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Integrated navigation system - safety prediction model for ship retrofit strategy

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ABSTRACT: The introduction of highly integrated and automated technology into navigation systems, aiming, amongst others, to decrease personnel onboard the ship, calls for efficient tools to assess the possible impacts of this new trend on the safety levels associated with the operation of the ship. This trend has lead in recent years to the investigation of the adoption of advanced risk assessment techniques. The scope of the paper is to present a quantified safety assessment methodology that can be applied while retrofitting navigation systems. The methodology is based on the review of the IMO Formal Safety Assessment technique and consists in the development of a Safety Prediction Model for the safety assessment of the different automation/ integration levels subject of a retrofit. The application presented in the paper is part of the work performed under the ATOMOS IV research project, partly funded by the DGTREN Directorate of the European Commission.

1 THE ATOMOS IV PROJECT AND THE RETROFIT CONCEPT

The primary objective of the ATOMOS IV project is to bring advanced computer and control technology to the European Fleet, in the fastest and most cost-effective manner possible. Since the Fleet is not being actively renewed, introduction through new building is slow. However, whilst most ship equipment has a long operational life, control systems based on computers become outdated within a few years of installation. If a reliable process for replacing this technology with new systems is made available the effectiveness and safety of a vessel could be enhanced several times during its operational life.

As a consequence, the development of a methodology for assessing the potential benefits of the retrofit of the European Fleet is the primary goal of ATOMOS IV.

Achieving retrofit of modern control systems is expected to provide at least the following benefits:

– improved safety of operation;
– introduction of more human-centred and usable systems;
– access to information;
– faster and more reliable operation.

In addition, through the real retrofit of the Swedish icebreaker Frej with the ATOMOS fully integrated Ship Control Centre, the project is applying and validating the processes and the tools related to the successful implementation of control system retrofit: e.g. human-centred development process for ship control centres and interfaces, risk-based development applying safety assessment techniques, principles-based assessment for programmable systems, preparatory and refresher training using computer-based training tools.

The decision process for retrofitting existing ships starts from the prediction/ evaluation of the expected costs, savings and safety improvement. The safety prediction is therefore considered as a source of information to the ship owner, giving the necessary confidence that a particular retrofit strategy has positive impacts on the overall risk level associated with the operation of that particular ship.

The purpose of the present paper is to provide a preliminary assessment of the expected safety benefits originated by the implementation of a particular upgrading strategy on a specific ship.

After the introduction on the possible technology configurations of a ship, the theoretical framework of the Safety Prediction Model (SPM) is depicted and a preliminary calibration of the parameters is presented.

2 DEFINITION OF THE AUTOMATION/ INTEGRATION LEVELS

The Automation/ Integration Levels (AILs) can be defined on the basis of several possible configurations of technologies needed onboard, their monitoring principles and, above all, their control philosophy.

In general, every ship might be considered as a unique specific application of the current available architectures of control/monitoring devices. Nevertheless, for the purpose of developing the SPM in a feasible way, the possible configurations are grouped in a minimal set of congruent AILs. The analysis presented below is only one possible way to approach the task; in the future, as needed, the classification can be modified/refined on the basis of improved knowledge of the problem.

It is however highlighted that the SPM developed in the present document is conceived in the most versatile way. Should the definition of AIL change, the model can be easily adapted to the new baseline.

In order to define a coherent set of AILs, two main aspects have been taken into account:

– the increasing automation that can be included on a ship;
– the increasing integration that can be adopted for different technologies needed to support ship's operation.

In particular, the following levels of increasing automation are considered: Remote Monitoring; Remote Control; Integrated Remote Monitoring/ Control.

The above levels of automation are usually concurrently introduced with an increased integrated architecture of the total system: No integration; Unmanned Machinery Space (UMS); Physical Integration (Central Control Station - CCS); Interconnection; Integration; Fully Integrated Ship Control.

