POLISH MARITIME RESEARCH 4(67) 2010 Vol 17; pp. 72-78
10.2478/v10012-010-0039-7

Bayesian methods in reliability of search and rescue action

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ABSTRACT

This paper concerns the application of bayesian network to planning and monitoring life saving actions at sea. The presented bayesian network was formed a.o. on the basis of the determined life raft safety function. The proposed bayesian network makes it possible to determine reliability of conducted life saving action, with accounting for a large number of events which influence course of the action. Reliability control was proposed to be applied to search and rescue - SAR action in contrast to risk control. Reliability levels were defined to make the assessing of safety of conducted SAR action, possible.

Keywords: coordinator, SAR action, reliability, Bayesian network

INTRODUCTION

Life saving actions at sea constitute suitably coordinated operations undertaken with the use of avaliable forces and means necessary to provide effective help to people being in potential or real danger at sea. Success of such action is decided first of all by its appropriate coordination defined as an ordered action aimed at providing help to people in distress at sea.

Plannning and executing the action is carried out on the basis of limited information. Presently is observed a general trend of implementing the decision-aiding systems aimed at improving safety in sea shipping. The bayesian network proposed in this paper is a tool which may serve as an element of a decision- aiding system for SAR-action coordinator.

DESCRIPTION OF BAYESIAN NETWORK OF SAR ACTION

The operational reliability of SAR action, (R_{SAR}), is the reliability of executors, subjects and elements of the action, measured by the probability of task realization within a given time interval Δt or given hydrometeorological conditions – wind velocity [3, 4, 5].

General assumptions of bayesian methods [8]:

- by making use of Bayes theorem, results of observations are combined with a priori information by using which a posteriori distribution of an estimated parameter can be obtained,
- decision concerning choice of an estimator for a parameter in question is made in such a way as to make expected losses resulting from the decision as small as possible:

$$P(A_i | B) = \frac{P(A_i)P(B | A_i)}{\sum_{i=1}^{n} P(A_i)P(B | A_i)}$$

where:
A – original event
B – secondary event

The Bayes theorem enables the action coordinator to combine a priori information with results of past SAR actions. The SAR action coordinator having experience and skill acquired from SAR actions previously coordinated by him, is equipped with knowledge necessary for estimating probability of such action elements which change the values have been so far at hand.

The tests performed by the CTO [2, 12] and Aeronautical Institute [2, 13] made it possible to determine the wind leeway [2], and safety function – the life raft reliability R_{tr} [5, 6].

$$R(x) = P_r\{Z_{tr} > x\} \tag{1}$$

The safety function – life raft reliability [5, 6] is as follows:

$$R(x) = P(Z_{tr} > x) = 1 - \int_0^x f_Z(z)dz = \\ = 1 - \frac{\lambda_1^{\alpha_1}\lambda_2^{\alpha_2}}{3^{\alpha_1}2^{\alpha_2}B(\alpha_1, \alpha_2)} \int_0^x \frac{z^{\alpha_2 - 1}}{(\frac{\lambda_1}{3} + \frac{\lambda_2}{2}z)^{\alpha_1+\alpha_2}}dz \quad z > 0 \tag{2}$$

where:
R(x) – life raft reliability, safety function
Z_{tr} – maximum value of life raft speed (wind leeway),

x – wind velocity,
y – speed of life raft expressed numerically,
a, b – mean values of the independent non-negative random variables A, B
A – random variable of the gamma distribution $G(\alpha_1, \lambda_1)$
B – random variable of the gamma distribution $G(\alpha_2, \lambda_2)$

The reliability function values determined from Eq. (2) are presented in Tab. 1.

