LIFE CIRCLE ECONOMIC EFFICIENCY ANALYSIS

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Abstract

Generalized life cycle of concept, design, development and maintenance is studied. Various technological and managerial strategies were estimated, such as design for manufacturing, quality for manufacturing and relatively new fault tolerant design. Comparative efficiency of these approaches was analyzed. Life Circle analysis was developed based on the model of semi-Markov processes. Shown that fault-tolerant systems have advances over those based on the traditional approaches for long Life Circles.

1. Introduction

The development of long lasting complex projects is often complicated by the designer's inability to prove its economic efficiency. As a rule, various unfounded arguments such as "simplification," "improvement," "reduction", etc., are put forward without discussing the actual efficiency and the factors defining concept, design, development and operation (maintenance) of the project.

This paper proposes to complement the well-known approaches [1] to analysis of the economic efficiency of Life Cycles (LC) with the apparatus of semi-Markov processes. The peculiarities of LC define specific structures of the processes describing them, which can be called fully persistent. An analytical approach to determination of the functions and parameters of resource allocation at the steps of LC was developed, as applied to these structures, and simulated with the purpose of comparing its economic efficiency with the existing strategies.

2. Formulation of the problem

Modern information systems such as air traffic control, aviation safety monitoring, banking trade monitoring, are classified among the intelligence-intensive products where the R&D cost far exceeds that of production. Among the problems involved in estimating the economic efficiency, an important place is occupied by two following interrelated problems:

1. Estimation of the time, material (hardware and money), and labor resources required at individual steps of the design, manufacture, and service of system prototypes and

2. Estimation of the total cost of realization of the phases of LC.

To take into consideration the dynamics of costs at the LC steps [1], resource allocation models are required, which adequately reflect the structure of LC phases and the costs involved in each phase. As shown in [3], the current costs of Design-In-Process can exceed the costs of Work-In-Process by a factor of 2-4 even for a carefully planned production.

Since the costs of design, manufacture, and maintenance depend primarily on the duration of the corresponding steps, the need arises for developing and introducing into practice models of the LC phases, which is all the more important, because both in this country and abroad the majority of designers believe that the advantages of reduced duration of a step are difficult to estimate and, therefore, they prefer to rely upon guesses and intuition [4].

The existing models of phases mostly describe their determinate structures in terms of finite automata, Petri nets, or their various problem-oriented extensions such as E-nets, combi-nets, FIFO-nets, etc., [5, 6]. The models of these kinds are used for analysis of "reachability" the selected states, determination of critical paths of the project schedules and selection of potential concurrency in project phases. At the same time, economic analysis of LC is limited up to now by estimating of the potential costs for each phase of the project and calculation of optimistic and pessimistic Net Profit Values (NPV) for the project.

This paper proposes development of the model to analyze phases of the project in their interrelation. The phases of design, production (including the prototypes and their components) and maintenance of intelligence-intensive products are noted for many random factors, which affect both the duration and realization of the corresponding steps. These factors are:

– as indefiniteness of the time required to find the optimal designs,
– selection and training of specialists capable of achieving project goals,
– inadequacy of the instrumentation and equipment to the requirements of the production (design) of a particular product, hence, additional time for replacement or reconstruction,
– design errors inevitable in products of this kind,

– difficulties in choosing the circuitry required for a complicated engineering product,
– faults caused by environmental actions or human errors,
– unexpected bankruptcy of the subcontractors, and some other factors.

Reader is invited to extend this list using his/her own experience.

Under these conditions, one has to make use of probabilistic tools to construct the LC models. Here LC is represented as a linear sequence of n steps z_i, $i = \overline{1,n}$. Because of the presence of destabilizing factors, it may be required at any time $t_0 < t_1 < t_2 ...$ to return to a previous step or to repeat the current one instead of passing from z_i to z_{i+1}, $i = \overline{1,n}$.

In practice, most frequent are the phase interrupts while testing the prototypes of electronic equipment or software, when the errors of design or technology manifest themselves under the action of the environment or the principal errors of the designers manifest themselves. In these cases become necessary multiple modifications, which often radically change the initial concept of the project.

