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HARMONIZED DECISION-MAKING IN MANAGING RELIABILITY AND SAFETY

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Abstract. A hierarchical technical system functioning under random disturbances and being subject to critical failures at the bottom level which may result in an accident or a hazardous condition including environmental safety violations at the upper level is considered. Certain primary elements at the bottom level, together with their corresponding primary failures, can be refined by undertaking technical improvement. The list of the latter is pre-given as well. Assume that by means of simulation modeling (SM) it is possible to evaluate the increment of the system's reliability by implementing any set of technical improvements. The harmonization models center on determining an *optimal sub-set* of technical improvements in order:

• either to maximize the system's reliability subject to a restricted budget assigned for the improvements' implementation, or

• to minimize the system's budget subject to a reliability value restricted from below.

Keywords: Harmonization models; Basic parameters; Multi-parametric trade-off models; Hierarchical safety engineering models; Heuristic models based on sensitivity concepts.

1. Introduction

In recent years problems associated with developing various quality concepts have been discussed extensively in scientific literature. However, numerous publications refer mostly to quality control which is usually applied to products and services. As a matter of fact, the existing quality techniques, including the developed utility theory [7, 13], are not applicable to technical and organization systems which are actually supervising and monitoring the process of the system functioning: all those models are restricted to solving market competitive problems alone. Thus, nowadays, *the existing utility theory centers on analyzing the competitive quality of organization systems' outcome products rather than dealing with the quality of the systems' functioning, i.e., with organization systems in their entirety*. This may result in heavy financial losses, e.g. when excellent project objectives are achieved by a badly organized project's realization [4].

Thus, a conclusion can be drawn that the existing utility theory cannot be used as the system's quality techniques. In order to fill in the gap, we have undertaken research in the area of *estimating the quality of the system itself*, e.g. the system's public utility. We will consider complex organization system which functions under random disturbances. Such a system usually comprises a variety of qualitative and quantitative attributes, characteristics and parameters, which enable the system's functioning. The problem arises to determine a generalized (usually quantitative) value which covers all essential system's parameters and can be regarded to as a system's qualitative estimate. We will henceforth call such a generalized value *the system's utility*.

Another conclusion which can be drawn from the outlined above reference is that the creators of the existing utility theory have implemented safety concepts only in techniques to control the outcome products. Any research to estimate the system's utility as a whole from the point of Safety Engineering or Environmental Safety principles has not been published as yet [11]. Since considering safety concepts in modern operation management becomes a growing world-wide tendency, we will implement those concepts in the utility of the system's functioning. This, in turn, will result in decreasing the number of hazardous failures jeopardizing public and environmental safety in modern organization systems [2].

In papers [1, 2, 8] we have created a new multi-parametric optimization model in order to maximize the system's utility as a generalized quality measure of the system's functioning. Since such a model is, in essence, a trade-off compromise between the system's parameters, we will henceforth call that model *harmonization model* (HM).

We suggest calling the system's utility a weighted linear function of the system's parameters with constant coefficients. The parameters are divided into:

- independent parameters, where for each parameter its value may be preset and may vary independently on other parameters' values, and
- dependent parameters whose values may not depend uniquely on the values of independent parameters. However, when optimized (for the same values of independent parameters), they are solely dependent on those values.

Both independent and dependent parameters together with the coefficients of the utility function are externally pre-given.

If an organization system functions under random disturbances and comprises n_1 independent basic parameters $R_i^{(ind)}$, $1 \le i \le n_1$, and n_2 dependent basic parameters $R_j^{(dep)}$, $1 \le j \le n_2$, the harmonization problem boils down to maximize the system's utility

$$U_S = \left(\sum_{i=1}^{n_1} \alpha_i R_i^{(ind)} + \sum_{j=1}^{n_2} \alpha_j R_j^{(dep)} \right) \quad (1)$$

subject to certain restrictions. We suggest determining the optimal vector

$$\vec{R}_* = \left(R_{1*}^{(ind)}, R_{2*}^{(ind)}, \dots, R_{n_1*}^{(ind)}, R_{1*}^{(dep)}, R_{2*}^{(dep)}, \dots, R_{n_2*}^{(dep)} \right) (2)$$

which delivers maximization to the system's utility U_S, by means of the following sequential stages:

