as bottleneck resource preventing further improvement. Except constraints $C1$, $C2$, $C4$, there is an additional constraint $C5$related to the additional amount ranges of resources. According to bottle-neck resource i, $d_{3,i}^+ > 0$, its surplus amount range is $b_i - \left(Q_i^*\right) \leq l_i \leq 0$. With sufficient resources j, $j = 1, 2, \cdots, k$, $d_{3,j}^+ \leq 0$ the surplus amount will be $0 \leq l_j \leq b_j - \left(Q_j^*\right)$. Taking improvement objective and constraints into account, the extended model can be as follows

$$\max\ Z_1 = \left(CR^T W^T\right)^T (X' - X^*)$$
$$s.t.\ \begin{cases} R\left(CX'\right) \geq H & (C1) \\ GX' \leq Q\left(X^*\right) + AL & (C2) \\ 0 \leq X' \leq |\hat{E} - \overline{E}|/\overline{E} & (C4) \\ \begin{cases} b_i - \left(Q_i^*\right) \leq l_i \leq 0, & \forall d_{3,i}^+ > 0 \\ 0 \leq l_j \leq b_j - \left(Q_j^*\right), & \forall d_{3,j}^+ \leq 0 \end{cases} & (C5) \end{cases} \tag{13}$$

4) SITUATION 4: $d_1^- \geq 0, \exists d_{2,i}^- < 0, \forall d_{3,i}^+ \leq 0$

When $d_1^- \geq 0, \exists d_{2,i}^- < 0$, $i = 1, 2, \cdots m$ and $\forall d_{3,i}^+ \leq 0$, $i = 1, 2, \cdots, k$, the objective 1 as overall satisfaction goal is achieved while not all the objective 2 as independent satisfactions are achieved and resources are sufficient. In this case, except constraints $C2$, $C3$, $C4$, there is an additional limitation $C6$ related to the specific satisfaction improvement. The specific satisfaction in objective 2 should be improved following resource reallocation, $R\left(C\left(X' - X^*\right)\right) \geq 0$. Hence, the extended model incorporating resource substitution can be

$$\max\ Z_1 = \left(CR^T W^{\mathrm{T}}\right)^{\mathrm{T}} (X' - X^*)$$
$$s.t.\ \begin{cases} GX' \leq Q\left(X^*\right) + AL & (C2) \\ 0 \leq L \leq B - Q(X^*) & (C3) \\ 0 \leq X' \leq |\hat{E} - \overline{E}|/\overline{E} & (C4) \\ R\left(C\left(X' - X^*\right)\right) \geq 0 & (C6) \end{cases} \tag{14}$$