***Tab. 1.** Values of the reliability function for 6-person life raft [5, 6]*

Wind velocity x [kn]	Life raft without drift anchor 6-1 pers.	Life raft without drift anchor 6-6 pers.	Life raft with drift anchor 6-1 pers.	Life raft with drift anchor 6-6 pers.
	R(x)	R(x)	R(x)	R(x)
40	0.999996	0.9999999	0.99998	0.9999999997
44	0.9991	0.9999997	0.9982	0.9999997
48	0.9712	0.99992	0.9546	0.9998
52	0.7785	0.9962	0.7122	0.9943
56	0.3895	0.9474	0.3128	0.9311
60	0.1046	0.7405	0.0717	0.6947
64	0.0151	0.3945	0.0088	0.3434
68	0.0012	0.1304	0.0006	0.1037
72	0.00006	0.0267	0.00003	0.0193
76	2.23971×10^{-6}	0.0035	8.1781×10^{-7}	0.0023

The survival probability of object in water, $S_p(t)$, is presented in Fig. 1.

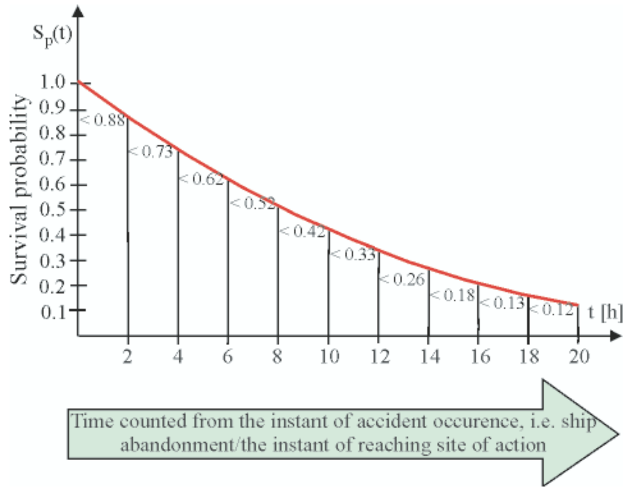


***Fig. 1.** The survival probability of object in water, $S_p(t)$, in function of time, at 20°C water temperature, elaborated acc. [1]*

$$S_p(t) = e^{-0.1654\,t^{1.3213}e^{-0.071\cdot tw}}$$

where:
tw – water temperature

The defined parameters $R_{(x)}$, $S_p(t)$ independent of coordinator of SAR action make it possible to form a bayesian network.

The determined reliability parameters of particular elements of SAR action system enable to perform reliability analysis of SAR action by using the bayesian network.

The bayesian network for one search ship and one searched for object, elaborated with the use of Hugin Program, v. 7.3