Stage I - implement a look-over algorithm to examine all feasible combinations of independent basic values $\left\{ R_i^{(ind)} \right\}$;

Stage II - determine *optimal* values $\left\{ R_{j\ opt}^{(dep)} \right\}$ for all dependent parameters by means of values $\left\{ R_i^{(ind)} \right\}$ obtained at the previous stage; for each j-th dependent parameter an individual optimization model (called henceforth the partial harmonization model PHM_j), is used. The latter enables the optimality of each value $R_{j\ opt}^{(dep)}$ which *solely* depends on the combination $\left\{ R_i^{(ind)} \right\}$;

Stage III- calculate the system's utility U_S via (1) for the combination

$$\left\{ R_i^{(ind)} \right\}, \left\{ R_{j\ opt}^{(dep)} \right\} \quad (3)$$

obtained at *Stages I* and *II*;

Stage IV- Calculate the optimal system's utility by determining the optimal combination (2) for all independent and dependent parameters which delivers the maximum to U_s.

If, due to the high number of possible combinations $\left\{ R_i^{(ind)} \right\}$, implementing *Stage I* requires a lot of computational time, we suggest using a simplified heuristic search procedure, e.g. a cyclic coordinate search algorithm [1, 8].

Thus, we suggest an approximate harmonization's problem solution as follows. At the first stage a relatively simple search algorithm in the area of independent parameters is implemented. At the second stage, in order to evaluate the optimal value of each dependent parameter, an optimization problem PHM_j, $1 \le j \le n_2$, has to be solved. Thus, the idea is to obtain independent parameters' values at the first stage and to use them as input values of all partial harmonization models at the second stage.

PHM is usually a stochastic optimization model which is solved on the basis of simulation modeling. However, in certain cases, e.g. reliability and safety engineering problems, various *PHM* require more complicated formulations. In such cases we suggest to use additional heuristic models in order to implement realistic quantitative links between the system's attributes. For various dependent parameters the *PHM* may be formulated and solved by means of expert information [1, 8].

The goal of this paper is to apply the harmonization theory in Reliability and Safety Engineering. A hierarchical technical system functioning under random disturbances and being subject to critical failures at the bottom level which may result in an accident or a hazardous condition including environmental safety violations at the upper level is considered. Certain primary elements at the bottom level, together with their corresponding primary failures, can be refined by undertaking technical improvement. The list of the latter is pre-given as well. Assume that by means of simulation modeling (SM) it is possible to evaluate the increment of the system's reliability by implementing any set of technical improvements [1, 3]. The harmonization models center on determining an *optimal sub-set* of technical improvements in order:

- either to maximize the system's reliability subject to a restricted budget assigned for the improvements' implementation, or

- to minimize the system's budget subject to reliability value restricted from below.

Two different cases are considered and solved by mean of sensitivity analysis:

- a simplified cost-sensitivity trade-off model to solve cost-reliability problems for a complicated hazardous technical system with two basic parameters: cost and reliability, and

- more complicated trade-off harmonization problems where the system's utility, cost expenditures, reliability values and other basic parameters are linked together by means of sensitivity relations.

2. Cost-reliability models

2.1. The System's Description

We will consider a complicated technical device functioning under random disturbances. The device's reliability, i.e., its probability to avoid critical failures within a sufficiently long period of time, has to be extremely high since critical failures present a definite threat to people's safety, to the environment, etc., and may result in an accident or a major hazardous condition. Thus, increasing the device's reliability is considered to be an important problem of Safety Engineering, on assumption that the existing reliability value proves to be insufficient [2, 15].

Consider, further, that there exist N technical improvements (TI) to increase the device's reliability. For each k-th TI, $1 \le k \le N$, investing ΔC_k cost expenditures results in increasing the device's reliability by ΔR_k. Assume that those parameters are obtained by means of simulation model SM and do not depend on the number of technical improvements which have already been implemented. Thus, the result of a routine k-th technical improvement does not depend on other $\{TI\}$.

The problems to be considered below present simplified particular cases of the general theory of harmonization models outlined in [1]. However, an effective and simple heuristic approach based on cost-sensitivity, can be suggested. To our opinion, the developed models can be applied to a broad spectrum of technical devices in the framework of Safety Engineering [1, 10].

