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Solving Situationally Definable Linear Problems of Resource Planning: a Review of Updated Technology

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Abstract. The situational resource planning is considered as essential part of situational management. A review presents the updated technology for solving situationally definable linear problems of resource planning, including the method of resource allocation by the target displacement of solution and the method of interval cost planning. The definition of a new class of planning and management problems – the situationally definable ones – is proposed. The statement of problems is oriented to the mode of computational experiment, taking into account the dynamically changing object awareness, the conditions of the object functioning and the clarified goals of the decision makers, whose expert knowledge plays an important role. State of the managed system and the planning conditions are represented by portraits of situations. At each step of the plan search, statement of the problem is described by a system of mandatory and orienting requirements, formed on the basis of results of the situation portraits analysis. The proposed methods are designed for implementation in online services operating in the digital twins environment. An example of application of the updated technology to the situational management of electricity production is given.

Keywords: situationally definable problem, portrait of situation, system of mandatory and orienting requirements, target displacement of solution, interval cost planning, situational managament of electricity generation.

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Introduction

Importance and complexity of planning and management problems increases simultaneously with increasing complexity of production and distribution in supply networks [1, 2]. Starting from some level of complexity, it is necessary to involve expert knowledge in order to successfully solve planning and managament tasks. It is advisable to combine computational methods for calculating the plan and informal methods for forming requirements and assessing the plan and management quality.

Since the end of the last century, awareness of the need for such a combination has been steadily growing. The paper [3] describes an algorithm which mixes math programming and emulation of production system for the MPMP (Multi Period Multi Product) problem. It shows that analytic model combined with emulation one works better than a model alone. Production planning tasks, having set-up solutions, are formulated and solved as mixed integer programming problems in the article [4]. Wang and Fang [5] have described a linear programming model for fuzzy objectives, which allows an expert to modify data and parameters of the model until an appropriate decision is found. Leung and co-authors [6] have proposed the multi-objective model for the problems of production planning, where a profit is to be maximized, and at the same time the production penalties from violation of quotas and workforce change are to be minimized. The article [7] presents a strategic planning model which captures the trade-off between delaying the start-time of an activity and the need for some activities to be performed now. The perspective approach to production planning is described in the paper [8]: the roles of experts are delegated to the self-directed adaptive software objects – “agents”.

Our conception is that expert planning and management in complex man-machine systems should be based on *online services* [9], working in the environment of *digital twins*[1]. Digital twins are involved in collecting data, simulating the state of an object, interrogating experts to form efficiency criteria and assess the plans efficiency. The informal approach to solving the planning and management problems, based on attracting expert knowledge, includes wide usage of formal methods in the computing arsenal of online services. The *Resource Planning Online Services* for solving problems of cost planning and resource allocation in accordance with mandatory and orienting requirements are being implemented at www.res-plan.com. Computational methods take into consideration the practical information incompleteness and experience in development and implementation of resource planning technologies [10, 11].

The article presents the updated technology of situational cost planning with changes in the requirements for the solution in terms of information incompleteness. The results were obtained in the performance of research work "Modeling of social, economic and environmental processes" (№ 0063-2016-0005) under the state task of FANO of Russia for the Federal research center "Informatics and control" RAS.

[1] General Electric. 2019. The Digital Twin. Available at: https://www.ge.com/digital/sites/default/files/The-Digital-Twin_Compressing-Time-to-Value-for-Digital-Industrial-Companies.pdf (accessed August 5, 2019).

Markuping text fragments and writing formulas

For markuping text fragments, the modeling language *TSM* (*Textual Symbolic Modeling*[2]) is used:

□ <text fragment> □ means definition;

◊ <text fragment> ◊ means note.

Italics are used to highlight the concepts and sentences, to which the authors want to attract the attention, and also for variables in formulas.

1. The updated technology

A technology for solving situationally definable problems is a part of a *situational managament technology*.

The concept of *situational management* was proposed by Klykov [12]. In the Pospelov’s monograph [13] *knowledge about the object of situational management is represented by logical-linguistic models*. In the Ilyin’s methodology of *situational informatization* [14] *a situation is presented by formal portrait of the particular set of spaces*. Situational informatization is considered as a means of organizational and technological improvement of managed system through sequent transitions from the starting situations to the target ones. Monitoring a managed system is carried out on the basis of situation portraits analysis.