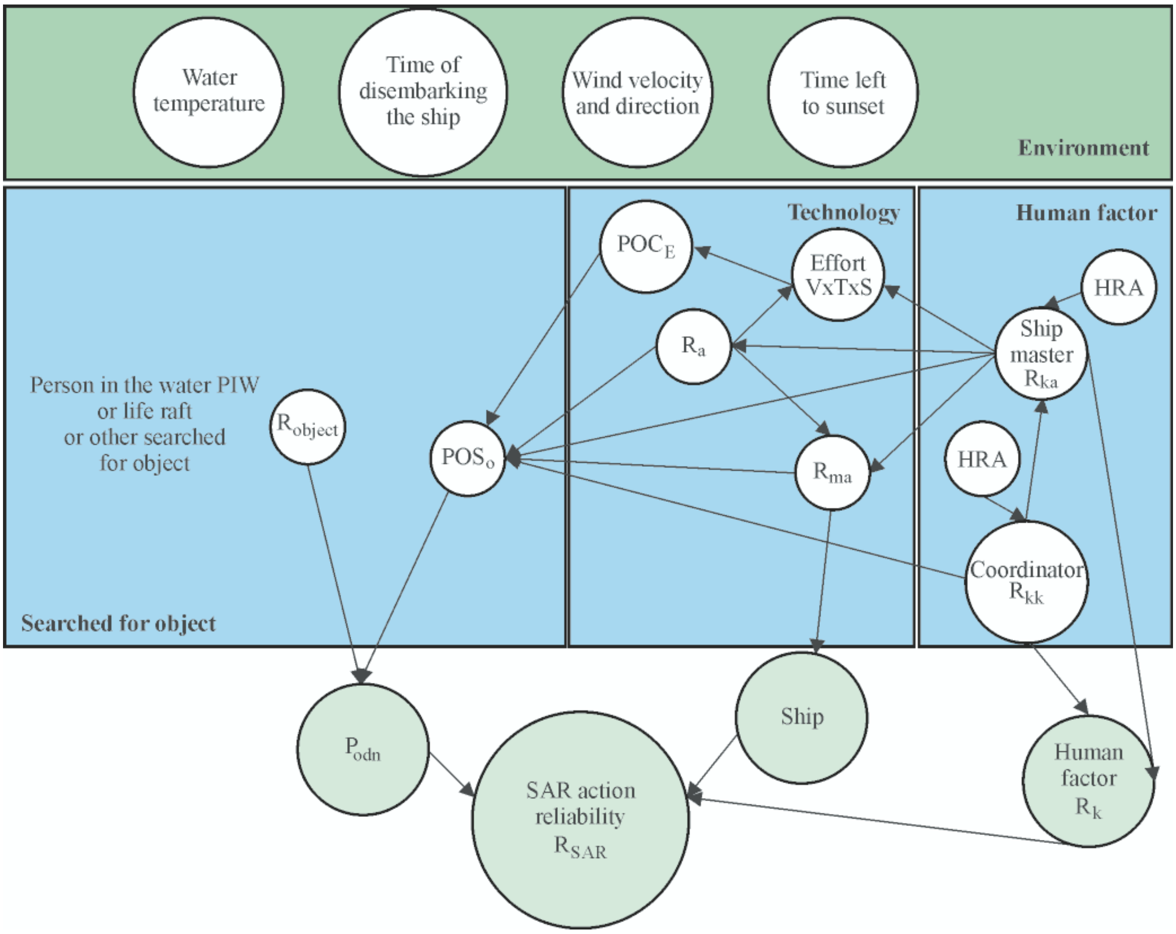


***Fig. 2.** The bayesian network for one search ship and one searched for object*

__Tab. 2.__ Events, descriptions and states of bayesian network of SAR action

Item	Description	State	
P_{odn}	probability of finding the searched object	high	low
R_a	technical operational reliability of the search ship (a)	technically serviceable/ stable	lack of technical serviceability /lack of stability on searching courses
POC_E	probability of containment of the object within a given search area (complying with an available effort of search ship)	location of the object complies with the assumed capability (effort) of the search ship	location of the object lies above the assumed capability (effort) of the search ship
R_E	effort aimed at possible finding the search object by the search ship	possibility of coping with the task	lack of possibility
POS_o	probability of reaching success in finding the searched for object	success	lack of success
R_{ka}	reliability of ship master and crew (experience, knowledge etc)	[sufficient] training acquired at sea	lack of sea training
R_{kk}	reliability of SAR action coordinator (experience, knowledge, practice etc)	experienced [enough]	lack of experience
R_{object}	reliability of life raft, a searched for object	[sufficient] reliability	unreliability
R_{ma}	reliability of the ship (a) assigned to SAR action	[sufficient] seaworthiness	lack of seaworthiness
HRA	human reliability assessment,	lack of errors /lack of stress	errors/stress
S_p	probability of survival in water (PIW)	reliability	unreliability

INFLUENCE OF POC ON RELIABILITY OF SAR ACTION

Search area [10, 11] may be determined for:

1) capabilities of the search ships (a + b + c).
   The available effort of search ship is as follows:

$$Z = V \cdot T \cdot W$$

where:

Z – available effort of search ship
V – speed of the ship sweeping a given area,
T – assumed time for SAR action, time left to sunset
W – sweep band width

2) the assumed probability of containment of searched for object, POC, [2, 10, 11].
   The detection probability equation in relation to a detector under monotonous motion is expressed as follows [7, 9]:

$$p(x) = 1 - e^{-\frac{2kh_O}{Vx^2}}$$

where:

k – detection factor
h_O – location height of observer
x – transverse distance between observer and sensor