2.2. Notation

Let us introduce the following terms:

2.2.1. Cost-Reliability Models in Safety Engineering

TI_k	-	the k-th technical improvement to increase the system's reliability, $1 \le k \le N$;
N	-	the number of possible technical improvements;
ΔC_k	-	cost expenditures to implement TI_k (pre-given);
ΔR_k	-	increase of the system's reliability due to implementing TI_k (to be calculated by means of simulation model SM);
R^*	-	the minimal acceptable system's reliability value to avoid hazardous failures (pre-given);
C^*	-	the restricted budget to undertake technical improvements (pre-given);
R_0	-	system's reliability value prior to undertaking amendments (pre-given);
SM	-	simulation model to estimate the system's reliability.

2.2.2. Harmonization Models in Safety Engineering

TS	-	Complicated multi-level technical system with hazardous failures at the upper level;
N	-	the number of possible technical improvements TI_k, $1 \le k \le N$;
ΔC_k	-	cost value required to carry out TI_k;
SM	-	simulation model to calculate the system's reliability value;
ΔR_k	-	additional reliability value obtained as a result of undertaking TI_k (to be calculated by means of simulation model SM);
P_ℓ	-	additional non-basic parameter, $1 \le \ell \le m$;
m	-	the number of non-basic parameters;
α_C	-	the budget's partial utility;
α_R	-	the reliability's partial utility;
α_{P_ℓ}	-	partial utility of parameter P_ℓ;
R^*	-	the system's reliability level to avoid hazardous failures (pre-given);
C^*	-	maximal additional budget (pre-given);

$\Delta P_{\ell k}$	-	additional value of parameter P_ℓ obtained as a result of undertaking TI_k, $1 \le \ell \le m$, $1 \le k \le N$;
$\Delta U_{\ell k}$	-	additional system's utility obtained as a result of undertaking TI_k, $1 \le k \le N$ (to be calculated by means of simulation model SM);
R_0	-	system's reliability value prior to undertaking amendments (pre-given);
$\Delta R\{\xi_1,...,\xi_Q\}$	-	increase of the system's reliability due to implementing Q different technical improvements $\{TI_{\xi_q}\}$, $1 \le q \le Q$, $\xi_q \le N$ (calculated by means of a simulation model SM).

2.3. The Direct Cost-Reliability Problem

Determine the optimal set of technical improvements TI_{ξ_q}, $1 \le q \le Q \le N$, $\xi_q \le N$, which requires the minimal amount of costs to undertake the TI in order to increase the device's reliability by not less than $R^* - R_0$,

i.e.,

$$\underset{\{\xi_q\}}{Min} \left\{ \sum_{q=1}^{Q} \Delta C_{\xi_q} \right\} \tag{4}$$

subject to

$$R_0 + \sum_{q=1}^{Q} \Delta R_{\xi_q} \ge R^* . \tag{5}$$

2.4. The Dual Cost-Reliability Problem

Determine the optimal set of TI_{ξ_q}, $1 \le q \le Q \le N$, $\xi_q \le N$, in order to maximize the device's reliability subject to the restricted amount of costs ΔC to undertake the corresponding TI, i. e.,

$$\underset{\{\xi_q\}}{Max} \left\{ \sum_{q=1}^{Q} \Delta R_{\xi_q} \right\} \tag{6}$$

subject to

$$\sum_{q=1}^{Q} \Delta C_{\xi_q} \le \Delta C . \tag{7}$$

Since all TI are independent of each other, both problems (4-5) and (6-7) are NP- complete, and, an optimal solution can be obtained only by means of implementing an algorithm (mainly by means of dynamic programming) that checks the feasibility of all possible combinations of Q elements from N, while Q itself changes from 1 to N. If N is high enough, the corresponding algorithm requires a lot of computational time according to the justification outlined in [1]. We suggest using a heuristic procedure based on cost-sensitivity. Note, that if relation

$$\sum_{i=1}^{Q} \Delta R_i \ge R^* - R_0 \tag{8}$$

does not hold, the direct problem (4-5) has no solution. As to the dual problem, the corresponding restriction

$$\sum_{i=1}^{Q} \Delta C_i \le C^* \tag{9}$$

results in a trivial solution $Q = N$, i.e., all technical investments have to be implemented.