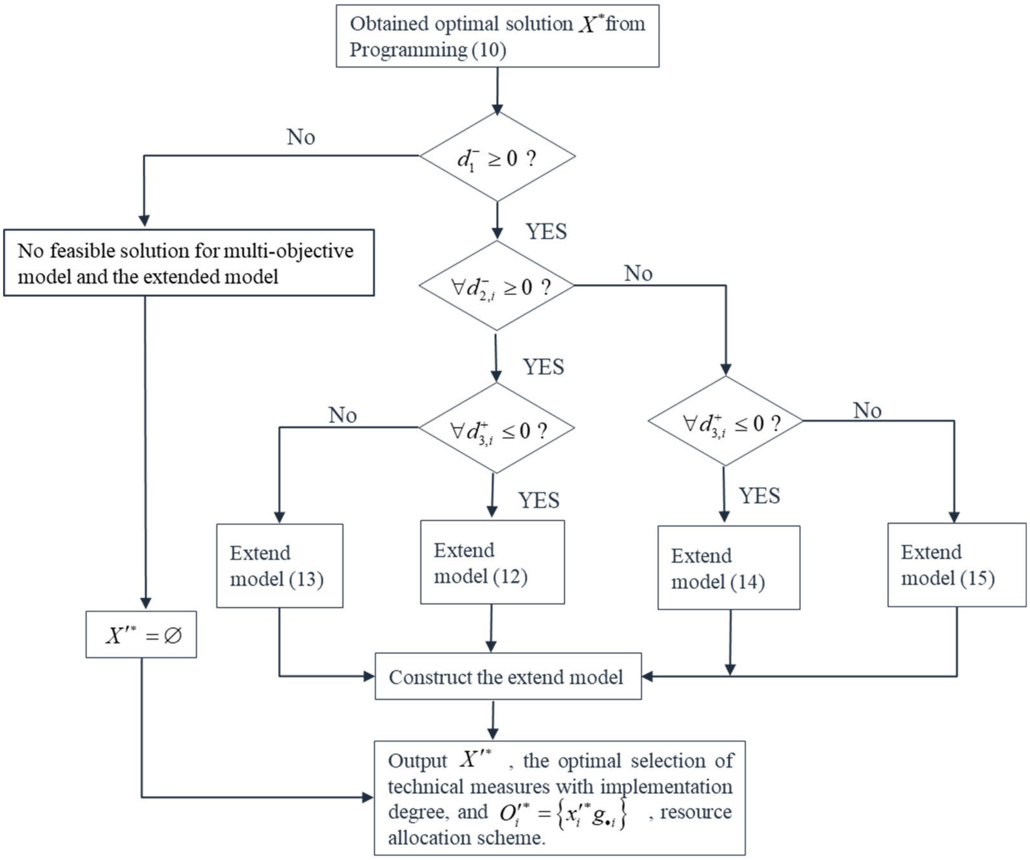

FIGURE 2. Model selection diagram.

5) SITUATION 5: $d_1^- \geq 0, \exists d_{2,i}^- < 0, \exists d_{3,i}^+ > 0$

When $d_1^- \geq 0, \exists d_{2,i}^- < 0, i = 1, 2, \cdots, m$ and $\exists d_{3,i}^+ > 0$, $i = 1, 2, \cdots, k$ although the overall satisfaction is achieved, not all the independent satisfaction improvements meet the customer's demands and not all the resources are sufficient. Similarly, the extended model can be expressed as

$$\max\ Z_1 = \left(CR^T W^{\mathrm{T}}\right)^{\mathrm{T}} \left(X' - X^*\right)$$
$$s.t. \begin{cases} GX' \leq Q\left(X^*\right) + AL & (C2) \\ 0 \leq X' \leq |\hat{E} - \overline{E}|/\overline{E} & (C4) \\ \begin{cases} b_i - \left(Q_i^*\right) \leq l_i \leq 0, & \forall d_{3,i}^+ > 0 \\ 0 \leq l_j \leq b_j - \left(Q_j^*\right), & \forall d_{3,j}^+ \leq 0 \end{cases} & (C5) \\ R\left(C\left(X' - X^*\right)\right) \geq 0 & (C6) \end{cases} \quad (15)$$

To sum up, Fig.2 presents the process of selecting the corresponding model in above situations. In a specific case, one can choose a proper model based on the optimal condition $d_1^-, d_{2,i}^-$ and $d_{3,i}^+$, and use resource substitution to solve for further improvement. Referring to the algorithm of single objective program, one can obtain the $X'^* = \left(x_1'^*, x_2'^*, \cdots, x_n'^*\right)^T$, which can assure the optimal objective realization while taking the resource substitution into account. In addition, the new resource allocation scheme for distributing development resource to technical measure t_i is $O_i'^* = \{x_i'^* g_{\bullet i}\}$ and the additional resource result is $L^* = \left(l_1^*, l_2^*, \cdots, l_k^*\right)^T$.

Based on the above analysis, the values of the deviations influence the selection of the extended models with different constraints. However, the independent variables in each extended model are the same, there are k sorts of resources. The computational complexity can be written as $O\left((k+1)^4 L^2\right)$.

V. CASE STUDY

A. CASE BACKGROUND

An enterprise developed a family financial management application, but the download number, user activity and user retention of current application version did not meet expectations. In order to better meet the market goals and customers' demands, the R&D team needs to iterate on application releases following the proposed procedures.