By integrating the above given function it is possible to determine the sweep width W, [7, 9]:

$$W = \int_{-\infty}^{+\infty} 1 - e^{-\frac{2kh_O}{Vx^2}} dx = 2\sqrt{\frac{2\pi kh_O}{V}}$$

Example

SAR action has to be undertaken for the following searched for objects: 6-person life rafts and a person in the water (PIW) in the following hydrometeorological conditions: cloud ceiling of 300 m, 7-9°B, water temperature of 20°C, visibility up to 5 NM, wave height of 1÷1,5 m. Time left to sunset of 4 h. Three ships: (a), (b) and (c) are engaged in the action;. the search area $A_o = 100$ [NM^2]

Areas for Z values - the available efforts of the search ships (a), (b) and (c):

- for the ship (a) at V=16 kn:

$$Z = V \cdot T \cdot W = 16 \cdot 4 \cdot 0.25 = 16.0 \text{ [NM}^2\text{]}$$

$$\mathbf{POC_a = 0.71}$$

- for the ship (b) at V=9 kn:

$$Z = V \cdot T \cdot W = 9 \cdot 4 \cdot 0.25 = 9.0 \text{ [NM}^2\text{]}$$

$$\mathbf{POC_b = 0.58}$$

- for the ship (c) at V=4 kn:

$$Z = V \cdot T \cdot W = 4 \cdot 4 \cdot 0.25 = 4.0 \text{ [NM}^2\text{]}$$

$$\mathbf{POC_c = 0.27}$$

where:

T – assumed time for SAR action, time left to sunset

The sweep band width determined for PIW:

- acc. Table N-4 – Sweep width for merchant vessels 0.5 NM, [10, 11]
- acc. Table N-7 – Weather correction factors for all types of search facilities 0.5 [10, 11]

<u>For the area swept by the search ship (a):</u>

$$Z = V \cdot T \cdot W = 16 \cdot 4 \cdot 0.25 = 16.0 \text{ [NM}^2\text{]}$$

(Expanding square search pattern acc. to IAMSAR [10, 11])

The total probability of SAR action reliability under the made assumptions:

- **POC_a = 0.71**
- influence of human factor: R_{kk} = 0.85
- influence of search ship: R_{ma} = 0.81
- influence of finding- the- object parameter: P_{odn} = 0.48
  R_{SAR} = 0.57

<u>For the area swept by the search ship (b):</u>

$$Z = V \cdot T \cdot W = 9 \cdot 4 \cdot 0.25 = 9.0\ [NM^2]$$

(Expanding square search pattern)

The total probability of SAR action reliability under the made assumptions:
- **POC_b = 0.58**
- influence of human factor: R_{kk} = 0.85
- influence of search ship: R_{ma} = 0.81
- influence of finding- the- object parameter: P_{odn} = 0.45
  R_{SAR} = 0.53

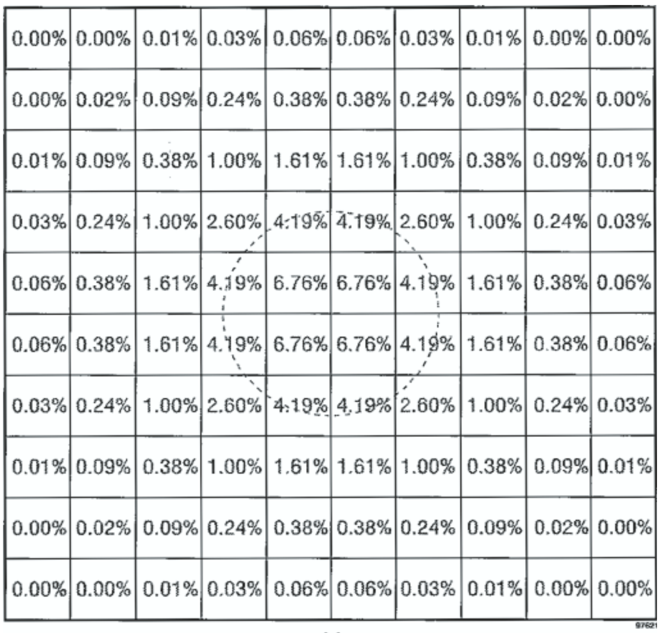
<u>For the area swept by the search ship (c):</u>

$$Z = V \cdot T \cdot W = 4 \cdot 4 \cdot 0.25 = 4.0\ [NM^2]$$

(Expanding square search pattern)

