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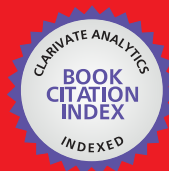
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Probabilistic Modeling, Estimation and Control for CALS Organization-Technical-Economic Systems

Igor Sinitsyn and Anatoly Shalamov

Abstract

Theoretical propositions of new probabilistic methodology of analysis, modeling, estimation and control in stochastic organizational-technical-economic systems (OTES) based on stochastic CALS informational technologies are considered. Stochastic integrated logistic support (ILS) of OTES modeling life cycle (LC), stochastic optimal of current state estimation in stochastic media defined by internal and external noises (including specially organized OTES-NS (noise support) and stochastic OTES optimal control) according to social-technical-economic-support criteria in real time by informational-analytical tools (IAT) of global type are presented. OTES-CALS are nonlinear and continuous-discrete. So we use approximate methods of normal approximation of probabilistic densities both for modeling and estimation. Spectrum of possibilities may be broaden by solving problems of OTES-CALS integration for existing markets of finances, goods and services. Analytical modeling, analysis, parametric optimization and optimal stochastic processes regulation in limits of illustrate some technologies and IAT given plans.

Keywords: continuous acquisition logic support (CALS), estimation control, planning and management technologies, modeling and analysis technologies, organizational-technical-economic systems (OTES), stochastic systems (StS)

1. Introduction

Probabilistic foundations of one of the modern directions in the field of after sale product service—integrated logistic support (ILS) are systematically treated. Stochastic continuous acquisition logic support (CALS) is the basis of ILS functioning in the presence of noises and stochastic factors in organizational-technical-economic systems (OTES). While spelling this chapter we firstly tried to explain reader the new approaches for creation informational technologies (IT) of modeling, optimal data processing in stochastic systems (StS) for high-quality manufacturing products (MP). Secondly, we consider optimization problems for complex of enterprises being part of virtual enterprise (VE).[1] In broad sense VE

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[1] Virtual enterprise is such an enterprise that consolidates geographically separated economical subjects and interact in the process mutual production using chiefly electronic communicational means.

presents geographically distributed OTES whose consolidated budget at fixed time period is divided between two basic structure types of VE. First structure is responsible for MP creation and production with given functional and exploitational-technical qualities.[2] Second structure is responsible for professional quality and staff life quality (professional skills, medical services, etc.). In this case OTES criteria for complex optimal OTES control[3] are defined by the social-technical-economic efficiency indicators. Such indicators depends on the resources costs at required quality of basic processes in both structures during life cycle (LC).

Besides standard ILS problems solving by such OTES systems modern IT provides deep OTES integration in general structures of local and global markets of finances, goods and services (FGS).

New approaches for OTES control are based on the probabilistic methodology for analytical modeling of stochastic processes coming from stochastic nature of internal and external noises. Special attention is paid to stochastic noises generated by injurious OTES-NS (noise supplier).

In the modern ILS models and strategies ERP (enterprise resource planning) and MRP2 (manufacturing resource planning) only statically deterministic mathematics is used for solving planning problems. Unlike the existing methodology the suggested stochastic methodology firstly takes into account stochastic optimal planning processes dynamics and secondly performs current operative control using modern methods of stochastic analysis, modeling and estimation (filtering, for casting, identification, etc.) and control methods and technologies [1–4]. It gives opportunity to raise the level and the quality of OTES control by means of informational-analytical tools (IAT). There tools are being global control VE net based on CALS principles and technologies. Stochastic imitational models and complex imitational models give the opportunity to estimate the accuracy of analytical models and solve problems of optimal data processing and control in high dimensional and fast OTES-CALS.

Stochastic CALS methodology was firstly developed in [5] for modeling and analysis. Let us consider the development the stochastic estimation and control problems. We hope that these approaches will be useful for probabilistic systems engineering [6].

2. CALS technologies and OTES

According to contemporary notions in broad sense ILS being the CALS basis represents the system of scientific, design-project, organization-technical, manufactural and informational-management technologies, means and fractional measures during LC of high-quality MP for obtaining maximal required available level of quality and minimal product technical exploitational costs.

Contemporary ILS standards [7–12] being CALS vanguard methodology not in the right measure answer necessary purposes. CALS standard, have as debatable achievements and the following essential shortcomings:

- informational-technical-economic models being not dynamical;

- integrated data base (DB) for analysis of logistic support (ALS) is super plus on one hand and on the other hand does not contain information necessary for

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[2] Functional product quality means how technical MP answers the functional purpose, exploitation, maintenance and repair. Exploitational-technical quality of MP is defined as adjustment to control, support and restoration during MP lifetime.

[3] OTES control is being business process management (BPM).
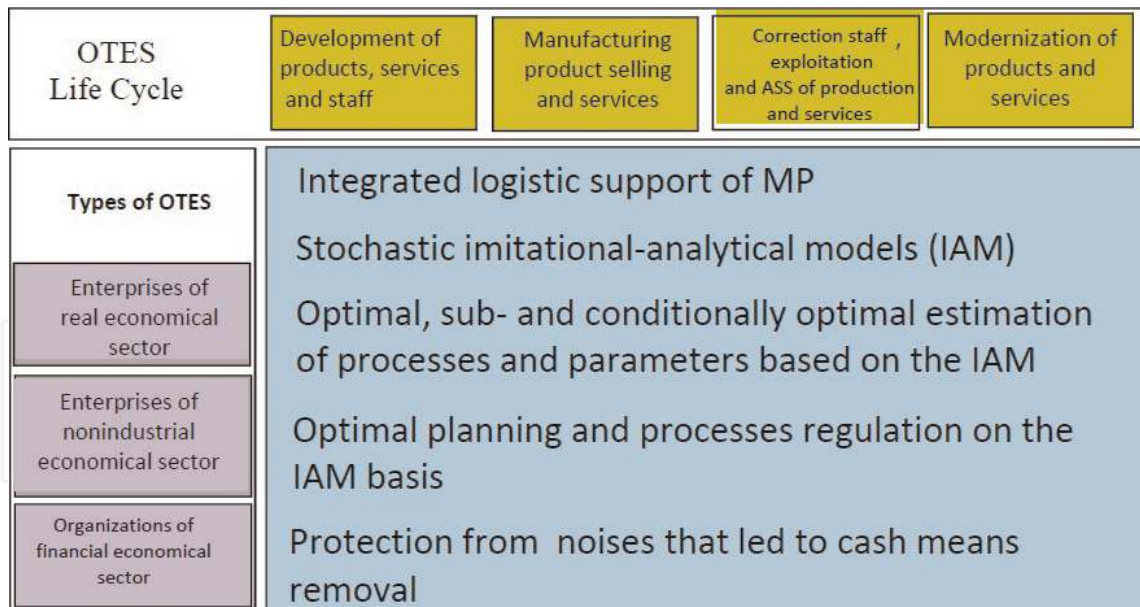
Figure 1.
Integrated modeling, estimation and control technologies for cost life cycle control in after sale support (ASS) systems.

complex through cost life cycle (CLC) estimation according to modern decision support algorithms;

- computational algorithms for various LC stages are simplified and do not permit forecasting with necessary accuracy and perform optimal control at conditions of internal and external noises and stochastic factors.

So ILS standards do not provide the whole realization of advantages for modern and perspective IT including staff structure in the field of stochastic modeling and control of two interconnected spheres: techno-sphere (technics and technologies) and social ones. These systems form the new the system class: OTES-CALS systems. Such systems destined for the production and realization of various services including staff structure, engineering and other categorical works providing exploitation, after sales MP support and repair, staff, medical, economical and financial support of all processes. New developed approach is based on the new stochastic modeling and control IT (**Figure 1**). These technologies are based on generalized social-technical-economic efficiency indicators for LC processes in comparison with usual CALS standards.

Research and control object in OTES are processes total LC of homogeneous sets of MP and resources. Special attention is paid to staff as object of professional training, improvement and medical service.

3. Probabilistic modeling and analysis

3.1 Basic elements of OTES stochastic modeling

According to [13, 14] we introduce composite elements (CE) as OTES with the following elements: (1) basic technical means (TM) and TM being part of serving equipment; (2) staff. For creation unique stochastic model of interoperable OTES processes it necessary to define the data set forecasting CLC indicators at given period of exploitation. This set of indicators includes: (1) coefficient of CE performance at planning for given period of exploitation; (2) level of professional and

medical readiness; (3) investment readiness. Analogously the technical resources corresponding values of professional, staff health and investment resources are defined. Informational-analytical tools (IAT) perform probabilistic analytical modeling of OTES technical means for after sales servicing (ASS).