HDQ can be built to aid decision-making when allocating optimal resource as shown in Fig. 1 in Section 2. Following the market assessment, clients' demands are divided into six categories, $D = \{d_1, d_2, \cdots, d_6\}$, d_1: aesthetically pleasing interface; d_2: satisfying functionality; d_3: data security; d_4:

TABLE 1. Details of technical measures.

technical measures	maximum improvement (%)	Human consumption	Finance consumption	Time consumption
t_1	8.5	0.2	0.22	0.5
t_2	9	0.2	0.24	0.5
t_3	12.4	1	0.35	1.2
t_4	12	0.8.	0.42	1.1
t_5	15.3	0.7	0.36	1
t_6	14.5	0.6	0.28	0.9

TABLE 2. Resource allocation scheme for technical measures.

technical measures	realistic improvement (%)	Human consumption	Finance consumption	Time consumptio n
t_1	0	0	0	0
t_2	9	1.8	2.16	4.5
t_3	12.4	12.4	4.34	14.88
t_4	1.2	0.96	0.504	1.32
t_5	4.1	2.87	1.476	4.1
t_6	0	0	0	0
surplus resource		1.97	1.52	0.2

accessible usability; d_5: responsive efficiency; d_6: high reliability. Through AHP analysis, the weight vector of above demands is $W = (0.04, 0.31, 0.37, 0.07, 0.1, 0.11)$. $T = \{t_1, t_2, \cdots, t_6\}$, which are t_1: color assortment; t_2: interactive design; t_3: function implementation; t_4: data encryption; t_5: system testing; and t_6: system maintenance are six improvement recommendations developed by R&D teams through brainstorming and group discussion. Table 1 shows the most expected effect and resource consumptions information. The amount of human, finance and time resources required to ensure the implementation effect of improvement recommendations are 20 standardization equivalents staff, 10 thousand dollars, 25 days as budgets respectively.

B. MULTI-OBJECTIVE MODEL FOR DETERMINING MEASURES IMPROVEMENT AND RESOURCE ALLOCATION SCHEME

According to the information in HDQ, similar as Programming (10), the multi-objective programming model can be expressed Programming as in (16), shown at the bottom of the next page, in which includes three objectives, overall satisfaction improvement, independent satisfaction improvement and resource consumption control, as well as the constraint of measure expected implementation effect range are included.

By solving the multi-objective programming, one can obtain the optimal technical measures improvement $X^* = (0\%, 9\%, 12.4\%, 1.2\%, 4.1\%, 0\%)^T$. Comparing to previous application version, the technical measures t_2, t_3, t_4, t_5 were chosen to be applied, because they can provide the optimal improvement effects of 9%, 12.4%, 1.2% and 4.1%, respectively. In the optimal condition, $d_1^- = 0, \forall d_{2,\bullet}^- = 0$ and $\forall d_{3,\bullet}^+ = 0$, the objectives of the overall satisfaction improvement, the independent satisfaction improvement and the resource consumption control are achieved, with overall satisfaction improving 16.0% and six specific demands improving 9.91%, 20.57%, 14.18%, 14.02%, 12.12%, and 16.25%, respectively. The total resource consumptions are 18.03 standardization equivalents staff, 8.48 thousand dollars and 24.8 days, respectively. Additionally, referring to $O_i^* = \{x_i^* g_{\bullet i}\}$, the optimal resource allocation scheme for each technical measure can be calculated as presented in Table 2.

One can find the almost all the time resource is consumed, which can be regarded as the bottle-neck resource that prevents further optimization. However, there are surplus finance and human resources that can be effectively substituted to the additional bottle-neck resource for further optimization. To have a better implementation effect and reduce resource waste, one can construct the proper extended model that incorporates resource substitution.

C. EXTENDED MODEL CONSIDERING RESOURCE SUBSTITUTION

The deviations in the optimal condition of the above multi-objective programming model are $d_1^- = 0, \forall d_{2,i}^- = 0$ and $\forall d_{3,i}^+ = 0$. Taking the substitution relationship among resources into consideration, the extended model as in (17), shown at the bottom of page 10, can be developed from Programming (12).

By solving the above linear programming, one can obtain the optimal improvements of technical measures as $X'^* = (0\%, 9\%, 12.4\%, 0\%, 0.7\%, 8.2\%)^T$, the technical measures t_2, t_3, t_5, t_6 are chosen to be implemented, in which the optimal improvement effects are 9%, 12.4%, 0.7%, 8.2%, respectively. When solutions are implemented, the overall satisfaction increases by 17.77% while the specific satisfactions improve by 11.58%, 22.65%, 16.05%, 15.24%, 12.21%, and 18.36%, respectively. The total resource consumptions are 19.61 standardization equivalents staff, 9.05 thousand dollars, 27.46 days, respectively with time resource increasing by 2.66 days due to substitution of surplus human and financial resources. Taking into account resource substitution, Table 3 shows the optimal resource allocation scheme for each technical measure as $O_i'^* = \left\{x_i'^* g_{\bullet i}\right\}$.