Nonobservance of the prescribed time is common in the practice of testing complex on-board equipment; system software. On the contrary, the lack of defects in design and technology of a more or less complicated object used information processing and/or control systems is regarded as a great achievement that arouses the suspicion of the test and safety engineers.

Having these arguments in mind one has to accept that the probabilities of returns to the previous steps or of repeating the current one are other than zero. We denote by p_{ij} the probability of passing from z_i to z_j in one step and assume that the Markovian property of no aftereffect is satisfied. Strictly speaking, this assumption is valid only in special cases where the costs of not fulfilling a project far exceed those of design or, stated differently, where it is required to realize the project in any time, but not to abandon the initial aim. Nevertheless, under certain constraints on the values of the probabilities (their closeness to the extreme values, 0 or 1, which is the case in practice) this assumption is quite admissible.

Let the durations τ_i, of a system residing in the states z_i, $i = \overline{1,n}$, be generally independent of the next state of the phase and be random variables described by the distributions $F_i(t) = P(\tau_i < t)$. This assumption is made to simplify calculations and, in essence, is not necessary.

Thus, the necessary and sufficient conditions are defined for describing the LC by a uniform semi-Markov process (USMP) [8]

$$M = \left\langle \mathbf{Z}, \mathbf{p}_0, \mathbf{Q}(t), t \right\rangle, \qquad (1)$$

where $\mathbf{Z} = \{z_i,\ i = \overline{1,n}\}$ is the space of USMP states, $\mathbf{p}_0 = \{p_i[t = 0) : p_1(0) = 1,\ p_i(0) = 0\ \forall i > 1\}$ is the vector of the initial distribution of state probabilities, $\mathbf{Q}(t) = \| Q_{ij}(t),\ i,j = \overline{1,n} \|$ is the transition matrix with elements $Q_{ij}(t) = p_{ij}F_i(t)$ and $p_{ij} = P(z = z_j \mid z = z_i)$, $i = \overline{1,n}$, are the transition probabilities of the appropriate embedded Markov chain. The resulting USMP will be called fully persistent (Fig.1).

To determine the total input of resources $C_i(T_i)$ during execution of the ith LC phase, we can use

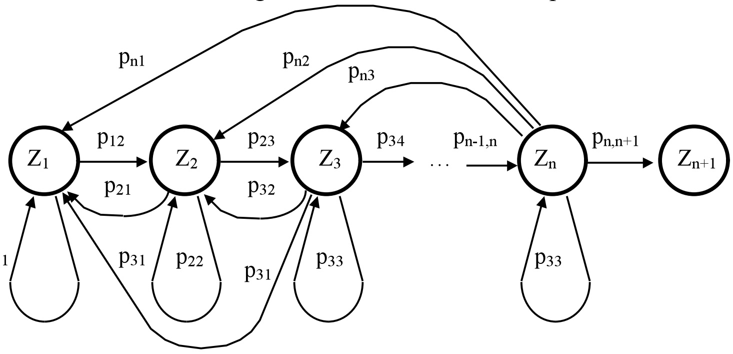

Fig.1 The structure of transition graph for Semi-Markov Process

the general relationship

$$C_i(T_i) = \sum_{l \in L_i} [\int_0^{T_i} W_i^l(\tau)d\tau + W_{i_0}^l], \qquad (2)$$

where $W_{i_0}^l$ is the initial input of the resource of the lth kind during the ith phase, $W_i^l(\tau)$ is the instantaneous input of the resource of the lth kind upon executing the ith operation, and L_i is the index set of the kinds of resources used during the ith step.

If it is assumed that the problem of scaling and normalization of the coefficients W_i^l is solved for all $i = \overline{1,n}$, $l \in L$ for a known $C_i(\tau_i)$, the determination of the total resource consumption for the entire LC presents no basic difficulties.

Therefore, our problem reduces to finding T_i, the total duration of executing the ith step until completion of the LC (or the total time of the USMP residing in the state z_i).