The total probability of SAR action reliability under the made assumptions:
- **POC_c = 0.27**
- influence of human factor: R_{kk} = 0.85
- influence of search ship: R_{ma} = 0.81
- influence of finding- the- object parameter: P_{odn} = 0.36
  R_{SAR} = 0.49

The probabilities POC_a, POC_b, POC_c, are decisive for the reliability R_{SAR}
- POC = 0.99 R_{SAR} = 0.67 (for search area A_o = 100 [NM^2])
- POC_a = 0.71 R_{SAR} = 0.57 for the ship (a)
- POC_b = 0.58 R_{SAR} = 0.53 for the ship (b)
- POC_c = 0.27 R_{SAR} = 0.49 for the ship (c)



0.00%	0.00%	0.01%	0.03%	0.06%	0.06%	0.03%	0.01%	0.00%	0.00%
0.00%	0.02%	0.09%	0.24%	0.38%	0.38%	0.24%	0.09%	0.02%	0.00%
0.01%	0.09%	0.38%	1.00%	1.61%	1.61%	1.00%	0.38%	0.09%	0.01%
0.03%	0.24%	1.00%	2.60%	4.19%	4.19%	2.60%	1.00%	0.24%	0.03%
0.06%	0.38%	1.61%	4.19%	6.76%	6.76%	4.19%	1.61%	0.38%	0.06%
0.06%	0.38%	1.61%	4.19%	6.76%	6.76%	4.19%	1.61%	0.38%	0.06%
0.03%	0.24%	1.00%	2.60%	4.19%	4.19%	2.60%	1.00%	0.24%	0.03%
0.01%	0.09%	0.38%	1.00%	1.61%	1.61%	1.00%	0.38%	0.09%	0.01%
0.00%	0.02%	0.09%	0.24%	0.38%	0.38%	0.24%	0.09%	0.02%	0.00%
0.00%	0.00%	0.01%	0.03%	0.06%	0.06%	0.03%	0.01%	0.00%	0.00%

H
(10×10)

***Fig. 3.** Location of a searched for object, under assumption of normal distribution [10, 11]*

The faultlessly performed SAR action consists in:
- lack of stress, highly experienced ship master: R_{ka} = 1.0, and highly experienced coordinator of the action: R_k = 1.0,
- high technical operational effectiveness: R_a = 1.0, and high seaworthiness of the search ship: R_{ma} = 1.0
- maximum possible effort for sweeping the assigned area, POC = 0.71.

In the case of a faultlessly performed SAR action (for POC = 0.71) the initial reliability POS_o = 0.62 increases to POS_o = 0.76.

PROBABILITY OF FINDING A SEARCHED FOR OBJECT DURING SAR ACTION

The search area A_o constitutes a part of water area limited by a circle determined by its centre placed in the reference point P_o, and the optimum sweeping radius R_o, within which the probability of containment of searched for object is equal to POC = 0.999.

According to IAMSAR [10, 11]:
- The optimum search area (in case of its circular form):

$$A_o = 4 \cdot R_o^2$$

- The search area cover factor:

$$C = Z/A_o$$

- The SAR action success probability acc. IAMSAR [10, 11]:

$$POS = POD \cdot POC$$

The SAR action success probability POS is the product of the detection probability POD and the probability of containment of the object within a given area, POC.

The detection probability POD, [10, 11], depends on the area cover factor C.