1.1. Situationally definable problems of planning and management

□ *Situationally definable problems* are formulated on the basis of *mandatory and orienting requirements* derived from the analysis of *the portraits of the target and starting situation*. □

□ *Target situation* is a situation planned to be created as a result of *the management impact*. □

□ *Starting situation* is a situation, in relation to which the impact is being designed. □

□ *Achieved situation* is a situation that has actually arisen as a result of the management impact. □

[2] Ilyin, V. D. 2019. Simvol'noe modelirovanie [Symbolic modelling] // Bol'shaya rossiyskaya entsiklopediya – Great Russian Encyclopedia. Available at: http://dev.bigenc.ru/technology_and_technique/text/4010980 (accessed August 5, 2019).

□ *Portrait of the situation* is a formal description of the managed object state. It contains data characterizing the essential parameters of the object state, available variants of the impacts and description of the resources needed to implement these variants. □

Portrait of the situation is formed in the process of interpreting requests using an object model represented by a system of rules.

□ *Rule* is an expression of one of two types: either $D_1 \Rightarrow D_2$ or $D \Rightarrow I$ (here D, D_1, D_2 are arbitrary descriptions, and I is some instruction). □

A system of rules designed to form portrait of the situation implies the ordering of rules using the specialization relationship. If it is indicated that rule r_2 is a specialization of rule r_1, then r_1 is a generalization of r_2. Each *rule-specialization* is intended to trigger in more specific situations than the corresponding *rule-generalization*. For example, if the rule system contains the rules r_1 = "if an intruder plane is detected, it is necessary to force it to land" and r_2 = "if an intruder plane shoots, it is necessary to destroy it", then r_2 is a specialization of r_1; and if the premises of both rules are true, then only r_2 is to be executed.

A request is a specific description (belonging to some syntactically defined type of descriptions), which serves to determine the left parts of rules and can be used to establish the truth of other descriptions (using the rules of the type $D_1 \Rightarrow D_2$) or to get the prototype of management impact (using the rules of the type $D \Rightarrow I$).

Interpreting a request is the process of outputting descriptions from a request in accordance with a given system of rules. The outputted descriptions form a portrait of the situation.

1.2. Statement of linear resource planning problem

Linear problems of resource planning are usually solved by the simplex method [15, 16] or the interior point method [17]. In practice, use of these linear programming (LP) methods is very limited [18]. Firstly, the LP problem is incorrect because its solution may vary critically when the input is changed slightly [19]. Secondly, the resource constraints are inconsistent very often, and in these cases the problem has no classic decision. A solution found as a Chebyshev point is non-applicable in such case because it violates resource constraints which can not be violated in practice [10]. So the planners, having a classic LP software, are very restricted in obtaining the implementable and effective plan. Traditional LP software (eg, LINGO[3]) does not allow an expert intervention in the calculation process. If given system of constraints is incompatible, such software proposes to adjust the input data [10].

Taking into account these practical limitations, V. Ilyin has proposed the idea of informal statement and solving a linear problem of resource allocation [14, p. 148]. A. Ilyin has implemented this idea and developed such statement and *the method of target displacement of solution*. The developed technology of *interactive resource planning in accordance with the customizable system of requirements* gives the possibility to look for resource plan in accordance with expert knowledge of the plans workability and effectiveness. A variety of realizable solutions which can be investigated influences the final expert decision [18]. The software implementation of the technology was tested in a number of applications [10].

In the developed technology, an expert defines requirements to resource planning in the form of requirements on the values of linear functions $f_i(\mathbf{x})$, where $\mathbf{x}$ is resource allocation vector (vectors and matrix are written in bold).

In general case, a simple requirement can be written in one of three forms:

$$f_i(\mathbf{x}) = c_i\ [\leftarrow p_i], \qquad (1)$$

$$f_i(\mathbf{x}) \le c_i\ [\leftarrow p_i], \qquad (2)$$

$$f_i(\mathbf{x}) \ge c_i\ [\leftarrow p_i], \qquad (3)$$

where c_i – constant, p_i – priority of the requirement ($0 < p_i \le +\infty$), square brackets denote optionality of priorities. A composite requirement is a logical combination of simple requirements.

