Early Design Naval Systems of Systems Architectures Evaluation

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ABSTRACT

A methodology of global evaluation of a system of systems (SoS) architectures is presented through the case of a mine counter-measure system.

Due to the urgent need of keeping the sailor out of the minefield, future Mine Counter-Measure (MCM) systems will be Systems of Systems (SoS) where various kinds of UxV (air, surface and underwater unmanned systems) will play a prominent role. So the systems of systems of interest are constituted of a mother ship and different kinds of unmanned vehicles.

The aim is to get an assessment of overall efficiency of different candidate architectures in early design phases. Both the architecture of the components of the SoS and the overall architecture are taken into account. Each component can have variable levels of MCM capabilities according to their own architecture and their own equipment. So, in early design phases, there is a wide range of possible SoS architectures and the challenge is to select in a short time few of them in order to do a detailed design study.

In a context of mine warfare, the weight of survivability criteria (resistance of the systems and human safety) is also very important in the choice process.

This paper presents the different steps of an adapted methodology for global assessment including MCM efficiency and survivability aspects, illustrated by results obtained on three MCM architectures. As we are in early design phases, only analytical models are operated and we use levels of performances on a scale one to ten. Mine counter measure efficiency is put in balance with survivability capabilities.

For mine counter measure efficiency, a global efficiency is calculated taking into account the sensors performances, the mobility performances of the different unmanned vehicles, the duration of logistics operations…

For survivability capabilities, both a technical aspect (based on the characteristics of the architecture) and a tactical aspect (based on stand-off concept) are taken into account to assess a global survivability capability.

This analysis is completed by cost criteria and TRL (technology readiness level) criteria.

1.0 INTRODUCTION

In early phases of a project it is very often necessary to assess different solutions or alternatives to a given architecture. During these phases, the available data are limited and the time schedule is rather short. Furthermore the evaluation must cover a wide range of performances. So generally, full simulations cannot be used at this stage to perform evaluation. For all theses reasons, we developed a method and some tools to be able to do comparative assessments of different architectures at an early stage of a project.

This method is presented here through its application on a project of Mine Counter-Measure (MCM) systems.

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2.0 DESCRIPTION OF MINE COUNTER-MEASURE ARCHITECTURES

Several components can be used to build architectures of the MCM system:

- **Mother ship (MS)**: surface ship which can launch, operate and recover unmanned vehicles.
- **Autonomous Underwater Vehicle (AUV)**: system with a single or several MCM capabilities: detection, classification, localization, identification, neutralization.
- **Unmanned Surface Vehicle (USV)**: system which can carry, launch and recover AUV or operate mine detection sonar. The USV can be reconfigurable (both sonar and AUV can be installed) or not (the USV is designed either to operate a sonar or to operate a AUV)

The three MCM architectures evaluated in this paper are presented Figure 1:

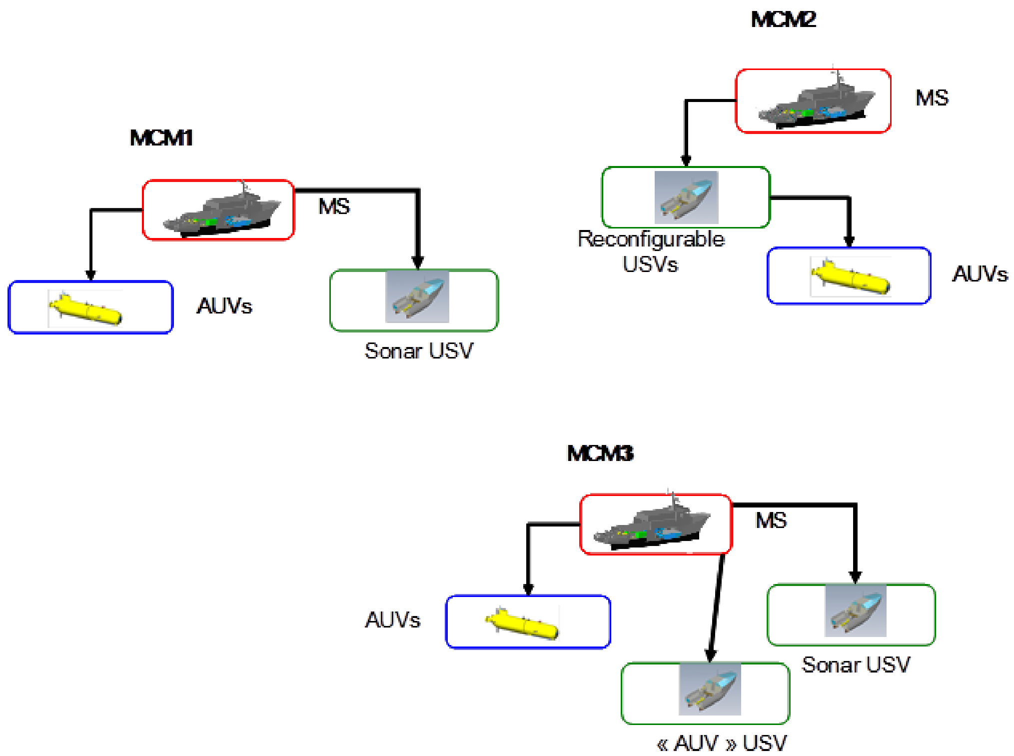

Figure 1: MCM Architectures

3.0 METHOD DESCRIPTION

In this chapter, the assessment method is described through the case of MCM system. The method is partly based on a generic SoS global assessment method built since 2007 (ref. 1).