2.5. The Direct Problem's Solution (Algorithm I)

In order to proceed, we will introduce a new definition. Call henceforth the *cost-reliability of a technical improvement* the ratio $\gamma = \Delta R / \Delta C$. It can be well-recognized that if TI_{k_1} has a higher cost-reliability than TI_{k_2}, investing one and the same cost expenditure results in a higher increase of the reliability parameter in case of implementing the TI_{k_1} than TI_{k_2}. This consideration is used below, in the step-by-step heuristic algorithm:

Step 1 Calculate cost-reliability values γ_k for all TI_k, $1 \le k \le N$.

Step 2 Reorder values γ_k in descending order. Thus, values γ_k, $1 \le k \le N$, will obtain a new order. Denote the corresponding new indices (ordinal numbers) of technical improvements by TI_{ξ_q}, $1 \le q \le N$.

Step 3 Determine the minimal value Q which satisfies

$$Q = Min \left[V : \sum_{q=1}^{V} \Delta R_{\xi_q} \ge R^* - R_0 \right]. \tag{10}$$

Step 4 Determine the quasi-optimal indices of the chosen technical improvements:

$$TI_{\xi_1}, TI_{\xi_2}, ..., TI_{\xi_Q} .$$

The idea of *Algorithm I* is to spend as little budget as possible in order to meet constraint (5).

2.6. The Dual Problem's Solution (Algorithm II)

The corresponding step-by-step heuristic algorithm is as follows:

Steps 1 and *2* fully coincide with the corresponding stages of *Algorithm I.*

Step 3 Determine the maximal value Q which satisfies

$$Q = Max\left[V: \sum_{q=1}^{V} \Delta C_{\xi_q} \le C^*\right]. \qquad (11)$$

Step 4 fully coincides with *Step 4* of *Algorithm I.*

It can be well-recognized that introducing the concept of cost-reliability enables a simple and effective solution of various cost-optimization problems in Safety Engineering.

Both optimization problems (4-5) and (6-7) are partial harmonization problems. Problem (4-5) is a $PHM_1(R) = C$ with one independent basic parameter - system's reliability value R, and one dependent parameter - the budget to be assigned for undertaking technical improvements. $PHM_1(R) = C$ centers on minimizing C subject to the prescribed reliability. Problem (6-7) is a $PHM_2(C) = R$ which centers on maximizing the reliability value R subject to restricted budget value C.

3. Harmonization models in safety engineering

3.1. Cost-Reliability Harmonization Model with Two Basic Independent Parameters

We will consider an interesting case (and for certain multi-level technical systems an important one!) of a system with possible hazardous failures at the upper level. Two independent basic parameters are imbedded in the model: budget C to carry out technical improvements, and the system's reliability value R. In order to simplify the problem assume that, similarly to the model outlined above, all technical improvements are additive, i.e., additional system's reliability $\Delta R\{\xi_1,\dots,\xi_Q\}$ obtained by implementing $\left\{TI_{\xi_q}\right\}$, $1 \le q \le Q$, is equal $\sum_{q=1}^{Q} \Delta R_{\xi_q}$.

Set the "weight" of increasing the device's reliability (per reliability unit) by α_r, and let the corresponding weight of cost investments per cost unit be α_c. The harmonization model is an extension of the cost-reliability model outlined in *Chapter 2*. The problem is as follows: Determine the optimal set of $\left\{TI_{\xi_q}\right\}$, $1 \le q \le Q$, $\xi_q \le N$, in order to maximize the harmonization objective

$$J = \underset{\{\xi_q\}}{Max}\left\{\sum_{q=1}^{Q}\left[\alpha_r \cdot \Delta R_{\xi_q} - \alpha_c \cdot \Delta C_{\xi_q}\right]\right\} \qquad (12)$$

subject to

$$\sum_{q=1}^{Q} \Delta C_{\xi_q} \le C^*, \qquad (13)$$

$$\sum_{q=1}^{Q} \Delta R_{\xi_q} \ge R^* - R_0 = \Delta R. \qquad (14)$$

Note that since the costs ΔC_{ξ_q} to be invested in the course of undertaking TI_{ξ_q} decrease the system's utility, i.e., decrease objective (12), they have to be taken with a negative sign, while increasing the device's reliability results in increasing the quality of the system as a whole.