The detection probability POD [7]:

$$POD = 1 - e^{-C}$$

where:

A_o – search area
POS – success probability
POC – containment probability of the object within a given search area
R_o – search area radius
C – search area cover factor
POD – detection probability

In the presented bayesian network the probability of finding the searched for object, P_{odn}, depends on reaching success of the SAR action conducted within a given area and reliability of the searched for object:

$$P_{odn} = R_{object} \cdot POS_o$$

The probability of success in sweeping the search area POS_o (bayesian network) takes into account the coordinator reliability R_k, ship master reliability R_{ka}, ship's technical operational reliability R_a, its seaworthiness R_{ma}, probability of containment of searched for object within a given area, POC_E.

The probability of finding the searched for object P_{odn} (bayesian network) takes into account the reliability of the searched for object (S_p and R_{object}), as well as the probability of success in sweeping a given area, POS_o, in contrast to the IAMSAR recommendations [8, 9], in which the area cover factor C = Z/A_o and POC appear.

SAR ACTION RELIABILITY CONTROL

The elaborated bayesian network which enables to determine the SAR action reliability R_{SAR}, may be used to control reliability. Obviously, SAR action coordinator will not be able to influence all events of the bayesian network. There will appear such parameters as the life raft safety function – the reliability R_{tr} or the survival probability of object- in- water, S_p, on which he would have only a minor influence since a properly planned action resulting in shortening duration time of the action would improve the reliability S_p in contrast to the R_{tr} which is directly affected by wind velocity.

The approach based on the control of reliability of subjects and elements of SAR action system is composed of the following phases:

1. Determination of reliability of subjects and elements of SAR action system.
2. Reliability estimation:
    a. assessment and determination of limit reliability parameters enabling SAR operations
3. Selection and hire of SAR subjects for SAR action with taking into account their reliability values.
4. Current control of reliability parameters of SAR action subjects and elements:
    a. changes in the planning and executing of SAR action system aimed at improving reliability of the elements whose reliability really lowers the whole action reliability R_{SAR}
5. Elimination of such SAR action subjects whose reliability parameters could lead to hazardous situation – break down of SAR action.
6. Monitoring the reliability parameters of SAR action elements.

The general principles of reliability evaluation are proposed as follows:

- low risk if: $R_{SAR} \geq 0.7$
    - SAR action should be monitored (admissible level)
- moderate risk if: $0.7 \geq R_{SAR} \geq 0.5$
    - reliability of an element/elements which lower SAR action reliability should be improved (admissible level, reservedly)
- high risk if: $R_{SAR} \leq 0.5$
    - this level should not be allowed to happen. Such drop will make the action dangerous, i.e. causing hazards to SAR action personnel and sea environment, and leading to loss of rescue ships. SAR action will end without any success (inadmissible level).

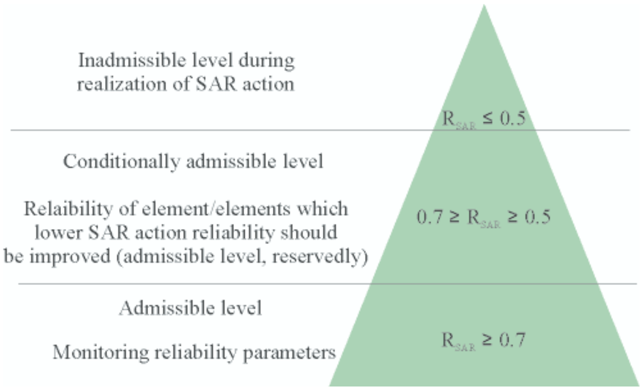


Fig. 5. Scheme of the application of the reliability principles to SAR action

To improve the reliability $\mathbf{R_{SAR}}$ the following steps should be made:

- to estimate the reliability parameters,
- to select only such elements which are able to bring effectively and fast a definite improvement of reliability,
- to decide whether the changes introduced to the system are realistic and capable of improving its reliability.