3. Determination of the distribution functions of total cost of lc steps

We introduce into the USMP (1) a state $z = z_{n+1}$, which represents a dummy operation of phase completion. It is absorbing and attainable from z_n by a direct transition with probability $p_{n,n+1}$. For the probabilities $G_i(t)$ of transition from z_i, $i = \overline{1,n}$, to z_{n+1} in time t, we have the following system of equations:

$$\mathbf{G}(t) = \mathbf{Q}(t) * \mathbf{G}(t) + \mathbf{R}(t)\,, \qquad (3)$$

where $\mathbf{G}(t) = \{G_i(t),\ i = \overline{1,n}\}$ is the vector of interval transition probabilities, $\mathbf{R}(t) = \{r_{i,n+1},\ i=\overline{1,n}\}$ is the vector of probabilities of direct transitions into z_n with all elements but $r_{n,n+1}(t) = p_{n,n+1}F_n(t)$ equal to zero, and $*$ denotes convolution.

Solution of the equation system (3) involves significant difficulties. What is more, the resulting functions $G_i(t)$ characterize the distribution of the total duration of the USMP residing in all states that lie along the paths connecting z_i to the absorbing state z_{i+1}.

To determine the distribution functions $H_i(t)$ of the total time T_i of the USMP residing in the states z_i, $i=\overline{1,n}$, one eliminates the times of process delay from all states z_j other than z_i, that is assumed, that $F_j(t) = 1(0)\ \forall j \neq i$.

Then, the analysis of the initial USMP can be reduced to considering n structurally identical processes characterized by two states $i_1 = z_i$ and $i_2 = z_{n+1}$ (absorbing), the distribution functions of the time of residing in states i_1 - $F_i(t)$, and the transition probabilities

$$p_{12}^{(i)} = p[z = i_2 | z = i_1] = k_i;$$

$$p_{11}^{(i)} = p[z = i_1 | z = i_1] = 1 - k_i\,.$$

Hence, (3) is reducible to n independent equations of the form

$$H_i(t) = k_i F_i(t) + (1 - k_i)\int_0^t H_i(t-\tau)\,dF_i(\tau). \qquad (4)$$

The coefficients k_i in (4) are the stationary probabilities that the process beginning at z_i gets into the absorbing state z_{n+1} before returning to z_i.

If $\mathbf{P} = ||p_{ij}||$ is an $(n \times n)$ matrix of the transition probabilities of the embedded Markov chain and $\mathbf{L} = ||P_i(l_j)||$ is an $(n \times n)$ matrix of probabilities that sooner or later the Markov chain gets from z_i to z_j, then the probabilities

$$k_i = 1 - (\mathbf{PL})_{ii}. \qquad (5)$$

It is well known [7] that

$$(\mathbf{PL})_{ii} = 1 - 1/\mathbf{N}_{ii} \qquad (6)$$

where $\mathbf{N} = (\mathbf{I} - \mathbf{P})^{-1}$ and $\mathbf{I}$ is the identity matrix. Thus, we finally get from (5) and (6) that

$$k_i = 1/(\mathbf{I} - \mathbf{P})_{ii}^{-1} = 1/N_{ii}. \qquad (7)$$

The total duration of the phase $T_\Sigma = \sum_{i=1}^{n} T_i$ is characterized by a convolution-like distribution function

$H_\Sigma(t) = H_i(t) * H_2(t) * \ldots * H_n(t)$, the random variables T_i being dependent.

For arbitrary distribution functions $F_i(t)$ where analytic determination of the distribution functions $H_i(t)$ and $H_\Sigma(t)$ is made difficult by awkward calculations, the solution can be found by one of the numerical methods described, for instance, in [8]. In practice, however, it is required quite often to know individual moment characteristics of the required distributions.