Model (12-14) comprises *two restrictions* since for both basic parameters C and R their corresponding upper and lower bounds are pre-given. It is a complicated NP-complete problem which requires only heuristic solutions, since using classical precise optimization algorithms meets unavoidable computational difficulties. We suggest to solve problem (12-14) by implementing the idea of cost-sensitivity, based on introducing values $\gamma_k = \frac{\Delta R_k}{\Delta C_k}$, $1 \le k \le N$, and, later on, reordering TI_k, $1 \le k \le N$, in the descending order of values γ_k. Thus, sequence TI_{ξ_q}, $1 \le q \le N$, is obtained.

To develop a heuristic procedure, we will modify objective (12) as follows:

$$J = \underset{\{\xi_q\}}{Max}\left\{\sum_{q=1}^{Q}\left[\left(\frac{\alpha_r \cdot \Delta R_{\xi_q}}{\alpha_c \cdot \Delta C_{\xi_q}} - 1\right) \cdot \alpha_c \cdot \Delta C_{\xi_q}\right]\right\} =$$

$$= \underset{\{\xi_q\}}{Max}\left\{\sum_{q=1}^{Q}\left[\left(\eta \cdot \gamma_{\xi_q} - 1\right) \cdot \alpha_c \cdot \Delta C_{\xi_q}\right]\right\}, \qquad (15)$$

where $\eta = \frac{\alpha_r}{\alpha_c}$ is a constant value which does not depend on the TI index.

Since values γ_{ξ_q} are monotonously decreasing, the multiplicand $\eta \cdot \gamma_{\xi_q} - 1$, $1 \le q \le N$, may for a certain number q turn negative.

Certain realistic assumptions are imbedded in the model:

1. Since the reliability parameter for a technical device with critical failures usually dominates over other parameters, we will assume that relation

$$\eta = \frac{\alpha_r}{\alpha_c} > 1 \text{ holds.}$$

2. Assume that for the TI_{ξ_1} with the *highest cost-sensitivity*, relation $\eta \cdot \gamma_{\xi_1} > 1$ holds, otherwise a degenerate conclusion can be drawn that the best compromise for the device under consideration is to not undertake any technical improvements at all.

On the basis of the above assumptions the following step-by-step heuristic algorithm to solve harmonization problem (12-14) can be suggested:

Step 1. Determine the maximal N_1 satisfying

$$N_1 = Max\left[V: \sum_{q=1}^{V} \Delta C_{\xi_q} \le C^*\right]. \qquad (16)$$

Step 2. Determine the minimal N_2 satisfying

$$N_2 = Min\left[V: \sum_{q=1}^{V} \Delta R_{\xi_q} \ge \Delta R\right]. \qquad (17)$$

Note that if $N_2 > N_1$, the problem has no solution. In case $N_2 \le N_1$ apply *Step 3*.

Step 3. Determine the maximal N_3 satisfying

$$N_3 = Max\left\lfloor V: \eta \cdot \gamma_{\xi_V} \ge 1 \right\rfloor \qquad (18)$$

subject to

$$N_3 \le N. \qquad (19)$$

Step 4. Determine value Q satisfying

$$Q = \begin{cases} N_1 & if \quad N_3 \ge N_1 \\ N_3 & if \quad N_2 \le N_3 \le N_1 \\ N_2 & if \quad N_3 \le N_2 \end{cases}. \qquad (20)$$

Step 5. Technical improvements $TI_{\xi_1}, TI_{\xi_2}, \ldots, TI_{\xi_Q}$ are taken as the quasi-optimal set $\{TI\}$ to be implemented, with objective

$$J = \sum_{q=1}^{Q}\left[\left(\eta \cdot \gamma_{\xi_q} - 1\right) \cdot \alpha_c \cdot \Delta C_{\xi_q}\right]. \qquad (21)$$

Objective (21) honors restrictions (13-14) and delivers the maximal value for the problem's heuristic solution $\{TI\}_{\xi_q}$, $1 \le q \le Q$.

Note, in conclusion, that the ratio $\eta = \frac{\alpha_r}{\alpha_c}$ may not be a constant value. In case of extremely high reliability values R, i.e., when R practically guarantees avoiding hazardous failures and relation $R >> R^*$ holds, the partial utility value α_R may undergo an essential decrease while value α_C will remain constant. Thus, certain technical difficulties may arise. However, from the principal point of view, the algorithm will not be subject to drastic changes.