Here, the global assessment focuses on:

- Mine warfare efficiency
- Survivability assessment

3.1 Mine warfare efficiency

The mine warfare operation is divided in three phases:

- Detection - classification – localization (DCL phase)
- Identification
- Neutralization

For each phase and for each component of the different architectures, the mine sensors are identified with their performance levels in terms of coverage rate (which can be dependant of the bottom nature), probability of detection and identification and neutralization capabilities.

Then, models are built to define a global efficiency for each architecture. These values are used to assess “satisfaction criteria” for 3 different scenarios:

- Scenario 1: protection of a national site
- Scenario 2: protection of a naval Force through a choke point
- Scenario 3: securisation of an area as a preliminary task for an amphibious operation

The “satisfaction” criterion is based on:

- The notion of an “acceptable” duration for the whole operation
- The level of mine clearance needed for the operation

3.2 Survivability Assessment

To assess survivability, we have to select several criteria. For the MCM illustration, the survivability criteria are as follows:

3.2.1Technical survivability criteria

- (Non) susceptibility regarding mine threat: to avoid a mine explosion (MS, USV, AUV).

This criterion can be broken down as follows:

- Stealthiness regarding mine threat
- Mine detection and avoidance

- (Non) vulnerability regarding mine threat: to avoid damages after a mine explosion in order to fulfill the mission (MS, USV, AUV).
- Survivability regarding mine threat: combination of (non) susceptibility and (non) vulnerability (MS, USV, AUV).

Criteria listed above are suited for components. Only high level criteria (survivability) are used for the whole MCM system.

3.2.2 Tactical survivability criteria

- To be compliant with stand-off concept (man never close to the mine threat) (MS).

This criterion is an operational criterion which has also a psychological impact. This latter aspect is very important in mine warfare.

Criteria are computed with the help of models. Input data of these models are parameters regarding the architecture of the MCM system and of its components. Two types of parameters are introduced: technical parameters and tactical parameters.

3.3 Technical parameters

Technical parameters are technical characteristics or technical performances of the components which directly drive their own efficiency and survivability.

By technical characteristics, we must understand data such as characteristics of propulsion system or electricity generators, type of steel, hull partition, sonar parameters…

By technical performances, we must understand data such as signatures, ranges of detection systems, turning circle, shock resistance, speed…

It is possible to work at “characteristic level” or “performance level”. It depends on the required accuracy of the assessment and the available level of information on the architecture design.

1. Regarding mine efficiency, the main technical performance parameters are:

- The coverage rate of the sonars which equip the USV and the AUV and their efficiency
- The capacity to identify or neutralize mines for the AUV used for identification and/or neutralization
- The speed and the endurance of the USV and AUV
- The capacity to transfer and to exploit data
- The reconfiguration and the replenishment delays for USV and AUV
- The sea keeping capability of the MS and the USV
- The communication capability between the MS and the unmanned vehicles

2. Regarding mine threat, the main technical survivability performance parameters are:

- Underwater signatures (MS, USV, AUV):
  - acoustic
  - magnetic
  - electric
- Moored mine sonar detection efficiency (MS, USV)
- Drifting mine radar detection efficiency (MS, USV)
- Drifting mine optronic detection efficiency (MS, USV)

- Hull resistance to a mine explosion quantified by shock factors (MS, USV, AUV)
- On-board equipment resistance to a mine explosion quantified by shock factors (MS, USV)

3.4 Tactical parameters

Tactical parameters are performances or characteristics of the components or external systems which drive the stand-off concept (man never close to the threat) and consequently the overall SoS survivability. For example:

- Reliability of initial information about the exact starting point of the mine field (provided by external intelligence process).
- Mine clearance efficiency of unmanned vehicles which determines the probability of presence of residual unknown mines.
- Electromagnetic and acoustic communication ranges between the components. For example the longer the communication range between MS and AUV operated by MS is, the longer the distance between MS and mine threat is.
- Unmanned vehicles range. For example, the longer the endurance of an USV operated by MS is, the fastest the mine warfare operation is performed (and so the more efficient it is, as the mount of time allowed for the operation is limited).

3.5 Notation grid and Models

3.5.1 Notation grid

All the models defined below are based on 0 to 10 scale. The mark 10/10 is obtained when the performance is at the "top level" according to the requirements. In some cases, when the requirements are not precise enough, the mark 10/10 represents the highest technical existing level.

3.5.2 Mine warfare models

For the DCL and identification phases, a "useful duration" is calculated taking into account the sensors capacities:

- For the DCL phase, the coverage rate and the probability of detection of each sensor is taken into account
- For the identification phase, the number of MILCO (mine like contact) which can be treated in a certain amount of time

The results depend obviously of the number and type of USV and AUV I (AUV used for identification) included in the architecture. The efficiency of the DCL phase impacts directly the number of mines needed identification.