Solving problems:

1. initial data forming;

2. modeling technical means and exploitation processes;

3. modeling streams of plan works;

4. modeling streams of non-plan works;

5. modeling streams of TM written off CP after random fault when we have exceeding of fixed number of repairs and/or reaching given resource;

6. modeling spare parts (SP) accumulation processes on stores;

7. modeling of SP delivery processes from stores into exploitation system;

8. cost modeling of after sales CP supply at given period of TM exploitation according payments items;

9. forming total cost model of TM after sale processes for whole CP list at given period of exploitation and providing given level of TM park.

In addition it is possible to give analogous list of problems for modeling staff and medical services.

### 3.2 Structural schemes of state change streams

State graph of TM, graph of equipment infrastructure and state staff graph are the basis of stochastic OTES-CALS model. For example, let us consider (**Figure 2**) basic CP state graph. This graph is constructed in accordance with basic LC processes for TM and OTES infrastructure for each CP. Being CP in any states that corresponds the definite costs of various resources and the total production value. This production value must be the object of monitoring and statistical data processing for estimation of probability characteristics (means, probabilistic moments, distributions, etc.). For each CP being the part of aggregate with the help special technologies are sequentially aggregated for final product (FP).

Main modeling stage of usage and service processes consists in probabilistic forecast of main indicators final values: sum of production costs and technical readiness level for OTES-CALS technical means maintenance at given time period. Thus, graph (**Figure 2**) must be supplemented additional graph for calculating integrals cost values at this time period according to [14] recommendations.

Vertex of basic graph maps CP current LC states in two level operational capability:

1. CP is on the stock in amount $X_1(t)$;

2. CP service able exploiting in aggregate in amount of $X_2(t)$
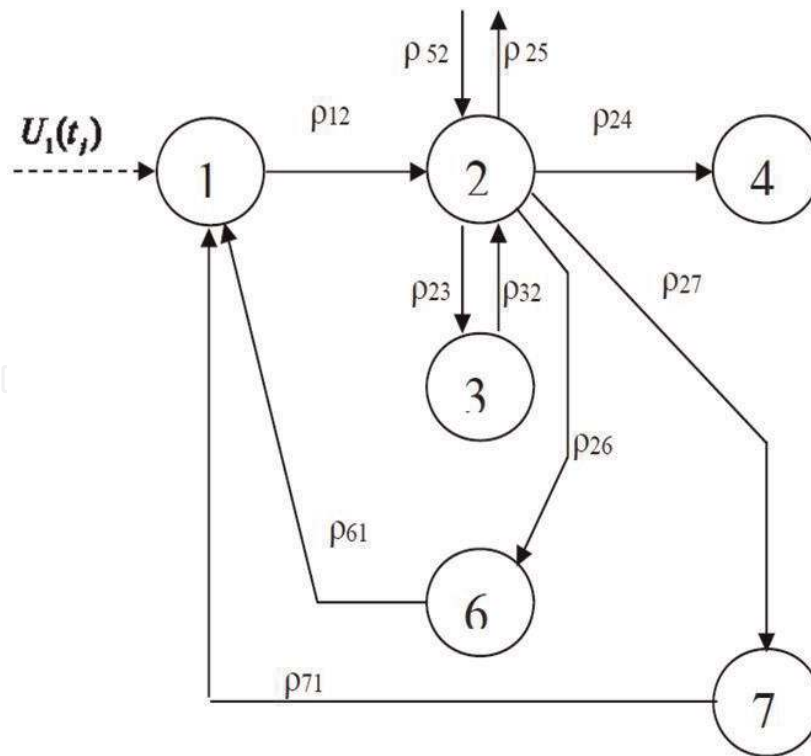
Figure 2.
Basic graph of TM state, professional level and staff health state.

3. CP is at user repair (first level) in amount $X_3(t)$;

4. CP is written off part and utilized in amount $X_4(t)$;

5. CP is at routine maintenance in amount $X_5(t)$;

6. CP is in factory repair (second level) at supplier in amount $X_6(t)$;

7. CP is in capital repairs at supplier in amount $X_7(t)$.

Graphs edges describe CP transition direction at states changes. Parameters $p_{ij}(t)$ are transition intensities from one state to another. Values $U_1(t_j)$ reflect the discrete filling process of the store by SP at time moments $t_j, j = 1, 2, ...$ for providing technical readiness of TM. In general case value and time moment of replenishment are random. These factors must be taken into consideration in LS for OTES-CALS model development. Basic graph of TM state, professional level of staff and health state are given on **Figure 2**.

The developed methodology is unique as for modeling TM and OTES-CALS dynamical staff potentials. Therefore, for constructing unique forecasting costs of staff potential the stochastic model it is necessary to apply developed integrated approach for description and modeling professional level personal health state [14, 15].

3.3 Stochastic processes and equations for OTES-CALS

Let us consider basic elements of stochastic OTES-CALS modeling and analysis using **Figure 3** for after sales maintenance support system.
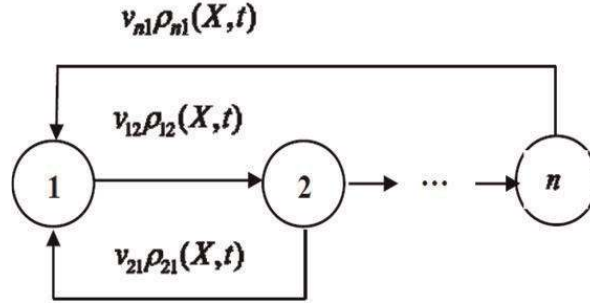
Figure 3.
General state graph for after sales maintenance support system.

Vertex of graph (**Figure 3**) corresponds 1, 2, ..., n states, where of the same type resource be. Let current amount of resources be $X_1(t)$, ..., $X_n(t)$, $X(t) = [X(t_1), ..., X(t_n)]^T$. Graphs edges corresponds transition of resources from state to state $h(k, h = 1, 2, ..., n, \ k \neq n)$ at random time moments forming Poisson streams transition events properly. Find some of resources states corresponding in queuing system for repeatedly recovery. General capacity is defined by the number of channels and being essentially nonlinear intensity[4] function depending on the amount of input resource units. This fact is mapped by $\rho_{kh}(X, t)$. In general case this nonlinear function has vector argument.

Stochastic equations and corresponding algorithms of analytical modeling for mathematical expectation $m = m(t)$, covariance matrix $\theta = \theta(t)$ and matrix of covariance functions $K(t_1, t_2)$ are as follows [5]:

$$dX = \varphi(X,t)dt + \int_{R_0^q} c(X, v, t)P(dv, dt) = \varphi(X,t)dt + \sum_{k,\ h=0}^{n} \int_{R_0^q} S_{kh}^T(v_{kh}, X, t)P(dv_{kh}, dt), \ X(t_0) = X_0,$$

(1)

$$\dot{m} = \mathrm{M}[\varphi(X,t) + S\rho], \ m(t_0) = m_0,$$
$$\dot{\theta} = \mathrm{M}\{[\varphi(X,t) + S\rho]X^{0T} + X^0[\varphi^T(X,t) + \rho^T S^T] + S\,\mathrm{diag}(\rho)S^T\}, \ \theta(t_0) = \theta_0,$$
$$\frac{\partial K(t_1, t_2)}{\partial t_2} = \mathrm{M}\{X_1^0[\varphi^T(X_2, t_2) + \rho^T(X_2, t_2)S^T]\}, K(t_1, t_1) = \theta(t_1).$$

(2)

Hence M is symbol of mathematical expectation; P is symbol of probabilistic measure; X and X^0 are noncentered and centered state vectors; $\varphi(X_t, t)$ is in general vector nonlinear function reflecting current value of OTES-CALS efficiency criterion; $S(v)$ structure matrix of Poisson streams of resources (production) with values v according to state graph; $S_u(v) = \left[s_{uk1}(v_{uk})...s_{ukn_g}(v_{uk})\right]$ is u-row of matrix $S(v)$; ρ is the intensity vector.

Forming the structure matrix $S = [S_{kh}]$ for OTES-CALS (**Figure 2**) is shown in **Table 1**.

Column 1. Transition direction in system graph. Total amount of rows is equal to amount transitions—m; amount of columns is equal to states amounts—n (graph vertex); two servicing columns: first and $n + 2$.

Column 2—$n + 1$. Values of intensities of transition—ρ_{kh}.

So columns from 2 till $n + 1$ presents $m \times n$ matrix S and column under number $(n + 2)$ is m dimensional vector with intensity vector ρ.

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[4] Stream of random events intensity is being mean number of events per time unit.