A combination of the above two aspects (automation and integration) can lead to the following levels (see Table 1):

Table 1. Definition of the Automation/ Integration Levels

Automation/ Integration Levels (*j*)	
AIL1 (*j*=1)	Manual: the ship is completely manual, all the monitoring and control tasks are performed by the crew under the supervision of the officers.
AIL 2 (*j*=2)	Remote Monitoring: one or more technologies are wired to a monitoring system, usually installed close to the associated equipment.
AIL 3 (*j*=3)	UMS: main engines and power generators are remotely controlled and monitored from the bridge. This level is considered because reflects a precise achievement in terms of classification.
AIL 4 (*j*=4)	Automation of Individual Systems (e.g. main engines, power management, auxiliary services): one or more systems are fully automated in terms of both monitoring and control. There is still no integration whatsoever among different systems.
AIL 5 (*j*=5)	CCS: one or more automation are physically located in a specific place called Central Control Station: it is the first step of true integration.
AIL 6 (*j*=6)	Interconnected System: the remote control/monitoring systems are connected and exchange data and information.
AIL 7 (*j*=7)	Integrated Bridge System (IBS, see IEC/CEI 61209, 1999): information are integrated in a network that delivers to every control/monitoring system the data needed to integrate functions.
AIL 8 (*j*=8)	One Man Bridge: a fully integrated console is able to control/monitor the whole ship through an integrated networking of every information. The ship can be sailed safely controlling everything from a single location.

The result of the process adopted to derive the above levels is depicted in the Figure 1.

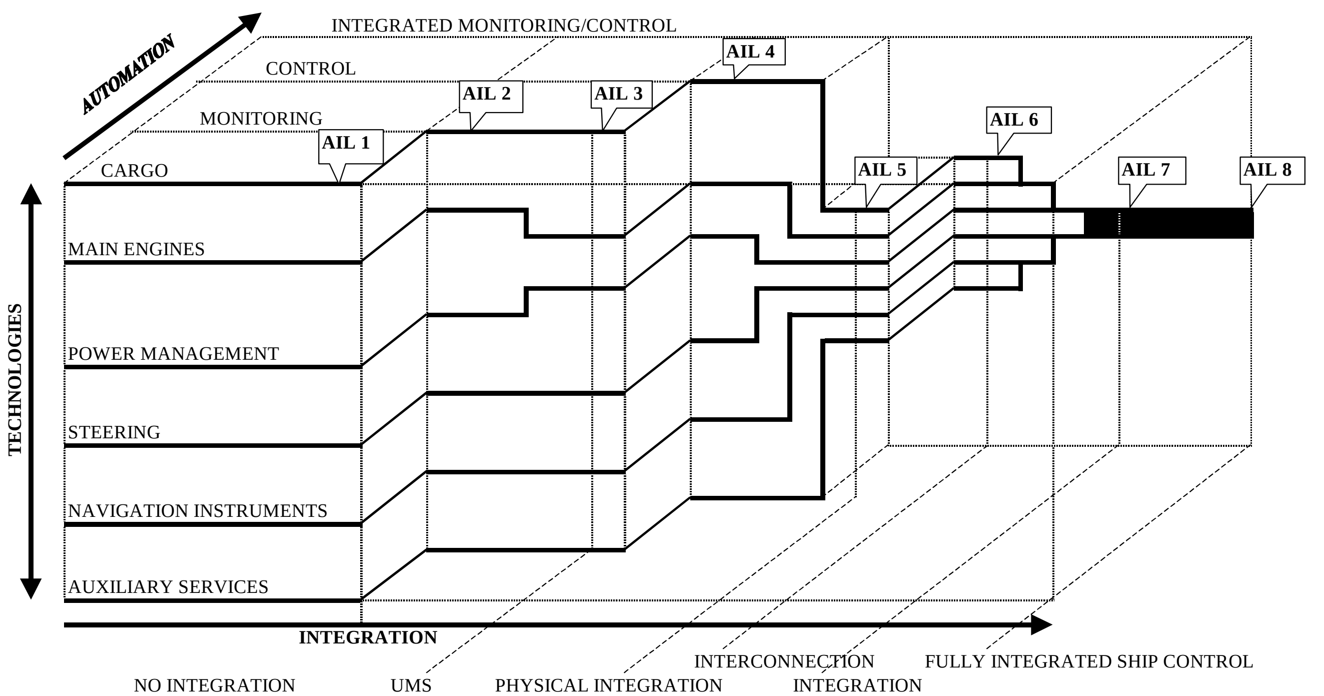

Figure 1. Overall Concept of Automation/Integration Levels

3 OVERVIEW OF THE SAFETY PREDICTION MODEL

For the sake of clarity, the following notions, used to formalise the SPM, are introduced (see Table 2).