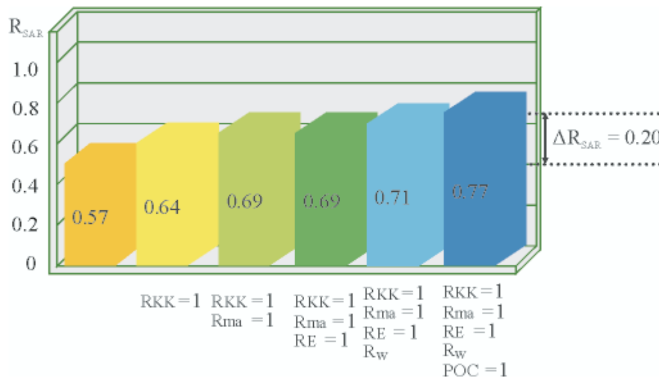


Fig. 6. The reliability increase ΔR_{SAR} = 0,20 by improving reliability of selected elements of SAR action (an example of reliability control)

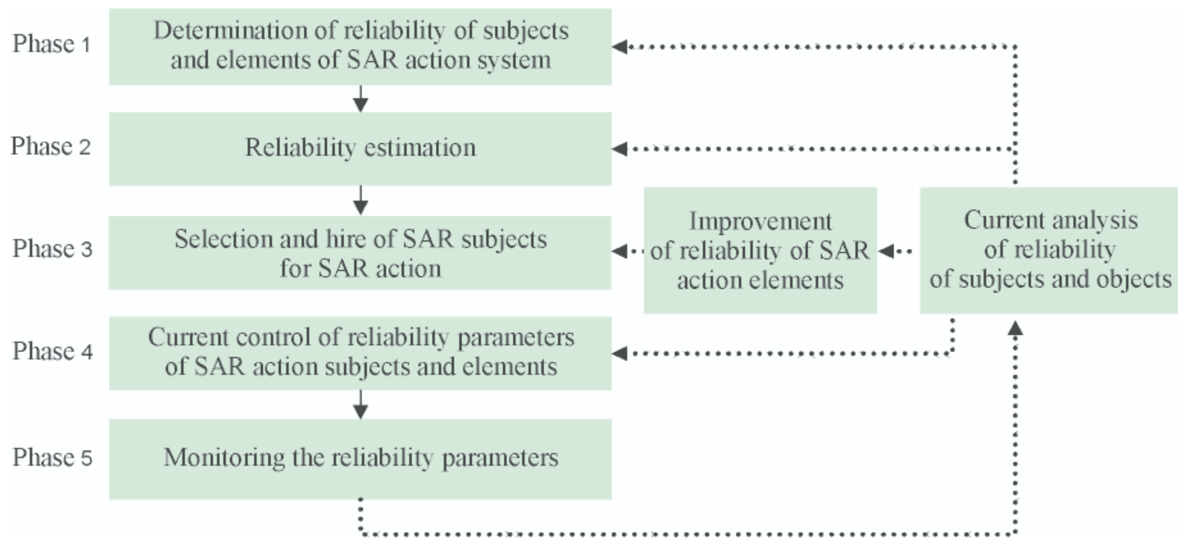


Fig. 4. SAR action reliability control diagram

The improvement of reliability of the selected elements of SAR action system as a result of the reliability control will improve the SAR action reliability R_{SAR}, up to its admissible level: $\mathbf{R_{SAR} = 0.77}$. Hence the action should be continued.

Tab. 3. Influence of reliability of ship master and SAR action coordinator on the SAR action reliability R_{SAR}

R	Description	[-]	[-]	[-]	[-]	[-]	[-]	[-]
R_k	SAR action coordinator reliability	**0.89**	0	0.54	**0**	1.0	0.93	**1.0**
R_{ka}	Ship master reliability	**0.87**	0.48	0	**0**	0.92	1.0	**1.0**
R_{SAR}	SAR action reliability	**0.57**	0.26	0.16	**0.1**	0.61	0.61	**0.64**

The following results from Tab. 3:

- The lack of sea practice and experience in qualifications of ship master and SAR action coordinator results in that the planned SAR action is from the very beginning doomed to failure as $\mathbf{R_{SAR} = 0.1}$.
- The drop in the SAR action coordinator reliability R_{kk} results in the drop of the ship master reliability R_{ka} and vice versa the drop in the ship master reliability lowers the drop in SAR action coordinator reliability (lack of communication).
- The high level of experience/sea practice in qualifications of ship master or coordinator makes mutually the coordinator's or ship master's reliability increasing (good communication, understanding) that leads to $\mathbf{R_{SAR} = 0.64.}$