Transitions 1	2	3	4	5	...	n+1	n+2
$k \to h$	s_{kh1}	s_{kh2}	s_{kh3}	$s_{kh\eta}$	...	s_{khn}	ρ_{kh}
$1 \to 2$	$-v_{12}$	v_{12}	0	0	...	0	ρ_{12}
$1 \to 3$	$-v_{13}$	0	v_{13}	0	...	0	ρ_{13}
...	...	...	...	...	...	...	...
$1 \to \eta$	$-v_{1\eta}$	0	0	$v_{1\eta}$	...	0	$\rho_{1\eta}$
...	...	...	...	...	...	...	...
$2 \to 1$	v_{21}	$-v_{21}$	0	0	...	0	ρ_{21}
$2 \to 3$	0	v_{23}	$-v_{23}$	0	...	0	ρ_{23}
...	...	...	...	...	...	...	...

Table 1.
Forming the structure matrix S.

Equation (2) are approximate and valid at conditions of normal (Gaussian) approximation method. For raising the accuracy of analytical modeling and analysis methods of probabilistic distributions (moments, semi-invariants, coefficients of orthogonal expansions of densities) [2, 3] may be used.

The developed ordinary differential equations with initial conditions may be used for basic risk problems of systems engineering [6].

3.4 Modeling and analysis of aircraft vehicles park life cycle

Following [16] let us consider informational-analytical tools (IAT) for aircraft vehicle park modeling and control by technical-economic efficiency criteria after sales maintenance products (ASMP).

IAT modular includes:

- normative data base (DB) of passported aggregates;

- operative DB;

- forecasting processes block for ASMP;

- optimization block of delivery programs (annual application);

- catalog of codified items supply.

3.4.1 Normative DB (NDB)

According to contract supplier creates NDB according to standards DEFSTAN 00-600, S1000D, S2000 M and specifications S1000D, S2000 M. For IAT acceleration there are designed emulated DB (DBE) in the form of additional tables. Information from NDB automatically comes into DBE. These data characterize:

- interrepair resource of final MP (FMP) and CP;

- mean duration of capital repair (CR) of FMP and CP;

- mean capacity of CR of FMP;

- tone between scheduled services of FMP and CP;

- mean duration of regulation works (RW) of FMP and CP;

- mean capacity of RW for FMP;

- fix resource (lifetime) of FMP and CP;

- fixed resource till first and next repair of FMP;

- CP price;

- MP mean time to first failure;

- mean capacity of MP operative repair (OR);

- mean duration of OR;

- mean capacity of overhaul repair (OHR);

- mean duration of OHR;

- sign of availability;

- CP maximum number of repairs;

- sign of repairing indication after fixed resource.

3.4.2 Data base monitoring

According to contract software tools as operative DB (ODB) is filling in accordance with corresponding instruction of annual planning.
For current application the following information is formed:

- planning time period;

- actual amount of FMP;

- amount of no repaired of FMP;

- amount of repaired FMP;

- amount of FMP being in capital repair (CR);

- required coefficient of good condition;

- CP mean annual planning lifetime;

- CP mean time to first failure;

- CP frequency of overhaul (OHR);

- mean capacity of regulation works (RW);

- mean cost of the first technical service;

- CP surplus in store.

3.4.3 Forecasting block of ASS processes

Corresponding software tools are described by mathematical model of park state changes amount of FMP and CP during fixed period of exploitation, material-technical technical service and types of repairs.

Output forecasting characteristics are the following:

- coefficient of technical readiness along the park for each CP (0…1);

- delivery cost of SP along CP parks;

- coefficient of technical readiness for FMP park;

- delivery cost of SP along FMP park;

- cost of ASS for LC cost estimation.

3.4.4 Optimization block for annual application

This software tool is destined for automatic work with delivery list SP for forming SP optimal program for any fixed time period of exploitation (including annual application) providing given level of technical readiness of FMP park at conditions of minimal purchasing price.

Structure of initial parameters includes:

- calculating reliability or exploitation for each CP;

- repairing system for each component (period, duration of works, etc.);

- service prices (repair and delivery);

- annual budget for CP repair and SP delivery;

- level of price escalation for planning time period;

- regular amount of FMP;

- CP real mean lifetime;

- amount of CP and FMP being in repair;

- planning time period (from 1 year to lifetime);

- planning annual lifetime FMP and CP;

- required level of technical readiness coefficient.

Among the cost parameters there are specified the following ones: annual budget, price of one CP, price of one CP repair. For each characteristic, annual escalation price coefficient is fixed.

Replenishment and repair programs are optimal if SP superplus on store are minimal. It is equivalent to cost supply minimum.

The received in computer experiments optimal programs are calculated for grant support of fixed level of readiness during exploitation time period at conditions of minimal sufficient budget which is determined in optimization process. In the case of the optimization delivery program at conditions of wittingly restricted budget the developed programs provide readiness level. This level is being maximally close to given value.

Let us demonstrate designed "Optimization SASS, Version 2.0" IAT for prognosis and optimization in various regimes. **Figures 4–6** corresponds search regime SP delivery program and repair capacity in years of planning time period for support fixed level of repair characteristic—0,75 (**Figures 4** and **5**) at minimally sufficient budget. As the result of optimal search program (**Table 2**) the following programs were obtained:
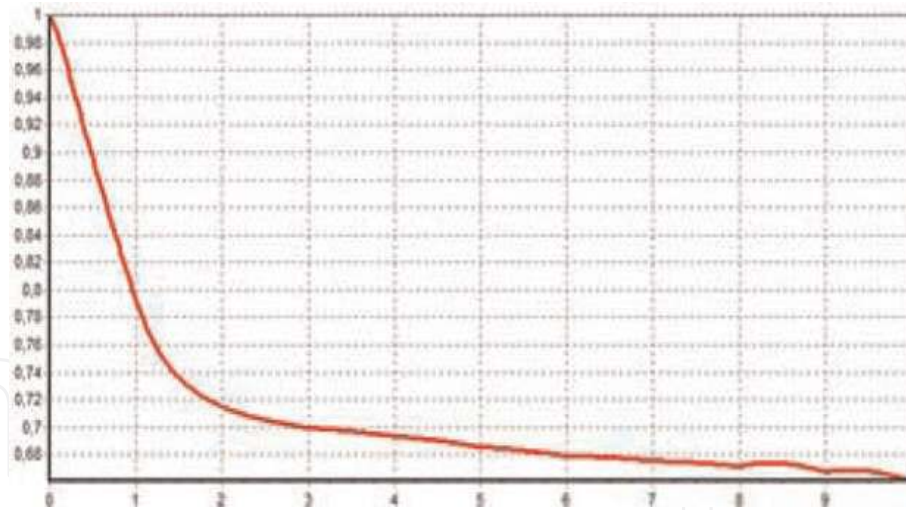
- for SP delivery (0, 0, 1, 3, 4, 5, 6, 6, 6) (in things);

- for CP repair capacity (21, 23, 23, 20, 20, 20, 20, 21, 22) (in years^{-1}).
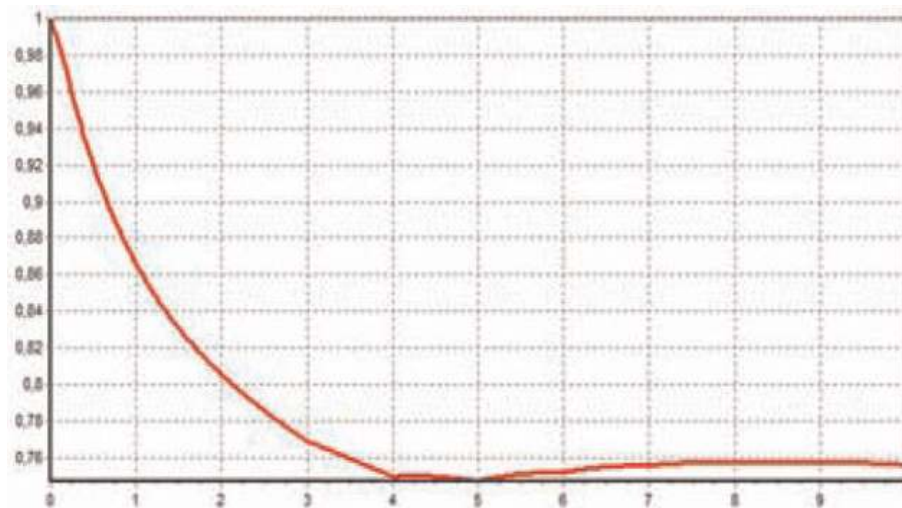
Figure 4.
Mean coefficient of serviceability (minimal adequate budget).
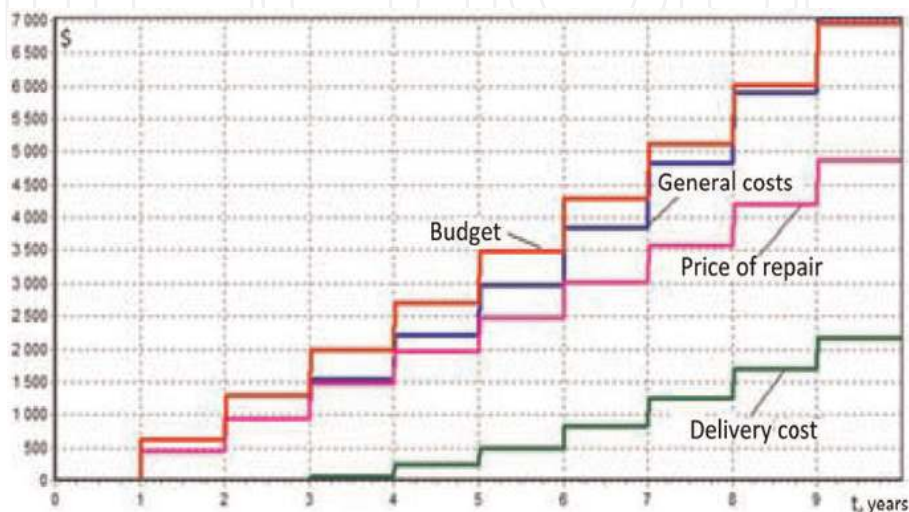
Figure 5.
Dynamics of costs and appropriations (minimal adequate budget).