Table 2. Fundamental Notions of the Safety Prediction Model

Notion
AIL j (j=1,2,…,n): the Automation/ Integration Level.
Accident category k (k=1,2,….,v): the event category, which is stood out in the taxonomy used within the Formal Safety Assessment (FSA) methodology (e.g. collision, contact, etc.).
Risk assessment model: the model adopted for the assessment of the frequency of occurrence and of the severity of the hazard. The evaluation is performed by means of the Fault Tree Analysis technique (FTA), where the hazard is the outcome of all possible causes (both systems' failures and human errors), and of the Event Tree Analysis technique (ETA), where the possible accident scenarios, developing from the selected hazard, are considered.
Safety level s: the frequency of occurrence of accident, expressible in suitable units, such as the expected the number of fatal events per year or the number of fatalities per year.
Safety Factor i (i=1,2,…,u): parameter influencing the safety level, e.g. the availability of a monitoring system, the increased HMI, the reduced crew, etc.

The SPM is structured in the following parts:

– prediction of the safety level of a generic ship for the accident category k and for the technology configuration j (see section 3.1);
– prediction of the safety level of a specific ship type for the Automation/ Integration level j (see section 3.2);
– calibration/quantification of the SPM (see sections 3.3, 3.4, 3.5, 3.6);
– considerations on possible external constraints affecting the estimation of the safety level (see section 3.7).

3.1 *Prediction of the safety level for a generic ship*

The following safety levels are considered:

– s_{kj}: safety level of a generic ship associated with the accident category k and with the AIL j;
– s_{kji}: safety level of a generic ship associated with the accident category k, the AIL j and the Safety Factor i. In other terms, it represents the frequency of occurrence of the accident k due to the Safety Factor i, for the AIL j.

The safety level s_{kj} is expressed as a function g_{kj} of the safety levels s_{kji} (i=1,2,…,u):

$$s_{kj} = g_{kj}(s_{kji}) \qquad i = 1,2,...,u \tag{1}$$

where s_{kji} is calculated by means of the Risk assessment model calibrated for the Safety Factor i, the accident category k and the AIL j.

Since the model is involved in predicting the effect of a particular retrofit strategy on an existing ship's configuration, instead of absolute values, we consider only differential values from a baseline configuration, which is assumed to be j=1:

$$d_{kj} = s_{k\ j=1} - s_{kj} \tag{2}$$

$$d_{kji} = s_{k\ j=1} - s_{kji} \tag{3}$$

Hence, combining Expressions 2 and 3 into 1:

$$d_{kj} = g'_{kj}(d_{kji}) \qquad i = 1,2,...,u \tag{4}$$

where:

$$g'_{kj}(d_{kji}) = s_{k\ j=1} - g_{kj}(s_{k\ j=1} - d_{kji}) \quad i = 1,2,...,u \tag{5}$$

It is assumed to use, for the evaluation of d_{kji}, a unique risk assessment model for every AIL j. Therefore:

$$d_{kji} \cong d_{ki} \tag{6}$$

Thus, Equation 4 is simplified in the following:

$$d_{kj} \cong g'_{kj}(d_{ki}) \qquad i = 1,2,...,u \tag{7}$$

Expression 7 is approximated with a linear combination of the differential safety levels d_{ki}.

$$d_{kj} \cong \sum_{i=1}^{u} d_{ki} r_{ij} + b_k \tag{8}$$

where r_{ij} = coefficient representative of the relationship between the Safety Factor i and the AIL j; b_k = denominate number.

The terms in Expression 8 must comply with the boundary conditions:

$$d_{k\ j=1} = 0 \quad d_{k\ j=n} = s_{k\ j=1} - s_{k\ j=n} \tag{9}$$

In order to have an estimate of the differential safety level d_{ki}, the Risk assessment model for the accident category k has been applied for every Safety Factor (SF) considering all the effects excluding the specific SF i under consideration. The result of the run of the Risk assessment model provides the safety level s'^{c}_{ki}.

The differential safety level d'_{ki} is then computed on the basis of the risk reduction associated with a full retrofit to AIL j=n, having assumed that this reduction is equal to the differential value of the safety level s'_{ki} with respect to the configuration AIL j=1 (see Expression 10).

$$d'_{ki} = s_{k\ j=1} - s'_{ki} \cong s'^{c}_{ki} - s_{k\ j=n} \tag{10}$$

In general the overall effect of all the involved SF is not the simple sum of the individual effects (see Expression 11) because of the non-linearity of the risk assessment model adopted for the calculation of the terms d'_{ki}.

$$\sum_{i=1}^{u} d'_{ki}(r_{i\ j=n} - r_{i\ j=1}) \neq d_{k\ j=n} \quad (11)$$

Therefore the differential safety level d_{ki} is computed by means of a weighted average (see Expressions 12 and 13):

$$d_{ki} \cong a_k d'_{ki} \quad (12)$$

where:

$$a_k = \frac{d_{k\ j=n}}{\sum_{i=1}^{u} d'_{ki}(r_{i\ j=n} - r_{i\ j=1})} \quad (13)$$