The requirements can be *mandatory* or *orienting*. Mandatory requirements have an absolute priority ($p_i = +\infty$), that is, they can not be violated. For example, if $f_i(\mathbf{x})$ expresses an expense of finite resource, then (2) is the

[3] Lindo Systems. LINGO 18.0 - Optimization Modeling Software for Linear, Nonlinear, and Integer Programming. Retrieved from https://www.lindo.com/index.php/products/lingo-and-optimization-modeling (n.d.)

mandatory requirement. If $f_i(\boldsymbol{x})$ is an efficiency indicator (objective function in terms of LP), then (1) or (3) can be considered as the orienting requirements. The orienting requirements specify the desired values of resource functions, setting the direction for displacement of solution.

Based on the analysis of the situation portrait, an expert performs step-by-step search for solution. At each step he customizes requirements that determine the change of solution. (Any requirement may remain unchanged during the search). If $\boldsymbol{x^0}$ is a given vector of resource allocation at the current step, then a composite orienting requirement (directing the displacement of solution) can be written as

$$\{ f_i(\boldsymbol{x}) = f_i(\boldsymbol{x^0}) + h_i\ [\leftarrow p_i],\ h_i \neq 0 \}$$

(the simple orienting requirements, related by conjunction, are enclosed in curly brackets).

□ $\boldsymbol{x}$ is considering as satisfying the given orienting requirements ($\boldsymbol{x}$ is *more efficient* than $\boldsymbol{x^0}$), if $f_i(\boldsymbol{x^0}) < f_i(\boldsymbol{x}) \leq f_i(\boldsymbol{x^0}) + h_i$ for $\forall\ h_i > 0$, and

$$f_i(\boldsymbol{x^0}) + h_i \leq f_i(\boldsymbol{x}) < f_i(\boldsymbol{x^0}) \text{ for } \forall\ h_i < 0$$ □

For example, implementation of the composite orienting requirement "the supply of gas should be increased by N_1 cubic meters for the customer C_1 and by N_2 cubic meters for the customer C_2" means that the supply is extended by M_1 for the C_1 and by M_2 for the C_2, where $0 < M_1 \leq N_1$ and $0 < M_2 \leq N_2$.

A requirement of optimization is defined as the special type of composite requirement. It can be written as

$$Q_{min}(\boldsymbol{x}) = f_i(\boldsymbol{x}) : \{P_1 \ldots P_k\}, \text{ or}$$
$$Q_{max}(\boldsymbol{x}) = f_i(\boldsymbol{x}) : \{P_1 \ldots P_k\}, \quad (4)$$

where $P_1 \ldots P_k$ are the simple mandatory requirements (for expenses of limited resources). This is the LP problem classic formulation. Notice, that it contains only mandatory requirements.

Our technology admits setting an optimization requirement to any function $f_i(\boldsymbol{x})$, choosing a subsystem of requirements as resource constraints, and trying to solve classic LP problem at any step of the decision process [18].

In general case, a two-sided composite requirement can be specified for any function $f_i(\boldsymbol{x})$. □ So, we can write the overall system as

$$\{[b_i \leq]\ a_{i1}x_1 + \ldots + a_{in}x_n\ [\leq B_i]\ [\leftarrow p_i];\ x_j \geq 0\} \quad (i = 1 \ldots m,\ j = 1 \ldots n) \quad (5)$$

(constants a_{ij}, b_i, B_i define resource functions and requirements in the form (1), (2) or (3); square brackets mean that requirements and priorities are not obligatory and some functions can be just efficiency indicators).

A generic linear resource planning problem – to find the resource allocation vector $\boldsymbol{x} = (x_1 \ldots x_n)$ producing the values of functions in (5) which are considered by the expert as feasible and the most efficient for a given situation □.

◊ The informal problem formulation is oriented to the computational experiment and significantly expands the practical applicability. An expert can change the system (1.5) at any step, try to solve a particular formal problem, and compare solutions [10, 11] ◊.

1.3. Method of target displacement of solution

The method is developed for experts, who formulate and solve a generic linear resource planning problem using the special software [10]. By default, the software proposes the Chebyshev point as initial plan. If constraints in (5) are compatible, it provides equal reserves for the basis constraints; if not, it minimizes the maximum deficit:

$$min_x\ max_i\ (a_{i1}x_i + \ldots + a_{in}x_n - b_i);$$
$$x_j \geq 0\ (i = 1 \ldots s,\ j = 1 \ldots n),$$

(s - amount of constraints after transformation of requirements from (5) to the form $\boldsymbol{Ax} \leq \boldsymbol{b}$, $\boldsymbol{x} \geq \boldsymbol{0}$).