In the harmonization model under consideration a straightforward heuristic method [14] to optimize objective (12) is used. As to partial harmonization models, they do not exist in this case, since there are no dependent basic parameters: both basic parameters are set by means of restrictions (13-14) and are pre-given beforehand. No parameter is optimized by means of partial harmonization. Both parameters influence one another: this mutual influence is implemented in the heuristic algorithm by means of analyzing partial utility values α_C and α_R.

4. Generalized harmonization models in safety engineering with non-basic parameters

The harmonization model under consideration comprises, besides two basic parameters C (the budget to be assigned to undertake technical improvements) and R (the system's reliability to avoid hazardous failures), a variety of non-basic parameters entering the system's utility model as well. Non-basic parameters are, e.g., the probability of completing the production program not later than the pre-given due date, reliability value to avoid non-hazardous failures which nevertheless may cause certain damage to the personnel and/or to the environment, specific design failures, etc. Unlike the outlined above cost-reliability models, all TI are *non-additive*, i.e., the aggregate increase $\Delta R\{\xi_1, \ldots, \xi_Q\}$ due to simultaneous implementation of $TI_{\xi_1}, \ldots, TI_{\xi_Q}$, may not be equal $\sum_{q=1}^{Q} \Delta R_{\xi_q}$. This makes the harmonization problem more complicated.

Two problems can be formulated:

4.1. Direct Problem

Determine $Q \le N$ technical improvements TI_{ξ_q}, $1 \le q \le Q$, $\xi_q \le N$, to maximize the system's additional utility

$$\underset{\{\xi_q\}}{Max}\left[\sum_{q=1}^{Q} \Delta U_{s\xi_q}\right] =$$

$$= \underset{\{\xi_q\}}{Max}\left\{\sum_{q=1}^{Q}\left[\alpha_C \cdot \Delta C_{\xi_q} + \left(\sum_{\ell=1}^{m} \alpha_{P_\ell} \cdot \Delta P_{\ell\xi_q}\right)\right] + \alpha_R \cdot \Delta R\left(\xi_1, \xi_2, \ldots, \xi_Q\right)\right\} \quad (22)$$

subject to

$$R_0 + \Delta R\left(\xi_1, \xi_2, \ldots, \xi_Q\right) \ge R^* . \quad (23)$$

4.2. Dual Problem

$$\underset{\{\xi_q\}}{Max}\left[\sum_{q=1}^{Q} \Delta U_{s\xi_q}\right] \quad (24)$$

subject to

$$\sum_{q=1}^{Q} \Delta C_{\xi_q} \le C^* . \quad (25)$$

It can be well-recognized that solving both problems (22-23) and (24-25) by means of precise algorithms results in tremendous and practically unavoidable computational difficulties. We suggest developing enhanced heuristic procedures based on sensitivity analysis. Two basic sensitivity values for each TI_k will be used:

reliability-sensitivity $\omega_k = \dfrac{\Delta U_{sk}}{\Delta R_k}$, (26)

and cost-sensitivity $\eta_k = \dfrac{\Delta U_{sk}}{\Delta C_k}$, $1 \le k \le N$. (27)

Note that both values ω_k and η_k, $1 \le k \le N$, can be obtained only by means of simulation, since ΔU_{sk} comprises ΔR_k and has to be calculated via simulation with an enormous number of simulation runs.

4.3. The Problem's Solution

The enlarged step-by-step *Algorithm I* to solve the direct problem is as follows:

Step 1. Calculate reliability-sensitivity values ω_k for all TI_k, $1 \le k \le N$.

Step 2. Reorder values ω_k in descending order. Thus, values ω_k will obtain a new order. Denote the corresponding new indices (ordinal numbers) of technical improvements by TI_{ξ_q}, $1 \le q \le N$.

Step 3. Determine the minimal value Q satisfying

$$Q = Min\left[V : \Delta R(\xi_1, \ldots, \xi_V) \ge R^* - R_0\right]. \quad (28)$$

Step 4. If $\Delta U_{SQ} < 0$ go to the next step. Otherwise go to *Step 6*.