4. Determination of the parameters of the cost distribution

Denote by $\alpha_i^{(m)}$ and $\beta_i^{(m)}$, respectively, the initial mth order moments of the original distribution $F_i(t)$ and of the required distribution $H_i(t)$ of the total time T_i of the process residing in the state z_i. Using the properties of the expectation of the sum of random variables, we have from (4) that

$$\beta_i^{(m)} = \int_0^\infty t^m\, dH_i(t) = k_i\, \alpha_i^{(m)} + (1 - k_i)\sum_{r=0}^{m} C_m^{\,r} \times$$
$$\times\, \alpha_i^{(r)} \beta_i^{(m-r)}. \qquad (8)$$

Hence, after appropriate transformations we get the following recurrent relationship for the initial moments of the random variable T_i:

$$\beta_i^{(m)} = \alpha_i^{(m)} + \frac{(1-k_i)}{k_i}\sum_{r=0}^{m-1} C_m^{\,r}\, \beta_i^{(r)} \alpha_i^{(m-r)}. \qquad (9)$$

Since $F_i(t)$ are eigenfunctions ($\forall i = \overline{1,n}$), that is, $\alpha_i^{(0)} = 1$, it follows from (8) that $\beta_i^{(0)} = 1$, that is, $H_i(t)$ are also eigenfunctions. Knowing $\beta_i^{(0)}$, one can easily obtain from (7) and (9) the formulas for the initial moments of any order.

Practical interest mostly concerns the values of the first initial $\beta_i^{(1)}$ and the second central $s_i^{(2)}$ moments of the required distribution, that is, of the expectation and variance of the random variable T_i. The expectation of T_i is

$$\overline{T}_i = \beta_i^{(1)} = \alpha_i^{(1)}/k_i = \overline{t}_i\, N_{ii}, \qquad (10)$$

where $\overline{t}_i = \alpha_i^{(1)}$ is the expectation of the duration of the state z_i. In turn, using the equality $D(x) = E(x^2) - E^2(x)$, from (9) and (10) the variance of T_i can be obtained.

$$D(T_i) = s_i^{(2)} = \frac{\sigma_i^2}{k_i} + \frac{\overline{t_i^2(1-k_i)}}{k_i^2} =$$

$$N_{ii}\,[\sigma_i^2 + + \overline{t}_i^{\,2}\,(N_{ii} - 1)], \qquad (11)$$

where σ_i is the root-mean-square deviation (*rmsd*) of the duration t_i of the USMP residing in the state z_i.

Taking into consideration the structure of phase, the total LC duration T_Σ is the interval of the USMP transition from z_1 to z_{n+1} and the distribution function $H_\Sigma(t)$ is, correspondingly, the interval transient probability $G_1(t)$

The vectors $\mathbf{m}^{(v)} = \|\mathbf{m}_i^{(v)}, i = \overline{1,n}\|$ of the initial moments of random variables of transition intervals t_i, as it was shown in [9] to be determinable from

$$\mathbf{m}^{(0)} = (\mathbf{I} - \mathbf{P})^{-1}\, \mathbf{s}^{(0)} = \mathbf{N}\mathbf{s}^{(0)};$$

$$\mathbf{m}^{(v)} = \mathbf{N}\Big(\mathbf{s}^{(v)} + \sum_{x=0}^{v-1} C_v^x \mathbf{A}^{(v-x)} m^{(x)}\Big), \qquad (12)$$

where $\mathbf{s}^{(v)}$ is an n-dimensional vector with all elements but $s_n^{(v)} = p_{n,n+1}\alpha^{(x)}$ equal to zero and $\mathbf{A}^{(v)} = \|p_{ij}\alpha_i^{(v)}, i,j = \overline{1,n}\|$ is the matrix of initial moments. Hence, the first two initial moments of $t_1 = T_\Sigma$ are

$$m_1^{(1)} = \sum_{i=1}^{n} \bar{t}_i N_{1i};$$

$$m_1^{(2)} = \sum_{i=1}^{n} N_{1i}\alpha_i^{(2)} + 2\sum_{i=1}^{n} N_{1i}\alpha_i^{(1)} \sum_{j=1}^{n} p_{ij} \sum_{k=1}^{n} N_{jk}\alpha_k^{(1)} =$$

$$= \sum_{i=1}^{n} N_{1i}(\sigma_i^2 + \bar{t}_i^2) + 2\sum_{i=1}^{n} N_{1i}\bar{t}_i \sum_{j=1}^{n} p_{ij} \sum_{k=1}^{n} N_{jk}\bar{t}_k \,. \qquad (13)$$