The differential safety level d_{kj} is translated into increase percentages with respect to AIL 1:

$$d^r_{ki} \cong a_k d'_{ki} / s_{k\ j=1} \quad (14)$$

On the basis of Expressions 8, 9, 12 and 13 b_k is formulated:

$$b_k = \frac{d_{k\ j=n}}{\sum_{i=1}^{u} d'_{ki}(r_{i\ j=n} - r_{i\ j=1})} \sum_{i=1}^{u} d'_{ki} r_{t\ j=1} \quad (15)$$

Introducing the Expression 12 into 8:

$$d_{kj} \cong \sum_{i=1}^{u} a_k d'_{ki} r_{ij} + b_k \quad (16)$$

where a_k and b_k are calculated with Equations 13 and 15.

The differential safety level d_{kj} is also translated into increase percentages with respect to AIL 1:

$$d^r_{kj} = \frac{d_{kj}}{s_{k\ j=1}} \cong \sum_{i=1}^{u} d^r_{ki} r_{ij} + b_k \quad (17)$$

3.2 *Prediction of the safety level for a specific ship typology*

The following safety levels are considered:

- s_{lj}: safety level of the ship type l at a particular configuration of the ship's automation/ integration j;
- s_{lkj}: safety level of the ship type l for the accident category k at the technology configuration j.

The safety level s_{lj} is expressed as a function f_{lj} of the safety levels s_{lkj} (k=1,2,…,v):

$$s_{lj} = f_{lj}(s_{lkj}) \qquad k = 1,2,...,v \quad (18)$$

where s_{lkj} is calculated by means of the Risk assessment model calibrated for the ship type l, the accident category k and the AIL j.

In analogy to the previous section we consider only differential values from a baseline configuration, which is assumed to be j=1:

$$d^{\wedge}_{lj} = s_{l\ j=1} - s_{lj} \quad (19)$$

$$d^{\wedge}_{lkj} = s_{l\ j=1} - s_{lkj} \quad (20)$$

Hence, combining Expressions 19 and 20 into 18:

$$d^{\wedge}_{lj} = f'_{lj}(d^{\wedge}_{lkj}) \qquad k = 1,2,...,v \quad (21)$$

It is assumed to use, for the evaluation of $d^{\wedge}_{lkj}$, a unique Risk assessment model for every ship type l. Therefore:

$$d^{\wedge}_{lkj} \cong d^{\wedge}_{kj} \quad (22)$$

Thus, Expression 21 simplifies in:

$$d^{\wedge}_{lj} \cong f'_{lj}(d^{\wedge}_{kj}) \qquad k = 1,2,....,v \quad (23)$$

Equation 23 is approximated with a linear combination of the safety levels $d^{\wedge}_{kj}$:

$$d^{\wedge}_{lj} \cong \sum_{k=1}^{v} p_{lk} d^{\wedge}_{kj} - \sum_{k=1}^{v} p_{lk} d^{\wedge}_{k\ j=1} \quad (24)$$

where p_{lk} = coefficient representative of the relation ship between the accident category k and the ship type l.

Combining Expression 2 with 24:

$$d^{\wedge}_{lj} \cong \sum_{k=1}^{v} p_{lk} d_{kj} \quad (25)$$

Therefore it is possible to formulate the Expression 25 taking into account the terms of the 16:

$$d^{\wedge}_{lj} \cong \sum_{k=1}^{v} p_{lk} \left(\sum_{i=1}^{u} a_k d'_{ki} r_{ij} + b_k\right) \quad (26)$$

where:

- a_k, d'_{ki}, b_k are calculated in the Expressions 13, 10, 15;
- the coefficient r_{ij} represents the weight of d_{ki} on d_{kj};
- the coefficient p_{lk} represents the weight of d_{kj} on d_{lj}.