D. COMPARISON ANALYSIS AND DISCUSSION

(1) The traditional research mainly focused on specific technical solutions and implementation in isolation, which easily ignored their connections to competition objectives, customer demands and resource consumption. Because of incomplete consideration, overdue development, schedule chaos and resource conflict, various Apps developments have failed to produce desired effects. In this paper, HDQ framework

is elaborately proposed as a systematic analytical platform that comprehensively integrated users' core requirements, technical measures implementation, R&D objectives and resource consumption as well as their complicated relationships. Transformed from HDQ, several development objectives and constraints are addressed in the programming model to identify the optimal arrangement of technical measures and resource allocation scheme. The proposed method successfully builds a bridge between customer and engineering sides, thereby solving the problem of "isolated information islands". According to the optimal measure implementation and resource allocation scheme, the whole development

$$
\min Z = P_{obj(1)} d_1^- + P_{obj(2)} W D_2^- + P_{obj(3)} \phi D_3^+
$$

$$
s.t.\begin{cases}
\left(\begin{bmatrix} 0.6 & 0.4 & 0.2 & 0 & 0 & 0.2 \\ 0.4 & 0.6 & 0.4 & 0 & 0.4 & 0.2 \\ 0.2 & 0.4 & 0.6 & 0.6 & 0.4 & 0.4 \\ 0 & 0 & 0.6 & 0.6 & 0.2 & 0.4 \\ 0 & 0.4 & 0.4 & 0.2 & 0.6 & 0.2 \\ 0.2 & 0.2 & 0.4 & 0.4 & 0.2 & 0.6 \end{bmatrix} \begin{bmatrix} 0.6 & 0.2 & 0 & 0 & 0.2 & 0.2 \\ 0 & 0.4 & 0.6 & 0 & 0.4 & 0.4 \\ 0 & 0 & 0.2 & 0.6 & 0.4 & 0.2 \\ 0 & 0.4 & 0.4 & 0 & 0.2 & 0.2 \\ 0 & 0 & 0.4 & 0 & 0.6 & 0 \\ 0 & 0 & 0.2 & 0.4 & 0.6 & 0.4 \end{bmatrix}^T \begin{bmatrix} 0.04 \\ 0.31 \\ 0.37 \\ 0.07 \\ 0.1 \\ 0.11 \end{bmatrix} \right)^T \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix} \\
\qquad + (d_1)^- - (d_1)^+ = \begin{bmatrix} 0.04 \\ 0.31 \\ 0.37 \\ 0.07 \\ 0.1 \\ 0.11 \end{bmatrix}^T \begin{bmatrix} 4.26\% \\ 6.67\% \\ 9.30\% \\ 6.67\% \\ 12.20\% \\ 11.63\% \end{bmatrix} \\
\begin{bmatrix} 0.6 & 0.2 & 0 & 0 & 0.2 & 0.2 \\ 0 & 0.4 & 0.6 & 0 & 0.4 & 0.4 \\ 0 & 0 & 0.2 & 0.6 & 0.4 & 0.2 \\ 0 & 0.4 & 0.4 & 0 & 0.2 & 0.2 \\ 0 & 0 & 0.4 & 0 & 0.6 & 0 \\ 0 & 0 & 0.2 & 0.4 & 0.6 & 0.4 \end{bmatrix} \begin{bmatrix} 0.6 & 0.4 & 0.2 & 0 & 0 & 0.2 \\ 0.4 & 0.6 & 0.4 & 0 & 0.4 & 0.2 \\ 0.2 & 0.4 & 0.6 & 0.6 & 0.4 & 0.4 \\ 0 & 0 & 0.6 & 0.6 & 0.2 & 0.4 \\ 0 & 0.4 & 0.4 & 0.2 & 0.6 & 0.2 \\ 0.2 & 0.2 & 0.4 & 0.4 & 0.2 & 0.6 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix} + \begin{bmatrix} (d_{2,1})^- \\ (d_{2,2})^- \\ (d_{2,3})^- \\ (d_{2,4})^- \\ (d_{2,5})^- \\ (d_{2,6})^- \end{bmatrix} \\
\qquad - \begin{bmatrix} (d_{2,1})^+ \\ (d_{2,2})^+ \\ (d_{2,3})^+ \\ (d_{2,4})^+ \\ (d_{2,5})^+ \\ (d_{2,6})^+ \end{bmatrix} = \begin{bmatrix} 4.26\% \\ 6.67\% \\ 9.30\% \\ 6.67\% \\ 12.20\% \\ 11.63\% \end{bmatrix} \\
100 \begin{bmatrix} 0.2 & 0.2 & 1.0 & 0.8 & 0.7 & 0.6 \\ 0.22 & 0.24 & 0.35 & 0.42 & 0.36 & 0.28 \\ 0.5 & 0.5 & 1.2 & 1.1 & 1.0 & 0.9 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix} + \begin{bmatrix} (d_{3,1})^- \\ (d_{3,2})^- \\ (d_{3,3})^- \end{bmatrix} - \begin{bmatrix} (d_{3,1})^+ \\ (d_{3,2})^+ \\ (d_{3,3})^+ \end{bmatrix} = \begin{bmatrix} 20 \\ 10 \\ 25 \end{bmatrix} \\
\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \le \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix} \le \begin{bmatrix} 8.5\% \\ 9\% \\ 12.4\% \\ 12\% \\ 15.3\% \\ 14.5\% \end{bmatrix}
\end{cases} \tag{16}
$$