Regroup the second sum in (13) by uniting the terms corresponding to the pair products $\bar{t}_i\ \bar{t}_k$, $i,k = \overline{1,n}$, and get

$$\sum_{i=1}^{n} N_{1i}\bar{t}_i \sum_{j=1}^{n} p_{ij} \sum_{k=1}^{n} N_{jk}\bar{t}_k = \sum_{i=1}^{n} N_{1i}\, p_{ij} N_{jk} =$$

$$= \sum_{i=1}^{n} N_{1i} \sum_{k=1}^{n} \bar{t}_i\ \bar{t}_k\, \mathbf{P}_{-(i)}\mathbf{N}_{|(k)}.\ \sum_{k=1}^{n} \bar{t}_i\ \bar{t}_k \sum_{j=1}^{n} \qquad (14)$$

where $\mathrm{P}_{\_(k)}$ and $\mathrm{N}_{|(k)}$ are, respectively, the kth row of the matrix **P** and the kth column of the matrix **N**.

One can easily see from the matrix equation $(\mathbf{I} - \mathbf{P})(\mathbf{I} - \mathbf{P})^{-1} = \mathbf{I}$ that $\mathbf{PN} = \mathbf{N} - \mathbf{I}$.

Keeping this in mind, the Statement 1 (see the Appendix) takes place and after substituting (14) into (13) obtain the following expression of the second central moment of the random variable t_i:

$$m_1^{(2)} = \sum_{i=1}^{n} N_{ii}\left(\sigma_i^2 - \bar{t}_i^2\right) + 2\sum_{i=1}^{n}\sum_{j=1}^{n} N_{ij}N_{ji}\bar{t}_i\ \bar{t}_j \,.$$

Hence, the variance of the random variable $t_i = T_\Sigma$ equals

$$D(t_1) = m_1^{(2)} - (m_1^{(1)})^2 = \sum_{i=1}^{n} N_{ii}\,[\sigma_i^2 + \bar{t}_i^2 (N_{ii} - 1)] +$$

$$+\sum_{i=1}^{n}\ \sum_{\substack{j=1 \\ j\neq 1}}^{n} N_{ij}N_{ji}\bar{t}_i\ \bar{t}_j = \sum_{i=1}^{n} D(T_i) + 2\sum_{\substack{i,j \\ i\neq j}}^{n} N_{ij}N_{ji}\bar{t}_i\ \bar{t}_j \,.$$

Notably, the mutual covariance of the durations of LC phases is

$$\mathrm{cov}\,(T_i\, T_j) = E\,[(T_i - \bar{T}_i)(T_j - \bar{T}_j)] = N_{ij}N_{ji}\bar{t}_i\ \bar{t}_j \,. \qquad (15)$$

With the thus-determined parameters of the distribution functions of the random variables T_i, $i = \overline{1,n}$, and T_Σ of (3), various characteristics of the input of resources can be obtained, enabling not only to pass judgment on the available level of resources, but also to forecast and therefore plan properly their distribution with a pre-assigned confidence.

5. Simulation model for analysis of life cycle

Using the approach described in the last two sections, a simulation model for analysis of the LC economic efficiency was written in the modeling language GPSS/PC. Its inputs are the number n and the structure of the phases of the specimen's life cycle, the probabilities of successful and unsuccessful completion of the phases p_{ij}, $i,j = \overline{1,n}$, the form and parameters of the distribution functions of the durations T_i of phases $F_i(t)$, $i = \overline{1,n}$, the normative coefficients of the resource input into phases W_i, $i = \overline{1,n}$, and the initial capital investments W_{i0} in the LC phases. The results of modeling are presented below.

As applied to LC, the following phases can be identified: A) – pre-design, B) - design and development, C) - volume production, D) - maintenance and service. Fig. 2 depicts the structure of the corresponding graph.