The differential safety level $d^{\wedge}_{lj}$ is translated into increase percentages with respect to the safety level of the baseline configuration (AIL 1):

$$d^{r\wedge}_{lj} = \frac{d^{\wedge}_{lj}}{s_{l\ j=1}} = \frac{1}{s_{l\ j=1}} \sum_{k=1}^{v} p_{lk} \left(\sum_{i=1}^{u} a_k d'_{ki} r_{ij} + b_k\right) \quad (27)$$

Considering the terms of Equation 17, the ratio differential safety level $d^{r\wedge}_{lj}$ can be also expressed as a function of the ratio differential safety level d^{r}_{kj}:

$$d^{r\wedge}_{lj} \cong \frac{1}{s_{l\ j=1}} \sum_{k=1}^{v} p_{lk} d^r_{kj} s_{k\ j=1} \quad (28)$$

The model is then extended to the compilation of a Safety Prediction Matrix for each considered ship type l:

$$d^{\%}_{l\ j=a\to j=b}=\begin{cases}0 & if \quad b\le a\\ \dfrac{s_{l\ j=a}-s_{l\ j=b}}{s_{l\ j=a}} & if \quad b>a\end{cases} \tag{29}$$

The above expression can be formulated in terms of ratio differential values:

$$d^{\%}_{l\ j=a\to j=b}=\begin{cases}0 & if \quad b\le a\\ \dfrac{d^{r\wedge}_{l\ j=b}-d^{r\wedge}_{l\ j=a}}{1-d^{r\wedge}_{l\ j=a}} & if \quad b>a\end{cases} \tag{30}$$

The generic element of the above Safety Prediction Matrix represents the estimated percentage reduction of risk (or percentage increase on safety) associated with a retrofit strategy from an AIL *a* to an AIL *b* for a specific ship type l.

The calibration of the model is performed by means of the following steps:

- identification of the Safety Factors, affecting the safety level (see section 3.3);
- evaluation of the parameters d^r_{ki} by means of a sensitiveness analysis on the available risk assessment models (see section 3.4);
- determination of the coefficients r_{ij}, on the basis of the definition of the AILs (see section 3.5);
- determination of the coefficients p_{lk} on the basis of statistical inferences from historical accident records; calculation of the percentage differential safety levels $d^{r\wedge}_{lj}$ using Expression 27; compilation of the Safety Prediction Matrix by means of Expression 30 (see section 3.6).

In the following quantification of the model it is pointed out that:

- the safety levels are expressed in fatal events per year;
- the safety levels represent overall risk levels: they are not customised for a specific operating condition of the ship (e.g. operation in port);
- only average values of the safety levels are considered.

3.3 *Identification of the Safety Factors*

The SF are identified considering the key parameters of a ship "system" subject to a potential retrofit. In order to try to capture as much as possible a complete set of SF, we consider a full retrofit from AIL1 (conventional ship) to AIL8 (Fully Integrated Ship Control). For this purpose the task is performed using the work developed during the ATOMOS project, assumed an "ATOMOS" ship as being the highest AIL.

The ATOMOS concept can be viewed to be able to provide innovative solutions at different levels (Zuccarelli et al. 1998):

P at Process level, introducing a newer approach to the design development of a ship, in order to better perform and control the various phases of the ship's lifecycle;

F at Functional level, introducing new functions (or new integration of functions) to the conventional set of ship's functions in order to better or more safely perform the defined mission;

S at Systems/Technological level, introducing new systems and/or technologies to support both new and conventional functions;

H at HMI level, introducing new concepts to address a usable interface to the human element in order to provide an easier and safer control of the ship's systems to the operator (see also SOLAS V Reg. 15).

O at O&M level, introducing new operational and/or maintenance procedures based both on reduced crews and on enhanced support to the operator/maintainer by means of the integrated Ship Control Centre (SCC).

The first level (P), deals with a new "user centred design approach" for the development of a SCC (Gonzàles & Carbajosa, 1998).

At functional level (F), the ATOMOS concept introduces the following functions/integration:

- Planned Maintenance, consisting in the integration of planned maintenance systems with ISC.
- Voyage Planning and Navigation, consisting in the integration of voyage planning, track planning and navigation tools.
- Emergency Management, consisting in continuous monitoring of all relevant safety parameters.
- Hull Stress Monitoring, consisting in monitoring all parameters relevant to the structural integrity of the ship.
- Cargo Management, consisting in an expert layer, an algorithmic layer, an inference engine, a knowledge base and various data repositories containing basic ship data and information on cargo.

At systems/technological level (S), in general, the ATOMOS concept directly implies the adoption of advanced products. This means, on one side, that for conventional systems it is expected that an ATOMOS application presents a generalised evolution to new technologies and architectures, on the other side that the ATOMOS concept introduces some new systems, e.g.: Emergency Management System; Hull Stress Monitoring System; Enhanced Diagnostic System; Cargo Management System.

At HMI level (H), the ATOMOS concept have perhaps the greatest impact. It is expected that an application of the concept is based on an ISC architecture, where all the ship's control will be integrated and managed with an innovative HMI.