Then, at each step an expert assesses the values of functions, their feasibility and effectiveness. On the base of assessment, the current plan can be chosen as the final one, or the change requirements can be specified in the form (1), (2), (3) or (4). The requirements direct a displacement of the plan. Any plan can be stored in the database for comparative analysis and going back.

If $\boldsymbol{x^0} = (x^0_1 \ldots x^0_n)$ $(x^0_j \geq 0, j = 1 \ldots n)$ is a current solution (received on the previous step), and an expert has defined the orienting requirement for displacement from $\boldsymbol{x^0}$ to a target point $\boldsymbol{x} = (x_1 \ldots x_n)$ $(x_j \geq 0, j = 1 \ldots n)$:

$$\{f_i(\boldsymbol{x}) = f_i(\boldsymbol{x^0}) + h_i\ [\leftarrow p_i]\},$$

where $f_i(\boldsymbol{x}) = a_{i1}x_1 + \ldots + a_{in}x_n$, $i = 1 \ldots k$; $0 < p_i$, $h_i \neq 0$,

then the candidate to the better solution is

$$\boldsymbol{x} = (x_1^0 + \textstyle\sum_i p_i \triangle_i x_1 / \sum_i p_i\ \ldots\ x_n^0 + \sum_i p_i \triangle_i x_n / \sum_i p_i),$$

where $\triangle_i x_j = a_{ij}h_i / (a_{i1}^2 + \ldots + a_{in}^2)$, $j = 1 \ldots n$, $i = 1 \ldots k$.

It can be said that such solution is “closer” to the hyperplanes which define the requirements with higher priorities. The detailed algorithm is described in [10].

1.4. Situational cost planning for hierarchical system

The budgeting is very specific problem of the situational planning. The planned income depends on volume of sales, prices and other economic factors. The earlier the forecast is made, the less reason to present the result as a point, i.e. one number. However, even on the state level expenses are planned on the base of exact income predictions and expenditures requests. The plan also consists of exact numbers. That's why the budget sequestrations take place [10, 11].

The budgeting problem should be considered as specialization of *situational cost planning* problem for an arbitrary resource. A resource stock and the requests for it are specified as numeric segments. A plan consists of numeric segments also. Initially, the cost planning problem is solved for the top level of expense items. Then, if an expense item is detailed, a part of the resource allocated to the item is to be distributed between the detailing items, that is the particular cost planning problem is to be solved, etc. The priorities (weighting coefficients) can be set for expense items and used or ignored for each particular cost planning problem in the hierarchy.

The problem has the following statement.

□ Given the numeric segments $[a, A]$ ($a \geq 0$, $A > 0$, a is minimal and A is maximal estimated amount of the resource), $[b_i, B_i]$ ($b_i \geq 0$, $B_i > 0$, $i = 1...n$, b_i and B_i are minimal and maximal resource requests for the i-th expense item), and the requests priorities $p_i > 0$ ($i = 1...n$): a cost plan $[x_i, X_i]$
$\{0 \leq x_i \leq b_i, X_i \leq B_i, i = 1...n\}$ is to be found, which estimated by an expert as the feasible and the most effective for the given situation.

Considering the existence of resource deficit for the requests left boundaries sum and the right boundaries sum, we have one of the further conditions.

- $\{ \Sigma_i b_i > a, \Sigma_i B_i > A, i = 1...n\}$

Here *the left boundaries problem*, and subsequently *the right boundaries problem* are to be solved.

- $\{ \Sigma_i b_i \leq a, \Sigma_i B_i > A, i = 1...n \}$

Here the minimal requests are simply assigned to the left boundaries ($x_i = b_i$), and the right boundaries problem is to be solved.

- $\{ \Sigma_i b_i > a, \Sigma_i B_i \leq A, i = 1...n \}$

Here the left boundaries problem is to be solved, and the maximal requests are simply assigned to the right boundaries ($X_i = B_i$).