Figure 6.
Mean coefficient of serviceability (wittingly restricted budget).

Year	1	2	3	4	5	6	7	8	9	The sum
Deliveries	0	0	1	3	4	5	6	6	6	
Price of CP	52,5	55,125	57,8813	60.7753	63,8141	67,0048	70,355	73,8728	77,5664	
Delivery cost	0	0	67,8813	182,3259	255,2563	325,0239	422,1301	443,2386	465,3985	2211,25263
Repair capacity	21	23	23	20	20	20	20	21	22	
Price of repair	441	507,15	532,5075	486,2025	510,5126	536,0383	562,8402	620,5313	682,5844	4929,36675
General costs	441	507,15	590,3888	668,5284	765,7689	871,0622	984,9703	1063,7679	1147,9829	7140,6194
Budget	630	661,5	694,575	729,3038	765,7689	804,0574	844,2603	886,4733	930,7969	6946,7355

Table 2.
*Optimization results (restricted budget wittingly).*

General costs for delivery and repair are equal to $7150 at total budget $6947. Dynamics of costs and appropriations are given on **Figure 5**. Evidently, maximal costs are being repair costs. The repair costs are economically sound at given price ratio. Repair coefficient full during 4 years of exploitation is explained by the fact that the maintenance of repair coefficient is unprofitable during period when its value exceeds given level. It is obvious that CP repair begins with outset of exploitation period but SP purchasing after 4 years of exploitation.

Figures 6 and **7** corresponds programs of search of delivery and repair at conditions of financial restrictions. In this case general delivery and costs do not exceed annual budget and also whole planning time period. But it is impossible to deduct repair coefficient at 0,75 level (**Figure 6**). Optimal programs at the level of repair coefficient equal to 0,66 for the end of time period are given on **Table 3**. In this case budget restrictions are valid. Therefore, we have the following programs:

• for SP delivery (0, 0, 1, 1, 2, 3, 2, 9, 14) (in things);

• for CP repair capacity (21, 23, 23, 19, 18, 18, 17, 2, 0) (years^{-1}).

General costs are approximately equal 5860 $ at total budget 5788 $. Optimal dynamics of delivery and repair costs are given on **Figure 7**.
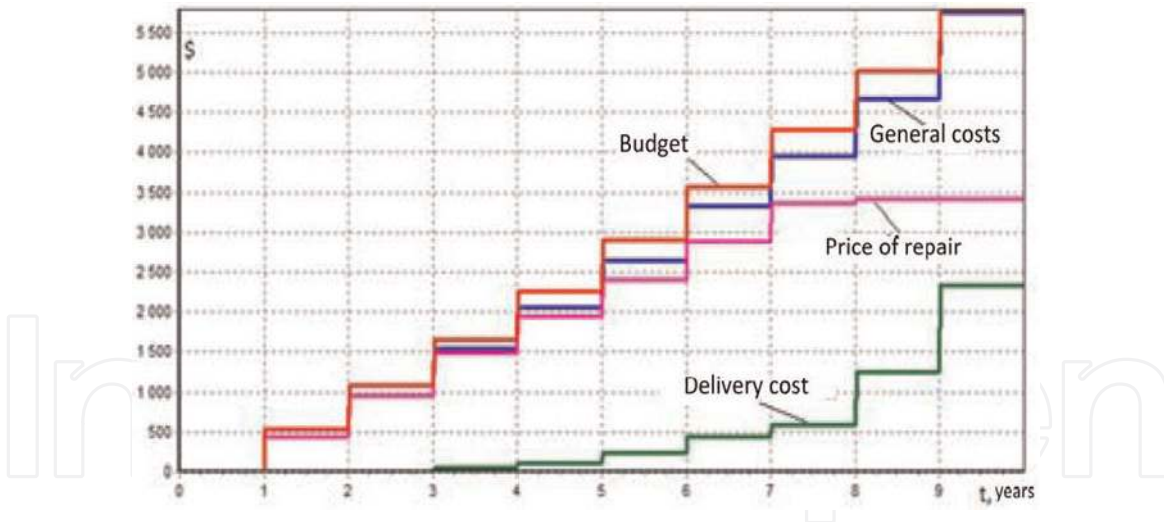
Figure 7.
Program of delivery and repair (restricted budget wittingly).

Year	1	2	3	4	5	6	7	8	9	The sum
Deliveries	0	0	1	1	2	3	2	9	14	
Price of CP	52,5	55,125	57,8813	60,7753	63,8141	67,0048	70,355	73,8728	77,5664	
Delivery cost	0	0	57,8813	60,7753	127,6282	201,0143	140,71	664,8549	1085,9298	2388,79381
Repair capacity	21	23	23	19	18	18	17	2	0	
Price of repair	441	507,15	532,5075	461,8924	459,4614	482,4344	478,4141	59,0982	0	3471,95803
General costs	441	507,15	590,3888	522,6677	587,0895	683,4488	619,1242	723,9532	1085,9298	5860,7518
Budget	525	551,25	578,8125	607,7531	638,1408	670,0478	703,5502	738,7277	775,6641	5788,9463

Table 3.
Optimization results (wittingly restricted budget).

4. Probabilistic optimal estimation and control

4.1 Optimal estimation

Nowadays such IT as filtering, extrapolation, identification, etc., are widely used in technical applications of complex systems functioning in stochastic media. These IT are based on statistical data analysis, modeling and estimation and gives only statistical estimates [2–4]. For OTES-CALS we have latent specially supported noises. Following [17–19, 22] let consider optimal filtering IT for special class of OTES using example 1.

Example 1. Let us consider typical OTES as system of after sales servicing (SASS). This system provides maintenance of technical readiness given level for MP park at quality conditions. Corresponding costs are fixed in bookkeeper documentation. Let us name it by "real" bookkeeper. In case of some types of noises it is possible to speak about "additional" bookkeeper. This bookkeeper is generated by fictional SASS for reserved taking out of the surplus of finances. On **Figure 8** the corresponding scheme is given where:

- SASS graph is given in upper part of **Figure 9**, number 1, 2, 3 being the following states: on store, in exploitation, in repair;