Modeling was carried out for determinate (D) and normally distributed (N) durations of phases. For each of these variants, three cases were considered with: (1) no returns and repetitions of phases, that is, $p_{12} = p_{23} = p_{34} = p_{45} = 1$, (2) small probabilities of returns and repetitions $p_{ij} < 0.05$, $j<i = 1.4$, and (3) big probabilities of returns and repetitions $p_{ij} > 0.10$, $j<i = \overline{1,4}$, in turn.

From the results of modeling follows:

The occurrence of even relatively small factors (small probability of return) affects substantially the initial forms of the distribution of costs of the LC phase realization, because the mixtures of convolutions of the initial functions confer a polymodal asymmetrical form with explicit "tails" to the laws of distribution, The mean costs and the estimated *rmsd* costs depend substantially on the probabilities of returns and repetitions and for a change in probability from 0 to 0.15 the mean values and rmsd increase, respectively, by 1.5-2 and 8-10 times.

The high sensitivity of the model enables one to use efficiently the resources so as to minimize the aggregate costs in all phases of the life cycle of intelligence-intensive products.

6. Proposals for structuring of the life cycle

During analysis of the economic efficiency of the OFCS life cycle from the modeling data, different variants of its organization were considered. In particular, approaches to the design, development, and production of prototypes were analyzed.

C1. Ordinary LC disregarding the economic consequences of design, production, and introduction of new products. This approach is characteristic mostly of the rigid centralized planning of system design, production, and service.

C2. Life cycle based on the so-called "design for manufacturing," making the most of the existing equipment for commercial production of systems. Additional investments to the initial phase of design lead to lower costs of production and maintenance owing to a reduction in both resource consumption and probabilities of return.

C3. The approach based on "quality function deployment" by increasing the input of resources into study, design, and commercial production with the aim of improving the reliability and quality of the product, which is used, like C2, abroad. A lower level of rejects, that is, offsets higher test costs by a lower probability of debugging and repeating the operations. In doing so, a substantial economic gain is attained during product service owing to the lower input of resources into maintenance and repair.

C4. Fault Tolerant Design of systems. In this case, it is proposed to increase investments into studies, development, and commercial production in order to implement decisions supporting fault-tolerance of the end product. Here, the probabilities of returns at the pre-design and design steps are as in the usual cycle, and that of the commercial production is even somewhat higher, which is due to the more complicated design of the fault-tolerant system as compared with its predecessors. Yet the fault-tolerant system practically needs no maintenance and repair or designer's intervention, that is, the current input of resources Wi and the return probabilities p_j, $j < i$, become negligible compared with other approaches.

The economic efficiency of the above approaches to design (in essence, to organizing OFCS LC) is shown in Fig. 2.