- $\{ \Sigma_i b_i \leq a, \Sigma_i B_i \leq A, i = 1...n \}$: here the problem is trivial – all the requests can be fulfilled: $x_i = b_i, X_i = B_i$.

To solve the left boundaries problem, the mandatory requirements are

$$\Sigma_i x_i = a, i = 1...n,$$

and the orienting ones are

$$x_i / x_j = p_i b_i / (p_j b_j) \text{ for } 1 \leq i \leq n, 1 \leq j \leq n$$
$$\text{if } b_j > 0 \text{ (if } b_j = 0\text{, then } x_j = 0).$$

To solve the right boundaries problem, the mandatory requirements are

$$\Sigma_i X_i = A, i = 1...n,$$

and the orienting ones are

$$(X_i - x_i) / (X_j - x_j) = p_i(B_i - b_i) / (p_j(B_j - b_j))$$
$$\text{for } 1 \leq i \leq n, 1 \leq j \leq n \text{ if } \{B_i > b_i, B_j > b_j\},$$
$$X_i / x_j = p_i B_i / (p_j B_j) \text{ for } 1 \leq i \leq n, 1 \leq j \leq n$$
$$\text{if } \{B_i = b_i, B_j = b_j\}. \;\square$$

The algorithms to solve the left and right boundaries problems can be found in [11].

In the course of the plan implementation, an expert step-by-step clarifies the input data and calculates the more accurate plan. This approach cardinally enhances a probability to stay within the budget.

2. Results and analysis

The technology of situational resource planning and management is based on the experts interaction with the online services based on digital twins:

1. Monitoring of the managed system
2. Forming portraits of situations
3. Analysis and assessment of situations
4. Forming the system of mandatory and orienting requirements

5. Formulation of a situationally defined planning problem

6. Calculation of a plan variants

7. Choosing the best plan

8. Implementation of the plan

The possibility of simultaneous work of a group of experts is provided. The decision maker chooses the plan for implementation, taking into account the recommendations of the expert (or the group of experts).

For different examples of resource allocation problem, a comparison was made between the method of target displacement solution, implemented in the "Resource-Complex" software system, with LP methods implemented in the well-known LINGO software system [10]. The comparison has confirmed the broader possibilities of the method of target displacement of the solution. The advantage was particularly noticeable in situations where the system of constraints is incompatible and the search for solution is complicated by dynamic changes in the forecasted data.

2.1. Situational managament of electricity generation

Perspective application of the target displacement of solution method was developed in [20, 21]. It is intended to improve the managament quality under a changing awareness of the object state in the nodes of electrical network of power system.

Let presume that self-learning digital twins are functioning on the servers in the nodes of the network system. They are designed for modeling the distribution of flows along arcs, the economic characteristics of generating nodes, etc. Digital twins are used in the forming and analysis of situation portraits, the forming of systems of mandatory and orienting requirements, the evaluation of solutions.

The considered network system includes G generating and S consuming nodes connected by L arcs. In accordance with physical and technological characteristics of the system (with a fixed network structure and set of the generating equipment), the electricity streams moving along the network arcs

$$y_i = \Sigma_g\, a_{ig}\, x_g + \Sigma_s\, b_{is}\, z_s \ (i = 1...L)$$

linearly depend on the quantity x_g of generated electricity ($c_g \le x_g \le C_g$, $g = 1...G$, c_g, C_g – the smallest and the largest allowable values for the set of the generating equipment operating at the node g) and the predicted quantity z_s of the consumed electricity ($d_s \le z_s \le D_s$, $s = 1...S$, d_s, D_s – the smallest and the largest values for the quantity consumed in the node s). The formulation and solution for the problem of finding the coefficients a_{ig}, b_{is} ($i = 1…L$, $g = 1…G$, $s = 1…S$), based on the measurement results, were proposed in [20].

A set of requirements reflecting the capacity limitations for each i-th arc:

$$\{0 \le \Sigma_g\, a_{ig}\, x_g + \Sigma_s\, b_{is}\, z_s \le Y_i,\ i = 1...L;\ c_g \le x_g \le C_g,\ g = 1...G;\ d_s \le z_s \le D_s,\ s = 1...S\},\ (6)$$

where Y_i – the largest allowable value for the stream along i-th arc.