- "additional" graph of SASS generating noises ζ_i being fictitious analogs of $X_i(t)$ is given by dashed line in lower part of **Figure 8**;
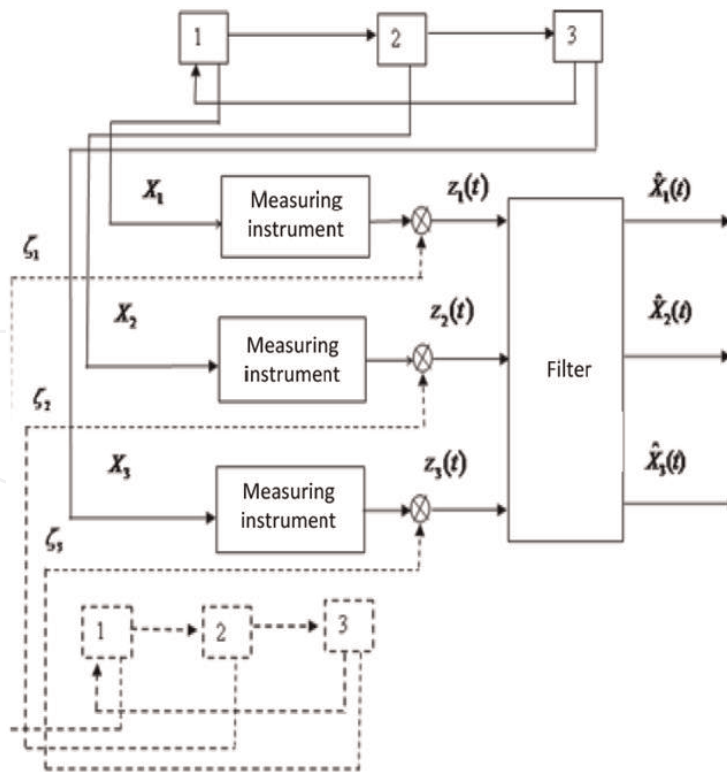
Figure 8.
Structure of stochastic SASS.
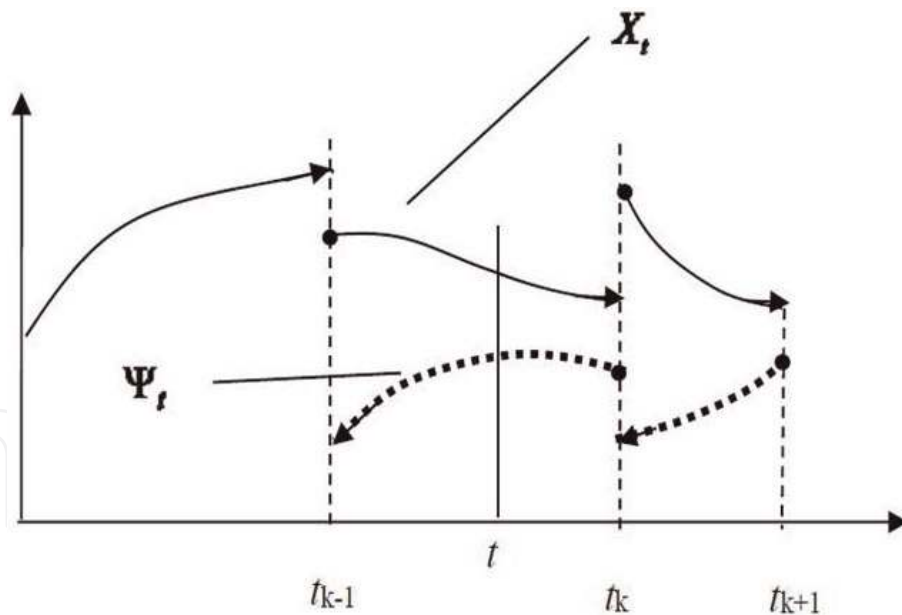
Figure 9.
Continuous discrete self-conjugated processes X_t and Ψ_t.

- in the middle part of **Figure 8** measuring observation devices are given; $z_i(t)$ measure parameters and processes on background noise ζ_i; $\hat{X}_i(t)$ being optimal estimates of real processes $X_i(t)$.

As it is known from [2–4] estimation technologies are based on: (1) model of OTES; (2) model OTES-OS (observation system); (3) model OTES-NS (noise support); (4) criteria and estimation methods; (5) filters (estimators) models.

It is required to develop it for the useful processes $X_i(t)$ filtration from its mixture with processes $\zeta_i(t)$ of system noise.

For solving this problem the linear Kalman filter is used [3, 4]. So we get the following result. Let complex stochastic models OTES, OTES-OS and OTES-NS are described by the following linear differential Equations:

$$\dot{X}_t = \overline{a}X_t + a_1 G_t + a_2 \zeta_t + a_0 + \chi_x V_\Omega, \tag{3}$$

$$\dot{G}_t = q(D_t)X_t + b_2 \zeta_t + \chi_g V_\Omega \tag{4}$$

$$\dot{D}_t = bX_t + \overline{b}_1 D_t + b_0 + \chi_d V_\Omega \tag{5}$$

$$\dot{\zeta}_t = \overline{c}_2 \zeta_t + c_0 + \chi_\zeta V_\Omega \tag{6}$$

Hence X_t, G_t, D_t, ζ_t are OTES, OTES-OS and OTES-NS; $q(D_t)$ is amplification factor of measurement block depending on number of resources in OTES-OS; $V_\Omega(t) = \begin{bmatrix} V_x^T(t) & V_g^T(t) & V_\zeta^T(t) & V_u^T(t) \end{bmatrix}^T$ is composite noise vector of white noises; $\chi_x, \chi_g, \chi_d, \chi_\zeta$ are matrices of corresponding dimensions. Then equation for optimal linear Kalman filter at $q(D_t) = q_t$ will be

$$\dot{\hat{X}}_t = \overline{a}\hat{X}_t + a_1 G_t + a_2 \zeta_t + a_0 + R_t q_t^T v_g^{-1}\big[Z_t - \big(q_t \hat{X}_t + b_2 \zeta_t\big)\big] \tag{7}$$

where v_g is the matrix of white noise intensities of internal noises OTES-OS and external noises from OTES-NS; ζ_t is the noise in the form Poisson process in OTES-NS; R_t is the solution of the following Riccati Equation:

$$\dot{R}_t = \overline{a}R_t + R_t \overline{a}^T + v_x - R_t q_t^T v_g^{-1} q_t R_t \tag{8}$$

where v_x is vector internal OTES noises.

4.2 Optimal control

Modern OTES are class of large scale systems of microeconomics of special type corresponding to five technological structures. These systems satisfy modern standards but need further effective control systems based on stochastic system theory during the whole LC of OTES elements.

Effective control of OTES needs optimal technologies for solution of the following problems:

- planning stocks of various recourses on the basis of forecasting external and internal demand;

- planning necessary manufacturing capacity and product delivery system in accordance with expected demand;

- distribution of finished products;

- planning loading capacities for repair and service with long work time, etc.

In general, case functional organization and control for the definite processes in OTES we need to solve the following problems:

- design mathematical models of various variants of logistical systems;

- work out methods of optimal complex planning of such processes as delivery, production, marketing and transporting of finished products, etc.

At modern design practice logistical systems and in whole OTES of given destination and for functional control known standards MRP/ERP, DEFSTAN 00-600, MIL STD 1388 [7–12] are used. These standards are typical for relatively stable economics. Such approaches are rested upon deterministic consumer demands models and corresponding local optimization methods implemented only in isolated nodes of logistic and production chains but global OTES optimization. For this reason MRP/ERP approaches cannot permit optimal complex planning LC processes at given period of time with calculating boundaries of proper values. This problem is very important for customer corresponding to profit finances. Deterministic approaches are useful only at conditions of economics with stable state of markets. At stochastic conditions, it is necessary to use corresponding approaches and analysis and synthesis OTES informational technologies based on stochastic models and methods that permit to calculate optimal control strategy.

Control of OTES being the integrated net of enterprises includes: (1) processes planning in accordance with goals and criteria; (2) effective operational (situational) control. The first concerns program control, the second—state regulation. Program control principles are as following: orientation finite goal expressed by goal graph and corresponding efficiency indicators, working restrictions, though planning and order-continuous principle [20, 21].

Basic stages of program control are the following: (1) optimization of resources distribution between goals and frequency of financing; (2) priorities of program separate goals and achievement means; (3) adaptation of program goal to changing external conditions. For one type of production, program control includes planning and adaptive distribution general budget between OTES participants (net nodes) based on stochastic estimation of processes and parameters and adaptation to external processes (noises).

For the stochastic OTES control actions are as follows:

- streams intensity transition between nodes;

- parameters of probabilistic distributions values of resources parties or products which involve the intransitions;

- frequency and size of discrete supply at replenishment (works volume) at calendar services;

- mean capacity service personal.

Analysis of these control categories shows that first part of control functions is continuous. The second part is discrete time functions (supply plan, plan of resources service and products at calendar plan, etc.). So it is necessary to consider OTES as mixed continuous-discrete stochastic system (StS) and apply probabilistic stochastic methods and IT of analysis, modeling, estimation and control.

Let us consider the basis of OTES filtering.