TABLE 3. Resource allocation scheme considering resource substitution for technical measures.

technical measures	realistic improvement (%)	Human consumption	Finance consumption	Time consumption
t_1	0	0	0	0
t_2	9	1.8	2.16	4.5
t_3	12.4	12.4	4.34	14.88
t_4	0	0	0	0
t_5	0.7	0.49	0.25	0.70
t_6	8.2	4.92	2.30	7.38
total consumption		19.61	9.05	27.46

TABLE 4. Comparison on overall and independent satisfaction improvement.

demand \ model	Multi-objective programming (16) ①	Extended model (17) ②	Comparative improvement rate (②-①)/①
d_1	9.91%	11.58%	16.85%
d_2	20.57%	22.65%	10.11%
d_3	14.18%	16.05%	13.19%
d_4	14.02%	15.24%	8.70%
d_5	12.12%	12.21%	0.74%
d_6	16.25%	18.36%	12.98%
overall satisfaction improvement	16.00%	17.77%	11.06%

process is under a complete and systematic consideration, which may ensure the overall R&D effect as well as achievements on specialized objectives.

(2) When comparing the results of basic multi-programming and extended model, it can be seen that resource substitution can directly increase improvement effect and resource utilization as shown in Table 4 and Table 5.

As shown in Table 4, because the extended model takes the resource substitution into account, both the overall and the independent satisfaction improvement of customers' requirements are effectively improved. Compared to the output of multi-objective Programming, overall satisfaction comparatively increases 11.06%, while specific customers' demands comparatively increase 16.85%, 10.11%, 13.19%, 8.70%, 0.74% and 12.98%, respectively.