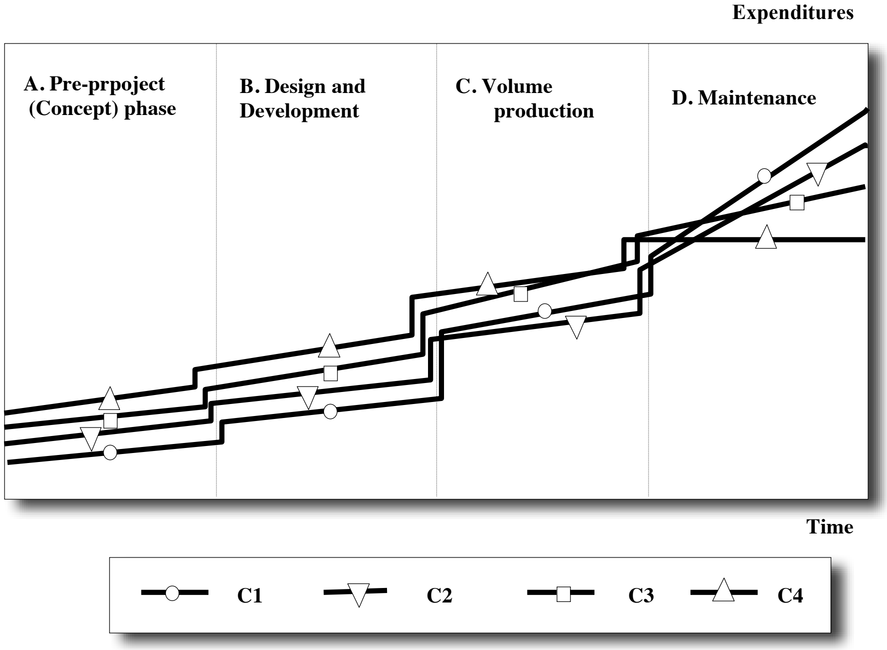

Fig.2. Comparison of economic effectiveness of design and development.

It follows from the graphs that the usual cycle of design, production, and service is recommendable if gain at earlier steps is required. For commercial production, some effect is produced by the "design for manufacturing" C2, which, in practice, is not inferior to the "quality function deployment" C3. Yet. if the products are used in great numbers, these approaches are inferior to C4 in terms of the total costs. Fault-tolerance becomes the most important for flight vehicles where, besides the economic criteria, one of the major priorities is safety.

7. Conclusions

1. A methodology is proposed for estimating and forecasting the expected duration of the phases of the life cycle of complex intelligence-intensive products as well as the input of resources into the phases of the product life cycle.

2. Simulation modeling provided the main statistical characteristics of cost distribution by LC phases. The model's sensitivity to the main initial data enables its use for efficient (optimal) planning of capital investments and organization of studies,

production, testing, and operation of promising electronic equipment.

3. As modeling and comparison show, the fault-tolerance-based approach to organizing the life cycle of intelligence-intensive produces is most efficient for mass production in terms of the criterion of total costs.

Appendix: Auxiliary Statement 1

For the USMP structure under consideration, the upper off-diagonal elements of the matrix N = $(I-P)^{-1}$ an egual to the corresponding diagonal elements, that is, Nji = Nii holds for all j < i, i = l.n.

Proof. We demonstrate that Nji = Nj+l,i, where j successively assumes values from l,2,...,i- 1, holds for an arbitrary i = l,n.

Let $j = 1$. Since $\mathbf{N} = (\mathbf{I} - \mathbf{P})^{-1} = \overline{P^{-1}}$, that is, $\overline{P}\,\mathbf{N} = \mathbf{I}$, we can write, in particular, that

$$\overline{P}_{-(1)}\,\mathbf{N}_{|(i)} = 0,$$

where $\overline{P}_{-(k)}$ and $\mathbf{N}_{|(k)}$ are, respectively, the kth row of the matrix $\overline{P}$ and the *k*th column of the matrix **N**.

The same can be expanded as

$$\overline{P}_{11}N_{1i} + \overline{P}_{12}N_{2i} = (1 - p_{11})N_{1i} - p_{12}N_{2i} = 0.$$

Since the sums of elements of $\overline{P}$ are zero for all rows but lhe nth one (where $\sum_i \overline{p_{ni}} = p_{n,n+1}$), we get $p_{12}N_{1i} - p_{12}N_{2i} = 0$, that is, $N_{1i} = N_{2i}$.

Similarly, for $j = 2$ we have $P_{-(2)}N_{|(i)} = 0$ or
$-p_{21}N_{1i} + (1 - p_{22})N_{2i} - p_{23}N_{3i} = 0$.

After some evident transformations, we get from $N_{1i} = N_{2i}$, and the validity of $1 - p_{21} - p_{22} = p_{23}$ that

$$N_{2i} = N_{3i}.$$

Continuing similar substitutions, we get for $j = i - 1$

$$\overline{P}_{-(1)}\,\mathbf{N}_{|(i)} = 0, \text{ that is, } N_{i-1,i}\left(1 - \sum_{k=1}^{i-1} p_{i-1,k}\right) - p_{i-1,k}N_{ii}, = 0$$

and make sure that $N_{ii} = N_{i-1,i}$. Owing to the continuity of our reasoning, $N_{1i} = N_{2i} ... = N_{ii}$, which is what we set out to prove.

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