Finally, at O&M level (O), the influence of the ATOMOS concept is based on the following assumptions:

– the ATOMOS ship is operated by a reduced crew;
– the ATOMOS ship is operated with the aid of some form of Decision Support System;
– the ATOMOS ship is maintained with a new philosophy based on the new planned maintenance function introduced.

On the basis of the above considerations a set of SF is finally defined. Each of the identified SF can influence the safety of the ship both in "positive" and in "negative" way, where "positive" means that the new feature is considered to increase safety, while "negative" means that some aspect can, on the contrary, potentially leads to increase risks.

For the purpose of the development of the SPM, the SF considered are presented in the following Table 3. It is however highlighted that the model is flexible to the introduction of new SF or to the revision of the actual set.

Table 3. SPM – Definition of the Safety Factors

Safety Factor (*i*)		
SF1	(*i*=1)	Improved operator's awareness during normal operations due to the availability of an advanced integrated system.
SF2	(*i*=2)	Improved operator's capability to identify alarms and malfunctions, maintenance planning integrated with performance monitoring.
SF3	(*i*=3)	Availability of a reduced crew.
SF4	(*i*=4)	Introduction/availability of an advanced decision support function.
SF5	(*i*=5)	Availability of an advanced Diagnostic & Alarm Handling System.
SF6	(*i*=6)	Use of the ATOMOS Network (see Petersen et al. 2002).
SF7	(*i*=7)	Technologically improved systems (e.g. ATOMOS ECDIS and ARPA; see also Earthy et al. 1998).
SF8	(*i*=8)	Introduction/availability of a Hull Stress Monitoring function.
SF9	(*i*=9)	Introduction/availability of a Cargo Management function.
SF10	(*i*=10)	Introduction/availability of an Emergency Management function.

3.4 *Relationship between Safety Factors and Safety Benefits*

The present paragraph presents the analysis performed in order to calibrate the SPM with respect to the estimation of reliable values of the parameter d^r_{ki} (please refer to Equation 14). The calibration is achieved through a sensitiveness analysis on the overall effect introduced by the ATOMOS concept. For this purpose, statistical as well as analytical models available for each accident scenario are used.

The estimation is performed separately for the following selected accident scenarios k: Collision (k=1); Fire/Explosion (k=2); Wrecking/Stranding (k=3); Foundering (k=4); Contact (k=5).

It is highlighted that not all Safety Factors influence the risk associated with every accident type. The basis of the calibration is the risk assessment model for each accident category. In each risk assessment model, safety factors have been associated with selected gates of both FTA and ETA analyses.

The association between gates and SF is reflected in the risk assessment models in different ways:
– as modification of the architecture of the FTA and/or ETA, or
– as modification of the reliability/availability figures used in the FTA/ETA.

The results of the sensitiveness analysis on the risk assessment model for each SF are the parameters d'_{ki}.

The following Table 4 shows the resulting ratio differential safety levels d^r_{ki} calculated with Expression 14 with $s_{k\,j=1}$ calculated with the risk assessment model.

Table 4. Ratio differential safety levels d^r_{ki}

d^r_{ki}	*i*=1	*i*=2	*i*=3	*i*=4	*i*=5	*i*=6	*i*=7	*i*=8	*i*=9	*i*=10
k=1	0.34	0.10	-0.03	0.29	0.03	0	0	0	0	0
k=2	0	0.39	0	0	0.40	-0.09	0.05	0	0	0
k=3*	0.31	0.17	-0.01	0.40	0.02	-0.01	0	0	0	0
k=4	0	0	0	0	0	0	0	0.11	0.11	0.01
k=5*	0.31	0.17	-0.01	0.40	0.02	-0.01	0	0	0	0

* Approximation: the same risk assessment model is utilised

3.5 *Relationship between Safety Factors and Automation/ Integration Levels*

The present paragraph introduces a first estimation of the coefficients r_{ij} representative of the relationship between each SF and the different AILs. It should be noted that the computation of the coefficients r_{ij} is the only non-analytical part of the SPM. Therefore, the estimation of each value can only be based on subjective judgements and expert opinions. The future work shall concentrate in the refinement of the coefficients r_{ij}, which has been preliminary derived by a group of 15 experts in different maritime fields: e.g. HMI, O&M, Risk Analyses, Automation.