$$\max\ Z_1 = \left(CR^T W^{\mathrm{T}}\right)^{\mathrm{T}} (X' - X^*)$$

$$s.t.\begin{cases}
\begin{bmatrix} 0.6 & 0.2 & 0 & 0 & 0.2 & 0.2 \\ 0 & 0.4 & 0.6 & 0 & 0.4 & 0.4 \\ 0 & 0 & 0.2 & 0.6 & 0.4 & 0.2 \\ 0 & 0.4 & 0.4 & 0 & 0.2 & 0.2 \\ 0 & 0 & 0.4 & 0 & 0.6 & 0 \\ 0 & 0 & 0.2 & 0.4 & 0.6 & 0.4 \end{bmatrix}
\begin{bmatrix} 0.6 & 0.4 & 0.2 & 0 & 0 & 0.2 \\ 0.4 & 0.6 & 0.4 & 0 & 0.4 & 0.2 \\ 0.2 & 0.4 & 0.6 & 0.6 & 0.4 & 0.4 \\ 0 & 0 & 0.6 & 0.6 & 0.2 & 0.4 \\ 0 & 0.4 & 0.4 & 0.2 & 0.6 & 0.2 \\ 0.2 & 0.2 & 0.4 & 0.4 & 0.2 & 0.6 \end{bmatrix}
\begin{bmatrix} x_1' \\ x_2' \\ x_3' \\ x_4' \\ x_5' \\ x_6' \end{bmatrix} \geq
\begin{bmatrix} 4.26\% \\ 6.67\% \\ 9.30\% \\ 6.67\% \\ 12.20\% \\ 11.63\% \end{bmatrix} \\
100\begin{bmatrix} 0.2 & 0.2 & 1.0 & 0.8 & 0.7 & 0.6 \\ 0.22 & 0.24 & 0.35 & 0.42 & 0.36 & 0.28 \\ 0.5 & 0.5 & 1.2 & 1.1 & 1.0 & 0.9 \end{bmatrix}
\begin{bmatrix} x_1' \\ x_2' \\ x_3' \\ x_4' \\ x_5' \\ x_6' \end{bmatrix} \leq
\begin{bmatrix} 18.03 \\ 8.48 \\ 24.8 \end{bmatrix} +
\begin{bmatrix} 0 & 1.7 & -0.6 \\ 0.56 & 0 & 0.37 \\ -1.75 & 2.73 & 0 \end{bmatrix}
\begin{bmatrix} l_1 \\ l_2 \\ l_3 \end{bmatrix} \\
\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \leq \begin{bmatrix} l_1 \\ l_2 \\ l_3 \end{bmatrix} \leq \begin{bmatrix} 20 \\ 10 \\ 25 \end{bmatrix} - \begin{bmatrix} 18.03 \\ 8.48 \\ 24.8 \end{bmatrix} \\
\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \leq \begin{bmatrix} x_1' \\ x_2' \\ x_3' \\ x_4' \\ x_5' \\ x_6' \end{bmatrix} \leq \begin{bmatrix} 8.5\% \\ 9\% \\ 12.4\% \\ 12\% \\ 15.3\% \\ 14.5\% \end{bmatrix}
\end{cases} \tag{17}$$

TABLE 5. Comparison on resource consumption percentage.

model / demand	Multi-objective programming (16)	Extended model (17)	Comparative consumption improvement rate
Human consumption percentage	90.15% (18.03/20)	98.05% (19.61/20)	8.76%
Finance consumption percentage	84.8% (8.48/10)	90.5% (9.05/10)	6.72%
Finance consumption percentage	99.2% (24.8/25)	109.84% (27.46/25)	10.73%

According to the data in Table 5, the extended model increases resource consumption efficiency. When compared to the result of multi-objective Programming, the consumption efficiencies of three resources, human, finance and time, comparatively improves 8.76%, 6.72% and 10.73%, respectively. After substituted from human and finance resources, the bottle-neck resource, time, is obtained the extension about 2.66 days. What is more important, the non-bottle-neck resources were efficient utilized and didn't exceed resource budgets. In other words, the R&D development was further optimized by suitable managerial arrangement without additional investment. The comparison figure of overall satisfaction improvement with the time increment under the situation of considering resource substitution and without resource substitution are shown in Fig.3. In Fig.3, the blue line represents the condition that do not consider resource substitution while the red line exhibits the situation considering the resource substitution. One can find that under the situation of considering resource substitution the overall satisfaction linear increases with the investment of transformed time resource and then tends to be stable and the upper limit is higher than without resource substitution. When time increment achieves 0.2, which is regarded as a turning point, the overall satisfaction improvement is becoming stable, the transformed ability of the other resources has achieved maximum, the constraint effect of time resource has been improved.