Step 5. If value Q exceeds the minimal value obtained at *Step 3* go to *Step 8*. Otherwise go to *Step 9*.

Step 6. If $Q = N$ go to *Step 9*. Otherwise apply the next step.

Step 7. Counter $Q + 1 \Rightarrow Q$ works. Go to *Step 4*.

Step 8. $Q - 1 \Rightarrow Q$. Apply the next step.

Step 9. Determine the quasi-optimal indices of the chosen technical improvements to be implemented:

$$TI_{\xi_1}, TI_{\xi_2}, \ldots, TI_{\xi_Q} .$$

The step-by-step procedure of *Algorithm II* to solve the dual problem is as follows:

Step 1. Calculate cost-sensitivity values η_k for all TI_k, $1 \le k \le N$.

Step 2. Reorder values η_k in descending order, similarly to *Step 2* of *Algorithm I.*

Step 3. Determine the maximal value Q satisfying

$$Q = Max\left[V : \sum_{q=1}^{Q} \Delta C_{\xi_q} \le C^*\right]. \quad (29)$$

Step 4. If $\Delta U_{SQ} \le 0$ go to the next step. Otherwise apply *Step* 7.

Step 5. If $Q = 1$ go to *Step* 7. Otherwise apply the next step.

Step 6. Counter $Q - 1 \Rightarrow Q$ works. Go to *Step 4.*

Step 7. Determine the quasi-optimal solution of *Algorithm II*, i.e., the quasi-optimal sub-set of $\left\{TI_{\xi_q}\right\}$, $1 \le q \le Q$.

Algorithms I and *II* cover a broad spectrum of Safety Engineering problems.

Note that the direct harmonization problem (22-23) is based on $(m+1)$ partial harmonization models with R being an independent parameter: $PHM_1(R) = C$, $PHM_{1\ell}(R) = P_\ell$, $1 \le \ell \le m$, which later on enter the utility increment ΔU_s. As to the dual problem (24-25), it comprises another $(m+1)$ PHM with budget value C being an independent parameter:

$PHM_2(C) = R$, $PHM_{2\ell}(C) = P_\ell$, $1 \le \ell \le m$.

In conclusion, partial utility parameters α_R and α_ℓ, $1 \le \ell \le m$, in practice, are usually piecewise functions depending on the parameters' values. This causes certain computational difficulties in solving harmonization problems. However, those difficulties do not inflict principal troubles and can be overcome.

5. Conclusions

The following conclusions can be drawn from the study:

1. Problems of estimating the utility of complicated and usually multilevel management systems by means of establishing and solving harmonization problems are very urgent, especially for organization systems with a variety of quality parameters. Applications of the utility theory in recent publications are restricted to market competitive models and do not deal as yet with complicated hierarchical systems' functioning. The nowadays existing multi-attribute utility theory can be applied only to the stage preceding the product's design and determining the objectives for future market competition.
2. We suggest implementing the utility concept as a generalized system's quality estimate which takes into account several essential parameters. The latter usually define the quality of the system as a whole. We have developed a generalized harmonization problem in order to maximize the system's utility. The corresponding model is optimized by means of a two-level heuristic algorithm. At the upper level (the level of independent parameters) a relatively simple search procedure, e.g. the cyclic coordinate algorithm, has to be implemented. At the lower level partial harmonization problems to optimize the dependant parameters, have to be used. Note, that nowadays there is no formalized linkage between the system's parameters and attributes and, thus, no optimization problem can be put and solved in order to maximize the product's utility within its specific life cycle. The developed research enables implementing such a linkage, in future, on the stages of both designing and creating new products and, later on, on the stage of marketing the product.
3. Harmonization approaches in Reliability and Safety Engineering have been successfully used to develop various cost–reliability optimization models. The latter are applicable to a broad spectrum of hierarchical technical systems with a possibility of hazardous failure at the top level and a pre-given multi-linkage of failure elements at different levels. Such systems cannot be analyzed by means of former publications [5,6,12].
4. In order to obtain quasi-optimal solutions of harmonization problems in Reliability and Safety Engineering, we have implemented the sensitivity analysis in the corresponding optimization algorithms. Sensitivity values (e.g. cost-reliability sensitivity) have been successfully utilized for developing heuristic computational techniques.

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