4.2.1 Problem statement

At first let us consider deterministic multidimensional dynamical system described by the following nonlinear differential and difference equations [1, 5]:

$$\dot{X}_t = \xi(X_t, \pi_t, t), \tag{9}$$

$$X_k = B(X_{k-0}, U_k), X_k = X(t_k) \tag{10}$$

Here X_t is $n_x \times 1$ phase vector; X_{k-0} is the value of X_t precede t_k; π_t is the control vector in continuous time; ξ, B are continuously differentiable $n_x \times 1$ vector functions; t_0 and t_f is initial and terminal time moments; U_k is $n_u \times 1$ dimensional control vector at time moments $t_0 < t_1, t_2, ..., t_{N_k} \leq t \leq t_f$; X_0 is initial condition. We choose the following functional J which includes discrete and continuous components representing expenditure functioning and control:

$$J = \sum_{k=1}^{N_k} \Gamma(X_{k-0}, U_k) + \int_{t_0}^{t_f} K(X_t, \pi_t, t)dt + H(X_f) \tag{11}$$

where Γ, K, H are known scalar differentiable functions. It is required to define optimal functions of continuous and discrete control π_t and U_k jointly supply minimum for functional J: $J^* = \min_{\pi_t, U_k} \left\{ \sum_{k=1}^{N_k} \Gamma(X_{k-0}, U_k) + \int_{t_0}^{t_f} K(X_t, \pi_t, t)dt + H(X_f) \right\}$. Hence for optimal control functions we have: $(\pi_t^*, U_k^*) = \underset{\pi_t, U_k}{\arg\min} J$.

4.2.2 General solution

Let us find general solution by variational method [1]. For this purpose we compose mixed (from continuous and discrete functions) Lagrange functional (Lagrangian):

$$L = \int_{t_0}^{t_f} \left[K(X_t, \pi_t, t) + \left(\Psi_t^T \cdot X_t \right)' \right] dt + \sum_{k=1}^{N_k} \Gamma(X_{k-0}, U_k) + H(X_f). \tag{12}$$

where variable Ψ_t is vector indefinite Lagrange multiplier. Vectors variables Ψ_t and X_t have discontinuity of the first kind at $t = t_k$. At these times X_t is continuous on the right and being continuous on the left from the theory two-point boundary-value problem. We get Ψ_t (**Figure 9**) by integration of corresponding equations from t_f to t_0. So taking into account (9), (10) and considering integrand as generalized function of the following form:

$$\frac{d}{dt}\left(\Psi_t^T X_t\right) = \dot{\Psi}_t^T X_t + \Psi_t^T \dot{X}_t + \left[\left(\Psi_{k+0}^T X_k - \Psi_k^T X_{k-0}\right)\right]\delta(t - t_k) =$$
$$= \dot{\Psi}_t^T X_t + \Psi_t^T \xi(X_t, \pi_t, t) + \left\{\Psi_{k+0}^T [B(X_{k-0}, U_k)] - \Psi_k^T X_{k-0}\right)\delta(t - t_k). \tag{13}$$

After substitution (13) into (12) and using δ-function property we get new expression for functional L:

$$L = \int_{t_0}^{t_f} \Xi_t dt + \sum_{k=1}^{N_k} \Theta_k + H(X_f) = \int_{t_0}^{t_f} \left[K(X_t, \pi_t, t) + \dot{\Psi}_t^T X_t + \Psi_t^T \xi(X_t, \pi_t, t)\right] dt +$$
$$+ \sum_{k=1}^{N_k} \left\{\Gamma(X_{k-0}, U_k) + \Psi_{k+0}^T [B(X_{k-0}, U_k)] - \Psi_k^T X_{k-0}\right\} + H(X_f), \tag{14}$$

where

$$\Xi_t = K(X_t, \pi_t, t) + \dot{\Psi}_t^T X_t + \Psi_t^T \xi(X_t, \pi_t, t) \tag{15}$$

$$\Theta_k = \Gamma(X_{k-0}, U_k) + \Psi_{k+0}^T [B(X_{k-0}, U_k)] - \Psi_k^T X_{k-0} \tag{16}$$

From Lagrangian stationary conditions we have the following algorithms Ψ_t, Ψ_{k+0} from and π_t^*, U_k^*:

$$\frac{\partial L}{\partial X_t} = \frac{\partial \Xi_t}{\partial X_t} = \frac{\partial K(X_t, \pi_t, t)}{\partial X_t} + \frac{\partial \xi^T(X_t, \pi_t, t)}{\partial X_t} \Psi_t + \dot{\Psi}_t = 0 \tag{17}$$

$$\frac{\partial L}{\partial \pi_t} = \frac{\partial \Xi_t}{\partial \pi_t} = \frac{\partial K(X_t, \pi_t, t)}{\partial \pi_t} + \frac{\partial \xi^T(X_t, \pi_t, t)}{\partial \pi_t} \Psi_t = 0 \tag{18}$$

$$\frac{\partial L}{\partial U_k} = \frac{\partial \Theta_k}{\partial U_k} = \frac{\partial \Gamma(X_{k-0}, U_k)}{\partial U_k} + \frac{\partial [B^T(X_{k-0}, U_k)]}{\partial U_k} \Psi_{k+0} = 0 \tag{19}$$

$$\frac{\partial L}{\partial X_{k-0}} = \frac{\partial \Theta_k}{\partial X_{k-0}} = \frac{\partial \Gamma(X_{k-0}, U_k)}{\partial X_{k-0}} + \frac{\partial [B^T(X_{k-0}, U_k)]}{\partial X_{k-0}} \Psi_{k+0} - \Psi_k = 0 \tag{20}$$

$$\Psi(t_f) = \frac{\partial H}{\partial X_f} \tag{21}$$

Relations (17)–(21) are necessary optimal control conditions in given continuous-discrete problem. Thus two-point boundary value is described by closed set of Eqs. (9)–(14) and Eqs. (17)–(21). So from (17), (20) we get equations for Ψ_t, Ψ_{k+0} conjugated with X_t, X_{k-0}. From (18), (19) we get implicit forms for π_t^* and U_k^*.

4.2.3 Solution of linear-quadratic problem

Consider linear continuously-discrete system [1, 5]:

$$\dot{X}_t = \xi_x X_t + \xi_\pi \pi_t, \tag{22}$$

$$X_k = B_x X_{k-0} + B_u U_k, \tag{23}$$

where ξ_t, ξ_π are matrix coefficients of, $n_x \times n_x$ and $n_x \times n_\pi$ dimensions changing at $t = t_k$; B_x, B_u are matrices coefficients of $n_x \times n_x$ and $n_x \times n_u$ dimensions.

It is given quadratic efficiency criterion:

$$L = \int_{t_0}^{t_f} \Xi_t dt + \sum_{k=1}^{N_k} \Theta_k + \frac{1}{2} X_{t_f}^T H X_{t_f} = \int_{t_0}^{t_f} \left[\frac{1}{2} \left(X_t^T K_t X_t + \pi_t^T K_\pi \pi_t \right) + \dot{\Psi}_t^T X_t + \Psi_t^T (\xi_x X_t + \xi_\pi \pi_t) \right] dt +$$

$$+ \sum_{k=1}^{N_k} \left[\frac{1}{2} \left(X_{k-0}^T \Gamma_x X_{k-0} + U_k^T \Gamma_u U_k \right) + \Psi_{k+0}^T (B_x X_{k-0} + B_u U_k) - \Psi_k^T X_{k-0} \right] + \frac{1}{2} X_{t_f}^T H X_{t_f}, \tag{24}$$

where

$$\Xi_t = \frac{1}{2} \left(X_t^T K_x X_t + \pi_t^T K_\pi \pi_t \right) + \dot{\Psi}_t^T X_t + \Psi_t^T (\xi_x X_t + \xi_\pi \pi_t) \tag{25}$$

$$\Theta_k = \frac{1}{2}\left[X_{k-0}^T\Gamma_x X_{k-0} + U_k^T\Gamma_u U_k\right) + \Psi_{k+0}^T(B_x X_{k-0} + B_u U_k) - \Psi_k^T X_{k-0}\right] - \Psi_k^T X_{k-0},$$

$$(26)$$

K_x, Γ_x, H_{t_f} and K_π, Γ_u being positive semidefinite and positive defined matrices of corresponding dimension. It is required to find optimal algorithm control for linear system described by Eqs. (22)–(24). Algorithm of optimal design based state feedback control gives the followings equations:

$$\dot{\Psi}_t = -\xi_x^T\Psi_t - K_x X_t \tag{27}$$

$$\Psi_{t_f} = HX_{t_f} \tag{28}$$

$$\pi_t = -K_\pi^{-1}\xi_\pi^T\Psi_t \tag{29}$$

$$\Psi_k = B_x^T\Psi_{k+0} + \Gamma_x X_{k-0} \tag{30}$$

$$U_k = -\Gamma_u^{-1}B_u^T\Psi_{k+0} \tag{31}$$

Algorithm includes: (1) integration in inverse time with initial condition (28) of vector differential Eq. (27) and difference Eq. (30) with data storage in each step; (2) formulae (29), (31) for calculating controls with usage of stored Ψ_t, Ψ_{k+0}. Note that during Eq. (27) integration at time moments $t = t_k$, $k = N_f, N_{f-1}, \dots, 1$ step-wise changes Ψ_t occur according to Eq. (30).