(3) In above case, though the time resource is regarded as the bottle-neck resource, its amount is enough. Considering the condition that one resource is not enough, change the budget of time resource to 20 days. In this situation, the human resource, finance resource and time resource are consumed 13.81 standardization equivalents staff, 8.13 thousand dollars and 21.36 days, respectively and the overall satisfaction improvement is 13.72% according to Programming (10). It is clear that the time is overload while the human and finance resource is sufficient. To get further improvement, the extended model can be developed from Programming (13) according to Fig.2. The growth chart of overall satisfaction improvement is shown in Fig.4

Based on above analysis, 1.36 days are overdue. To fill the pit of time, human resource and finance resource are

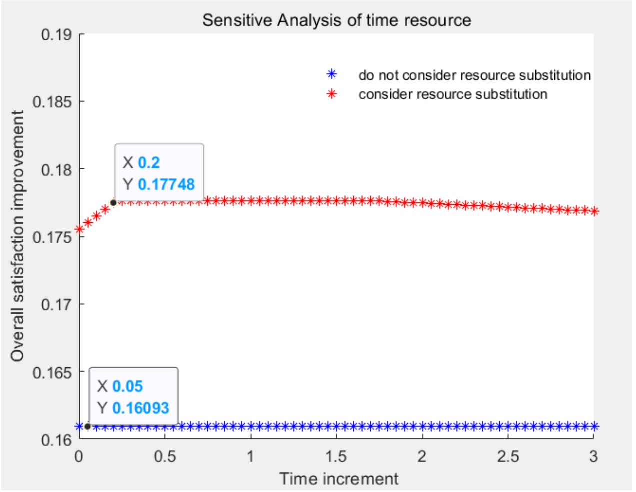

FIGURE 3. Sensitive analysis of time resource.

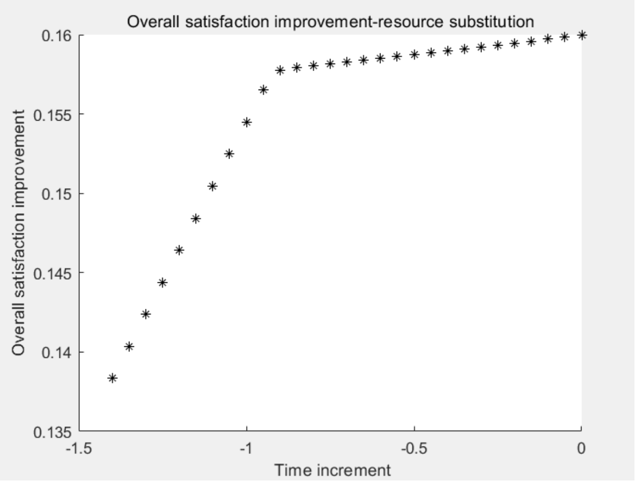

FIGURE 4. Overall satisfaction improvement-resource substitution.

transformed into time resource, which cut the project time and increase time resource from the perspective of schedule management. In Fig.4, with the investment of the transformed time resource from human resource and finance resource, the overall satisfaction improvement rate is on an upward trend. When time increment achieves 0.9 (corresponding -0.9 in the Fig.4), the growth rate is getting slow, the constraint effect of time has improved. What's more, the overall satisfaction improvement increases at least 2.28% (16.00%-13.72%), the human resource and finance resource get more reasonably consumed, which improves the resource utilization efficiency and avoids the resource waste.

VI. CONCLUSION AND FUTURE WORK

In practical development environment, there may be multiple projects at the same time. However, the project resources are overlap and insufficient, though it is an essential issue to arrange the schedule of each project, how to determine the implementation degree of technical measures and resource allocation scheme in a project combining with users' core demands is an another extreme important topic, especially in mobile application development. Consequently, this study develops a novel decision support platform that can assist development team in systematically managing customers' core demands, market objectives, R&D actions and resources allocation for optimal R&D arrangements in the development process. HDQ framework is designed to integrate related information and describe complicated relationship data in the corresponding modules, therefore creating a link between disparate sources of information. According to the related information in HDQ, the multi-objective programming model is built to identify the optimal arrangement of technical measures and resource allocation scheme, which provides valuable decision assistance to manage the mobile application R&D process. In order to realize further optimization, the extended model considering on the utilization of surplus resource is established to achieve the better improvement effect and enhance resource utilization efficiency. The proposed platform and methods not only provide the solution for the optimal selection of technical measures with the highest improvement degree, but also an output resource allocation scheme concerning the utilization efficiency of surplus resource.

There are certain limitations to this study that should be addressed in future research. Because mobile application R&D is a dynamic process, in which bottle-neck resource vary when resource substitution is taken into account. Moreover, the technical measures can be improved into specific sub-measures as the work progresses. Another important future research project will be how to make hierarchical decision on technical measures and resource allocation.

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