The following Table 5 provides the results of this preliminary estimation:

Table 5. Estimation of parameters r_{ij}

r_{ij}	*j*=1	*j*=2	*j*=3	*j*=4	*j*=5	*j*=6	*j*=7	*j*=8
i=1	0	0.15	0.25	0.4	0.5	0.6	0.8	1
i=2	0	0.15	0.25	0.4	0.5	0.6	0.8	1
i=3	0	0.15	0.2	0.3	0.5	0.5	0.75	1
i=4	0	0	0	0	0	0.2	0.6	1
i=5	0	0.15	0.3	0.4	0.5	0.6	0.8	1
i=6	0	0	0	0	0	0	1	1
i=7	0	0.15	0.25	0.4	0.4	0.5	0.75	1
i=8	0	0	0	0.5	0.5	0.5	1	1
i=9	0	0	0	0.5	0.5	0.5	1	1
i=10	0	0	0	0.5	0.5	0.5	1	1

The estimation has been based on the following considerations:
– each SF is assumed as ineffective at AIL 1;
– each SF is assumed as completely effective (i.e. realising completely its influence on the safety

level of the ship) only at the highest AIL (*j*=8). At each "intermediate" AIL (*j*=2 to *j*=7) the safety factor will influence the safety level by a fraction of its potential;

- SF1 and SF2 are assumed to influence Safety Levels in two steps: 25% for the first two AILs, basically due to the first increasing of automation, and then an increasing influence from AIL 4 to AIL 8;
- SF3 is supposed to vary constantly through AILs, with the exception of no increment between AIL 5 and AIL 6;
- SF4 is assumed to be available only in correspondence of an advanced integration; therefore only AILs 6, 7 and 8 are increasingly affected;
- SF5 is gradually introduced through all AILs;
- SF6 is only available at the last two AILs;
- SF7 is supposed to vary constantly through AILs, with the exception of no increment between AIL 4 and AIL 5 where only a physical integration is introduced;
- SF8, SF9 and SF10 are assumed to introduce their influences from AIL 4 onwards, with a full effectiveness in the last two AILs.

3.6 *Safety Prediction Matrix*

Following the model structure, the differential safety levels d^r_{kj} associated with each accident scenario for different AILs, are derived applying Expression 16.

The result is presented in the following table:

Table 5. Ratio differential safety levels d^r_{kj}

d^r_{kj}	*j*=1	*j*=2	*j*=3	*j*=4	*j*=5	*j*=6	*j*=7	*j*=8
k=1	0	0.07	0.11	0.18	0.22	0.33	0.53	0.73
k=2	0	0.13	0.23	0.34	0.42	0.50	0.58	0.76
k=3	0	0.07	0.13	0.20	0.25	0.38	0.63	0.89
k=4	0	0	0	0.11	0.11	0.11	0.23	0.23
k=5	0	0.07	0.13	0.20	0.25	0.38	0.63	0.89

The coefficients p_{lk} (see Equation 24) are estimated on the basis of the historical fatal accident occurrences extracted from the Lloyd's Maritime Information Service Limited (LMIS) database. This source has been used to retrieve the necessary information concerning the types of accidents at sea, which mostly have an effect on human casualties. In particular, the analyses have been performed on the following set of data extracted from the whole LMIS database:

- data relevant to ships owned by companies resident in the 15 EU countries;
- data related to accidents reported in the period from January 1990 to July 1996;
- data related to the EU owned Merchant Fleet for each year of interest.

The coefficient p_{lk} are evaluated as follows:

$$p_{lk} = \frac{q_{kl}}{\sum_{k=1}^{v} q_{kl}} \qquad (31)$$

where q_{lk} is the number of fatal events of the ship type *l* for the accident *k*. derived from the analysis of the LMIS database.

The following table reports q_{lk} for each of the following ship types: Bulk/ General Cargo (*l*=1); Fishing Vessels (*l*=2); Oil/Gas/Chemical Liquid Cargo (*l*=3); Passenger/RoRo Cargo (*l*=4).

Table 6. Statistical analysis of number of fatal events

q_{lk}	*k*=1	*k*=2	*k*=3	*k*=4	*k*=5	Tot
l=1	4	14	3	33	2	56
l=2	3	4	2	3	0	12
l=3	4	25	1	2	0	32
l=4	3	5	0	1	0	9

Applying Expression 31 is then possible to estimate the coefficients p_{lk} (see Table 7).

Table 7. Coefficients p_{lk}

p_{lk}	*k*=1	*k*=2	*k*=3	*k*=4	*k*=5
l=1	0.07	0.25	0.05	0.59	0.04
l=2	0.25	0.33	0.17	0.25	0
l=3	0.13	0.78	0.03	0.06	0
l=4	0.33	0.56	0	0.11	0

Finally, the ratio differential safety levels $d^{r\wedge}_{lj}$ for each ship type *l* and AIL *j* are calculated applying Expression 28 with $s_{lj=1}$ derived from the analysis of LMIS database.