Example

A_1 - the event consisting in that the ship master takes decision on searching for a castaway in an assigned area,

A_2 - the event consisting in that the coordinator takes decision on locating a castaway in the same area as that assigned by the ship master,

B - the event consisting in finding a castaway in the assigned area,

$\overline{B}$ - the event consisting in not finding a castaway in the assigned area: $P(B) = 0.6$, $P(\overline{B}) = 0.4$

$P(A_1|B) = 0.6$ - probability of correctness of the ship master's inference concerning location of a castaway,

$P(A_1|\overline{B}) = 0.5$ - probability of incorrectness of the ship master's inference concerning location of a castaway,

$P(A_2|B) = 0.7$ - probability of correctness of the coordinator's inference,

$P(A_2|\overline{B}) = 0.5$ - probability of that the castaway is not located within the area assigned by the coordinator (incorrect assumption made by the coordinator).

By using Bayes theorem the following values of the probability of finding the castaway within the area assigned by the ship master and coordinator, are obtained:

$$P(B|A_1) = \frac{P(B)P(A_1|B)}{P(B)P(A_1|B) + P(\overline{B})(P(A_1|\overline{B})} =$$

$$= \frac{0.6 \cdot 0.6}{0.6 \cdot 0.6 + 0.4 \cdot 0.5} = \frac{36}{56} = \frac{9}{14} = 0.6428$$

$$P(B|A_2) = \frac{P(B)P(A_2|B)}{P(B)P(A_2|B) + P(\overline{B})(P(A_2|\overline{B})} =$$

$$= \frac{0.6 \cdot 0.7}{0.6 \cdot 0.7 + 0.4 \cdot 0.5} = \frac{42}{62} = \frac{21}{31} = 0.6774$$

It can be assumed that the events A_1 and A_2 do not depend to each other. Then on the basis of the Bayes formula the probabilities of finding the castaway can be estimated if only the opinions of both the ship master and coordinator have been accounted for simultaneously:

$$P(B|A_1 \cap A_2) = \frac{P(B)P(A_1 \cap A_2|B)}{P(B)P(A_1 \cap A_2|B) + P(\overline{B})P(A_1 \cap A_2|\overline{B})} =$$

$$= \frac{P(B)P(A_1|B)P(A_2|B)}{P(B)P(A_1|B)P(A_2|B) + P(\overline{B})P(A_1|\overline{B})P(A_2|\overline{B})}$$

$$P(B|A_1 \cap A_2) = \frac{0.6 \cdot 0.6 \cdot 0.7}{0.6 \cdot 0.6 \cdot 0.7 + 0.4 \cdot 0.5 \cdot 0.5} =$$

$$= \frac{252}{362} = 0.7159$$

The example shows that accounting for two opinions may increase probability of success of SAR action.

In planning and executing SAR action, an additional information, e.g. provided by ship master, introduced to the Bayes theorem, leads to a higher accuracy of evaluation of a planned and executed SAR action.

CONCLUSIONS

- The determined reliability measure of SAR action based on the elaborated bayesian network will allow for influencing safety of to-be-rescued people and rescueing personnel.
- Bayesian network elaborated by a SAR action coordinator would be subjective. However, if elaborated on the basis of experience and sea practice of the coordinator aided by a team of advisors (e.g. by brain storming), it will be capable of reflecting reality of a realized SAR action.
- Every SAR action planned by its coordinator should be aided by an appropriate bayesian network which makes it possible to evaluate reliability of a planned and executed SAR action.
- During execution of coordinated SAR action it will be possible to monitor and control its reliability.
- The bayesian network makes it possible to account for more parameters and thus becomes more reliable for SAR action coordinator, that is especially important in the case of action realized on the basis of incomplete and uncertain information.

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