For reducing two-point boundary problem to ordinary we apply known approach and perform linear change of variables in Eqs. (22)–(31):

$$\Psi_t = \tilde{R}_t X_t \tag{32}$$

$$\Psi_k = \tilde{R}_k X_{k-0} \tag{33}$$

$$\Psi_{k+0} = \tilde{R}_{k+0} X_k \tag{34}$$

where $\tilde{R}_t$, $\tilde{R}_{k+0}$ are values of coefficients matrices. These variables are the solutions of continuous and discrete Riccati. These equations are integrated in inverse time. So we get optimal solutions in interconnected continuous and discrete parts of OTES-CALS in the following forms:

$$\pi_t^* = -K_\pi^{-1}\xi_\pi^T\tilde{R}_t X_t, \tag{35}$$

$$U_k^* = -\Gamma_u^{-1}B_u^T\tilde{R}_{k+0}\left(I + B_u\Gamma_u^{-1}B_u^T\tilde{R}_{k+0}\right)^{-1}B_x X_{k-0}. \tag{36}$$

Expansions (35) and (36) define on-line regulator on the basis of known values of phase current vector X_t, X_{k-0} For linear system with quadratic criterion described by the following equations:

$$\dot{X}_t = \xi_x X_t + \xi_\pi\pi_t + \xi_{0t} \tag{37}$$

$$X_k = B_x X_{k-0} + B_u U_k, \tag{38}$$

the optimal control π_t^* is expressed by

$$\pi^* = -K_\pi^{-1}\xi_\pi^T\left(\tilde{R}_t X_t + \frac{1}{2}g_t\right) \tag{39}$$

$$\dot{g}_t = \left(\tilde{R}_t \xi_\pi K_\pi^{-1} \xi_\pi^T - \xi_x^T\right)g_t - 2\tilde{R}_t \xi_{0t}, g_{t_f} = 0 \qquad (40)$$

Here ξ_{0t} is constant term; formula for U_k^* remains similar.

Example 2. For illustration let us consider SASS (**Figure 10**) for the technological supply process by serviceable CP. On **Figure 10** graphs nodes corresponds CP states:

- CP being in usage stage with amount $X_{t1}9$;

- CP being in repair with amount X_{t2} (after usage);

- CP being draft out with amount X_{t3}.

It is evidently $X_{t3} = N_0 - (X_{t1} + X_{t2})$; ρ_{12}, ρ_{13} being intensity parameters of ordinary CP Poisson streams entering for repair and draft of; π_t being repair productivity. Time of CP filling up is equal to T.

It is required to determine optimal parameter π_t^* of restoration and optimal volumes $U_k^* = U^*(t_k), t_k = kT$ which gives minimum to quadratic functional being sum of expenditure costs:

$$L = \frac{\alpha}{2}\sum_{k=1}^{N} U_k^2 + \frac{\beta}{2}\int_{t_0}^{t_f} \pi^*(t)dt + \frac{\delta}{2}M\left[\left(m_1(t_f) - \gamma\right)^2\right] \qquad (41)$$

Here $\alpha, \beta, \gamma, \delta$ are parameters of functional; $m_1(t_f)$ are mathematical expectation of CP remainder at t_f ready for use; $\gamma = K_{T\Gamma}N_0$ mean number of aggregates ready for use; $K_{T\Gamma} \in [0,1]$ being coefficient of technical readiness; N_0 originate amount of CP.

Is possible to show that at $\varphi(X,t) = 0$ mathematical expectation of CP amount and at step-vise X_{1t} is defined by the following equations:

$$\dot{m}_{1t} = -\rho_{12}m_{1t} + \pi_t m_{2t}, \quad m_{1t}(0) = N_0, \quad \dot{m}_{2t} = -\rho_{12}m_{1t} - \pi_t m_{2t}, \quad m_{2t}(0) = 0, \quad (42)$$

$$m_{1,k} = m_{1,k=0} + U_{1k}. \qquad (43)$$

These mathematical expectations are continuous and discrete variables. This problem being nonlinear because control function π_t enters into the right hand of equations in the form of composition with function m_{2t} depending upon control. So it is necessary to use general problem statement Eqs. (9) and ((1) and expressions (17)–(21).

Let us denote.

$$\xi^T(X_t, \pi_t, t) = \left[-\rho_{12}m_{1t} + \pi_t m_{2t} \quad \rho_{12}m_{1t} - \pi_t m_{2t}\right] \qquad (44)$$
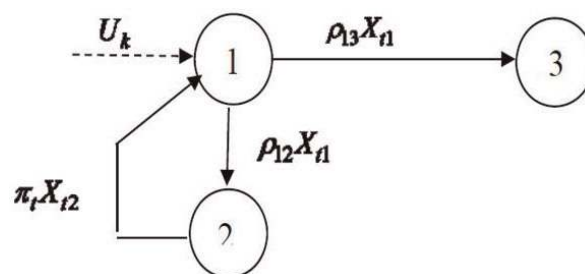
Figure 10.
System state graph.

For conjugated functions from Eqs. (17), (21) and (41) we get:

$$\dot{\psi}_{1t} = \rho_{12}\psi_{1t} - \pi_t\psi_{2t}, \quad \psi_{1t}(t_f) = \delta(m_{1t}(t_f) - \gamma), \quad \dot{\psi}_{2t} = -\rho_{12}\psi_{1t} + \pi_t\psi_{2t}, \quad \psi_{2t}(t_f) = 0. \tag{45}$$

Than from Eq. (19) follows $\psi_{1t,k+0} = \psi_{1t,k}$, $\psi_{2t,k+0} = \psi_{2t,k}$. So the conjugated variables ψ_{1t}, ψ_{2t} are continuous functions.

From Eqs. (18) and (19) we have the following expressions for optimal continuous and discrete controls

$$\pi^*(t) = \frac{1}{\beta}m_{2t}(\psi_2 - \psi_1), \tag{46}$$

$$U_k^*(t) = -\frac{1}{\alpha}\psi_{1,k+0}. \tag{47}$$

Taking into account that firstly $\pi^*(t)$ implicitly incoming into right hand of Eq. (42) and U_k^* secondly U_k^* and $\pi^*(t)$ implicitly connected between each other over $\psi_{1,k+0}$ such numerical methods as gradient method may be used [1, 23]. According to gradient method next $(i+1)$ iteration of $\pi^*(t)$ is calculated by $\pi^{i+1} = \pi^i - r\Delta^i$ where $\Delta^i = \beta\pi^i + m_{2t}(\psi_2 - \psi_1)$. Hence the recurrent iteration is calculated by the following expression:

$$\pi^{i+1} = \pi^i - r[\beta\pi^i + m_{2t}(\psi_2 - \psi_1)], \tag{48}$$

where r is chose from convergence and exactness condition.

Numerical results for m_{1t} and $\pi^*(t)$ are given o **Figure 11**, Values of jumps m_{1t} at $t_k = kT$, $k = 1, \dots, f$ corresponds to optimal values of deliveries U_k^*. Values of parameters are: $\rho_{12} = 0,7$ $\rho_{13} = 0,3$; $N_0 = 100$; $T = 0,5$; $t_f = 2$; $2\alpha = 0,5$; $2\beta = 0,1$; $2\delta_0 = 100$; $K_{TT} = 0,8$.

Two main conclusions follows from **Figure 11**:
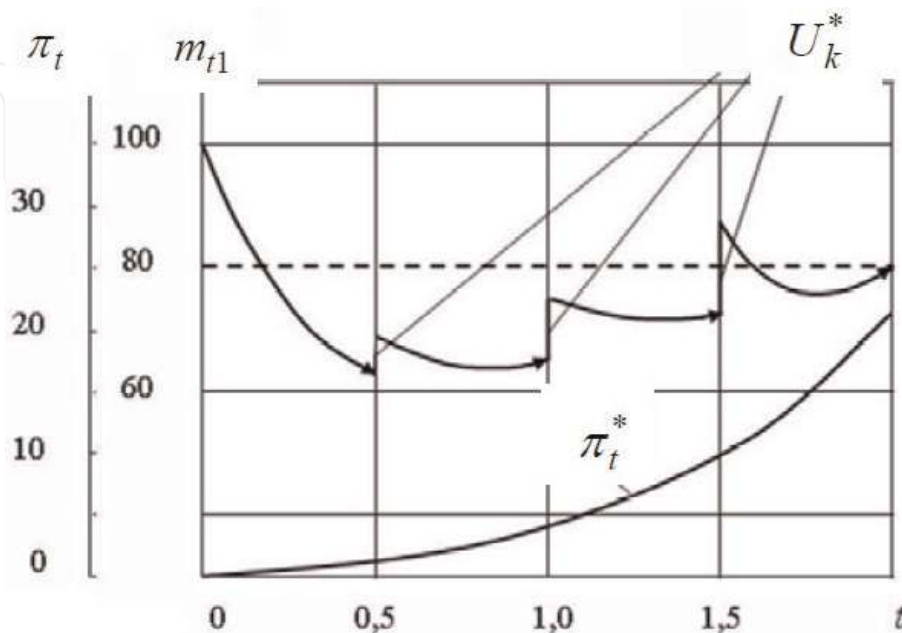
Figure 11.
Volumes U_k^* of delivery SP optimized jointly with repair capacity π_t^*.