Table 8. Ratio differential safety levels $d^{r\wedge}_{lj}$

$d^{r\wedge}_{lj}$	*j*=1	*j*=2	*j*=3	*j*=4	*j*=5	*j*=6	*j*=7	*j*=8
l=1	0	0.02	0.04	0.07	0.09	0.10	0.14	0.18
l=2	0	0.08	0.14	0.24	0.29	0.36	0.49	0.64
l=3	0	0.03	0.06	0.09	0.11	0.14	0.16	0.21
l=4	0	0.07	0.12	0.18	0.22	0.27	0.32	0.41

Expression 30 calculated for each ship type *l* leads to the compilation of different Safety Prediction Matrices. Figures 2 and 3 show, as examples, the Safety Prediction Matrices for the ship typologies Fishing Vessel (*l*=2) and Passenger/RoRo Cargo (*l*=4).

FISHING VESSEL (*l*=2)

	$s^{\%}_{l=2}$ $_{j=a\rightarrow j=b}$	Retrofit AIL (*j*=*b*)							
		j=1	*j*=2	*j*=3	*j*=4	*j*=5	*j*=6	*j*=7	*j*=8
Current Ship AIL (*j*=*a*)	*j*=1		0.08	0.14	0.24	0.29	0.36	0.49	0.64
	j=2			0.07	0.17	0.23	0.31	0.45	0.61
	j=3				0.11	0.17	0.26	0.40	0.58
	j=4					0.07	0.16	0.33	0.52
	j=5						0.10	0.28	0.49
	j=6							0.20	0.43
	j=7								0.29
	j=8								

Figure 2. Fishing Vessel – Safety Prediction Matrix

PASSENGER/ RORO CARGO (l=4)									
$s^{\%}_{l=4}$ $j=a \rightarrow j=b$		Retrofit AIL ($j=b$)							
		j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8
Current Ship AIL ($j=a$)	j=1		0.07	0.12	0.18	0.22	0.27	0.32	0.41
	j=2			0.06	0.12	0.17	0.22	0.27	0.37
	j=3				0.02	0.04	0.06	0.08	0.11
	j=4					0.05	0.10	0.17	0.28
	j=5						0.06	0.13	0.24
	j=6							0.07	0.20
	j=7								0.13
	j=8								

Figure 3. Passenger/ RoRo Cargo – Safety Prediction Matrix

The Safety Prediction Matrices are to be used as follows: given a Passenger/ RoRo Cargo ship, which has currently a configuration classifiable as AIL 2 and subject to retrofit to AIL 6, the predicted increase of the safety level is 22%.

3.7 *External Constraint of the SPM*

The SPM does not consider any external constraint affecting the implementation (or the availability) of a particular retrofit strategy. External constraints can also have an influence on the effectiveness of a particular Safety Factor on the overall safety level of a particular ship. A typical example might be the ship's flag. Flag obligations are different depending on the country and might have an impact on the crew reduction issue for different AILs.

However, the SPM is flexible enough to be able to include those aspects. In particular, the flag's obligations can be introduced by means of a constraint coefficient c_{ij} representing particular limitations to the effect of a Safety Factor on the Safety Levels for a particular AIL. Formally:

$$r_{ij}^{'} = r_{ij}\, c_{ij} \qquad (32)$$

where $r^{'}_{ij}$ is the corrected coefficient representing the effect of the Safety Factor i for the AIL j.

Just to make an example, if the flag's obligation does not allow crew reduction, the following constraint coefficient c_{ij} can be introduced:

- c_{ij}=0 for the SF = "crew reduction";
- c_{ij}=1 for the SF different from "crew reduction".

4 CONCLUSION

The present paper has discussed the theoretical framework for the prediction of the safety increase while retrofitting existing ships with highly integrated and automated technologies.

In particular the following results can be synthesised:

- the definition of a preliminary set of Automation/ Integration Levels on which the Safety Prediction Model is based;
- the definition of the Safety Prediction Model;
- the calibration of the parameters involved in the SPM on the basis of the information available.

The Safety Prediction Model has been developed in order to maintain a high level flexibility. The preliminary results presented allow a direct prediction of the percentage increases of safety introduced by a specific retrofit strategy for a specific ship type. This is formalised through the Safety Prediction Matrix based on the definition of the Automation/ Integration Levels associated with the retrofit strategies.

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