A set of balance requirements in each g-th generating node, to which m_g arcs adjoins:

$$\{ -\delta_g \le x_g - \Sigma_r\,(\Sigma_g\, a_{rg}\, x_g + \Sigma s\, b_{rs}\, z_s) \le \delta_g\ [\leftarrow p_g],\ r = 1...m_g;\ c_g \le x_g \le C_g,\ g = 1...G;\ d_s \le z_s \le D_s,\ s = 1...S;\ 0 < p_g \le \infty \},\ (7)$$

where δ_g – is the allowable (for technological reasons) value of the balance error in the node g;
p_g – the optional priority of the requirement for the g-th generating node.

A set of balance requirements in each s-th consuming node, to which m_s arcs adjoins:

$$\{ -\delta_s \le \Sigma_p\,(\Sigma_g\, a_{pg}\, x_g + \Sigma_s\, b_{ps}\, z_s) - z_s \le \delta_s\ [\leftarrow p_s],\ p = 1…m_s;\ c_g \le x_g \le C_g,\ g = 1...G;\ d_s \le z_s \le D_s,\ s = 1...S;\ 0 < p_s \le \infty \},\ (8)$$

where δ_s – is the allowable (for technological reasons) value of the balance error in the node s;
p_s – the optional priority of the requirement for the s-th consuming node.

◊ The cost of generation q_g at each g-th node is controlled by the digital twin. In each planning period, on the basis of measurement data, the digital twin calculates the dependence of cost on workload and presents it as a linear function used to form economic indicator of the quality of the generating node functioning:

$$q_g\,(x_g) = q_g{}^* + k_g\, x_g\ (c_g \le x_g \le C_g,\ g = 1…G),$$

where c_g, C_g – the smallest and the largest allowable values for the set of the generating equipment operating at the node g in the planning period; q_g^* – cost component independent of the node workload. ◊

□ *The problem of reducing the total cost of electricity generation and delivery* is to find a vector of workloads allocation $\mathbf{x} = (x_1, x_2 \dots x_G)$ ($c_g \le x_g \le C_g$, $g = 1...G$, c_g, C_g – the smallest and the largest allowable values for the set of the generating equipment operating at the node g), providing the lowest total costs

$$Q(\mathbf{x}) = \Sigma_g\, q_g(x_g) + \Sigma_i\, q_i\, \Sigma_g\, a_{ig}\, x_g\ [\leftarrow p_Q]$$

($g = 1...G$, $i = 1…L$; q_i is the cost of delivery of electricity unit along the i-th arc, controlled by a digital twin; p_Q is the optional priority of requirement to reduce total cost), while satisfying the requirements (6) - (8). □

2.2. Situational online cost planning

The online service "Cost Planning"[4] is intended to improve hierarchical budgeting quality and can be applied for budgets of any scale.

Its distinctive feature is that users specify numeric segments (not exact sums) for expected income and each expense item, since most of these values can not be predicted exactly. Any expense item can be detailed, and the resource is distributed hierarchically [11]. Important features are optional usage of the items weighting coefficients (priorities), ability to specify applied data precision for any table of expense items, and no limit of detail levels. The calculated budget plan is presented by numeric segments also. During implementation of the plan, users clarify data and calculate the more precise budget. Thus, if user sets the numerical segments cautiously and carries out the plan, the budget will not be violated.

3. Conclusions

1. The definition of a new class of *situationally definable problems of planning* is proposed.

2. The technolology for solving situationally definable linear problems of expert resource planning is designed to find solutions, considering information incompleteness, the dynamically changing object awareness, conditions of the object functioning and the goals of the decision makers. An important role belongs to the experts that assess *portraits of situations*, form *the systems of mandatory and orienting requirements* and evaluate the quality of the plan.

3. The technology is designed for implementation in the *online services operating in the environment of digital twins*.

4. The expediency of applying *the method of target displacement of solution* to the linear problems of expert resource planning, including modeling the distribution of flows and *situational planning of electricity generation*, is substantiated. The method is important practical supplement to classic methods for resource planning linear problems. It allows finding realizable solutions (in particular, for incompatible systems of constraints) and increasing the control quality.

5. *Situational cost planning for hierarchical system* is implemented in the active online service which significantly improves the quality of budget planning.

[4] Ilyin A. V. 2019. Resource Planning Online Services. Available at: https://www.res-plan.com/home (accessed August 5, 2019).

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