- optimal nonstationary restoring politics U_k^* and restoring channel capacity goes to $\gamma = 80$ at the end $[t_0, t_f]$;

- values U_k^* are conjugated with π_t^*;

- by variation α, β we choose the cost parameters $\alpha + \beta = 1$ type of control depending on cost ratio.

Thus the described restoring politics for given level gives CP owners the opportunity to form separate repair net based on CP order (on supplier side).

Peculiarities of optimal control stochastic continuous-discrete systems with state feedback.

For the linear equations:

$$\dot{X}_t = \xi_x X_t + \xi_\pi \pi_t + \xi_{0t} + V_t, \tag{49}$$

$$X_k = B_x X_{k-0} + B_u U_k, \tag{50}$$

where V_t is internal noise being white noise (in strict sense) with known probabilistic characteristics acting in continuous channel; U_k is known discrete function depending on control using formulae for linear stochastic regulator synthesis for system (49) and (50) optimal control and separation theorem we come to the following basic algorithm. It includes two steps:

- optimal deterministic regulator design;

- calculation of optimal estimates $\hat{X}_t, \hat{X}_{k-0}$ of (49) and (50) phase vector which is observed in mixture with white noise and substitution into regulator formulae. Exact solution exists only for linear stochastic systems. Using method of normal approximation or statistical linearization [2–5] relatively to state vector it is possible to get the simple approximate algorithm.

4.3 Optimal planning and control

As it was already mentioned in Subsection 4.1 OTES-CALS includes complex through along LC on-line planning of processes with goals and objectives and given criteria. Program—object planning is the separate part of applied control theory of LS processes for complex high-technology products which ensure solving LS integration tasks enterprises-participants. We introduce virtual enterprise (VE) as a system developing according with given goals, objectives and programs. On-line realization of plans and programs occur in presence on one side internal noises due to control stochastic and on the other hand by external noises from third party and organizations.

Following [2–4, 23] let us consider optimal regulator for operative control. Within given framework program/plan for OTES-CALS as VE functioning in stochastic media using social-technical-economic effectiveness criteria. We use probability filtering theory based on Kalman and Pugachev filters [2–4]. Optimal stochastic regulator (**Figure 12**) is designed on the basis of the partition theorem. So at first it is necessary to design optimal regulator and then filter for reducing noises.

Using Kalman filtering theory [2–4] for linear continuous-discrete OTES-CALS we get the following equations for stochastic optimal continuous-discrete regulator:

Filter equations

$$\dot{\hat{X}}_t = \overline{a}\hat{X}_t + a_2\zeta_t + a_0 + R_t q_t^T v_z^{-1}\left[Z_t - \left(q_t\hat{X}_t + b_2\zeta_t\right)\right] + \xi_\pi \pi_t^* \tag{51}$$

$$\hat{X}_k = B_x\hat{X}_{k-0} + B_x U_k^* \tag{52}$$

$$\dot{R}_t = \overline{a}R_t + R_t\overline{a}^T + v_x - R_t q_t^T v_z^{-1} q_t R_t \tag{53}$$

where $Z_t = \dot{G}_t$, v_x is matrix of in OTES-CALS internal noises intensities; v_z is matrix of OTES-OS and OTES-NS intensifies of noises; $R_0 = \mathrm{M}\left[\left(X_0 - \hat{X}_0\right)\left(X_0 - \hat{X}_0\right)^T\right]$ is initial conditions for Eq. (53). Direct time integration of Riccati Eq. (54) is used.

Regulator equations:

$$\pi_t^* = -K_\pi^{-1}\xi_\pi^T\left(\tilde{R}_t\hat{X}_t + \frac{1}{2}g_t\right), \tag{54}$$

$$\dot{g}_t = \left(\tilde{R}_t\xi_\pi K_\pi^{-1}\xi_\pi^T - \xi_x^T\right)g_t - 2\tilde{R}_{tt}a_2\zeta_t, \ g_{t_f} = 0 \tag{55}$$

$$U_k^* = -\Gamma_u^{-1}B_u^T\tilde{R}_{k+0}\left(I + B_u\Gamma_u^{-1}B_u^T\tilde{R}_{k+0}\right)^{-1}B_x\hat{X}_{k-0}, \tag{56}$$

Auxiliary equations:

$$\dot{\tilde{R}}_t = -\tilde{R}_t\xi_x - \xi_x^T\tilde{R}_t + \tilde{R}_t\xi_\pi K_\pi^{-1}\xi_\pi^T\tilde{R}_t - K_x, \ \tilde{R}_{t_f} = H_{t_f} \tag{57}$$

$$\tilde{R}_k = B_x^T\tilde{R}_{k+0}\left(I + B_u\Gamma_u^{-1}B_u^T\tilde{R}_{k+0}\right)^{-1}B_x + K_x \tag{58}$$

Inverse time integration of Riccati Eqs. (57) and (58) is needed Eq. (51). The continuous-discrete Kalman filter equations are inter connected with regulator equations (**Figure 12**).

At last we get equations describing OTES-CALS dynamics with optimal continuous-discrete regulator insuring minimal deviation from given plan during given time interval $[t_0, t_f]$

$$\dot{X}_t = \overline{a}X_t + a_2\zeta_t - \xi_\pi K_\pi^{-1}\xi_\pi^T\left(\tilde{R}_t\hat{X}_t + \frac{1}{2}g_t\right), \tag{59}$$

$$X_k = B_xX_{k-0} - B_u\Gamma_u^{-1}B_u^T\tilde{R}_{k+0}\left(I + B_u\Gamma_u^{-1}B_u^T\tilde{R}_{k+0}\right)^{-1}B_x\hat{X}_{k-0} \tag{60}$$

where ζ_t is external noise from OTES-NS also acting on OTES-OS.
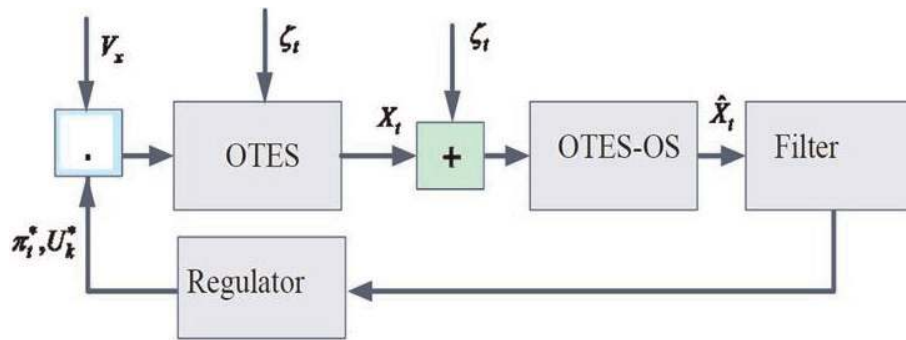
Figure 12.
Optimal stochastic regulator.

So the design of OTES-CALS includes two stages:

- solution of connected Eqs. (57) and (58) in inverse time with time fixation of coming current data massive;

- solution of differential Eqs. (51)–(53) and (55) in direct time using earlier fixed data and with substitution Eqs. (54) and (56).

5. Conclusion

The suggested probabilistic methodology for OTES-CALS allows to solve:

- problems of systems analysis, risk prognosis substations of forestall measures stability of extraction of latent effects on the basis of stochastic analytical modeling for applied LC problems;

- problems of optimal estimation and control on the basis probabilistic estimation and control methods.

Such systems are industrial, energetical, transport systems, financial and economic systems, insurance companies, etc.

Optimization being realized using social-technical-economic criteria. This permits to optimize project budgets for providing given quality MP and OTES-CALS staff potential.

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