Then a logistic duration is added to the "useful duration" to obtain the total duration of the DCL and identification phases. The logistic duration takes into account the transit time, the replenishment time, the data transfer and exploitation time. It also takes into account the sea keeping of the USV and the communication capabilities between USV and MS.

Depending on the scenario, an objective duration has been defined by the Navy. The comparison between this value and the calculated duration for DCL and identification phases enables us to know the time delay available for the neutralization phase.

Depending on the neutralization devices included in the architecture, the clearance rate can be computed.

This value can be compared to the objective value of the scenario.

Finally, for each scenario and each architecture we obtain a global mine warfare mark which takes into account a lot of parameters. Thus we can really compare the different architectures with regards to their mine warfare efficiency. To make this comparison, we use a tool which enables us to vary easily the different parameters and to observe the influence of such or such parameter on the overall efficiency.

3.5.3 Technical survivability models

Description is made for the MS. Comparable models are used for USV and AUV.

Technical models listed below are used to obtain technical performances marks from technical characteristics at a component level.

- Acoustic signature: experts have defined 4 kinds of ship architecture in function of different devices and characteristics of the ship (propulsion, propeller, hull shape…). For each kind of architecture, for different ship speeds and different types of mine, an acoustic risk level (r%) have been computed (risk of being acoustically detected by the mine). For each case, a mark is thus given: N = 10(1- r%). A global mark is then given using weights on the different speeds and the different mines. Equal weights are used for the threats and heavier weights are applied for operation speeds than for transit speeds.

- Magnetic signature: the method is the same as for the acoustic signature, except that there are only 2 main kinds of architecture: one with magnetic device to reduce the signature and one without this device. Performances of the magnetic device can also be taken into account (type of degaussing coil system).

- Electric signature: they are only assessed with an expert judgment depending on the presence (or the absence) of several devices (specific corrosion protection system, active shaft grounding system…).

- Mine detection capability for drifting mines: several specific devices can be used to detect drifting mines: radar, lidar and cameras. Different kinds of cameras can be used: infrared cameras in band II and III, optical cameras. Depending on the number of devices available on board the ship, a mark is given in terms of drifting mine detection capability. This mark depends on the ship speed. Weights can be applied on the different speeds, taken into account the mission profile, to obtain a global and only mark. The ship manoeuvrability should also be considered, but as the manoeuvrability characteristics are more or less the same for all the MS taken into account, this parameter has been ignored.

- Mine detection capability for moored mine: depending on the existence of a sonar or not on board the ship, and on the sonar performances (range, false alarm rate…).
- Shock resistance: both hull resistance and on board equipment resistance are taken into account. Several parameters are considered: steel elasticity limit, admissible momentum, bottom plate thickness, critical speed under shock for equipments. Let us take the steel elasticity limit for instance. For the expert, a steel elasticity limit of 355 MPa brings a rather high level of risk on a vulnerability point of view. So this case gets the mark 4/10. A steel elasticity limit of 390 MPa is much better according to expert judgment. So this case gets the mark 8/10. Thus, we can have the following model for the risk related to the steel elasticity limit:

$Re = 0,115\,E - 36,81$, avec $355 < E < 390$

Comparable models are built for the other parameters.

At the end, the signatures, mine detection and shock resistance marks are weighted (for example with equal weight) to obtain technical survivability criteria marks (susceptibility, vulnerability and survivability).

To compute the survivability of the whole system, depending on the architecture, we have to evaluate which components are the drivers of the survivability of the SoS. So, among the components which can be close to the threat, we have to identify the most precious ones, that means the ones which are more or less needed to fulfil the mission. Depending on this analysis, weights are associated with the components for each critical event:

- Event 1: the initial information of the exact starting point of the mine field has been misjudged. The occurrence of this event is a scenario parameter.
- Event 2: the clearance of the mine field has been done, but the efficiency has not been total. So there is a risk of unknown residual mines for the MS. The occurrence of this event can be calculated from the mine clearance efficiency.
- Event 3: some components are closed to the threat during the clearance operation. It may depend on the level of communication performances. For instance, if the communication range is too short, this can drive the MS to enter the mine field even though an AUV is used to treat the mine. In this case the MS becomes the most critical system. Event 3 is certain (at least for one component).

Seriousness (weighted sum of individual technical survivability marks) is calculated and combined with occurrence of the events to obtain risk value (according to a classical risk analysis approach). The complement of this risk value is the global technical survivability mark regarding mine threat.

3.5.4 Tactical survivability models

The tactical survivability evaluation permits to assess the probability for the stand-off concept (man never close to the mine threat) to be respected. The occurrence values of the different events identified above are re-used to focus on the cases where the MS is the closest component to the threat. The more the MS has to be close to the threat, the lower is the tactical survivability mark.

4. FIRST STEP: ASSESSMENT OF MINE WARFARE EFFICIENCY

Figure 2 presents mine warfare efficiency results obtained for each architecture.

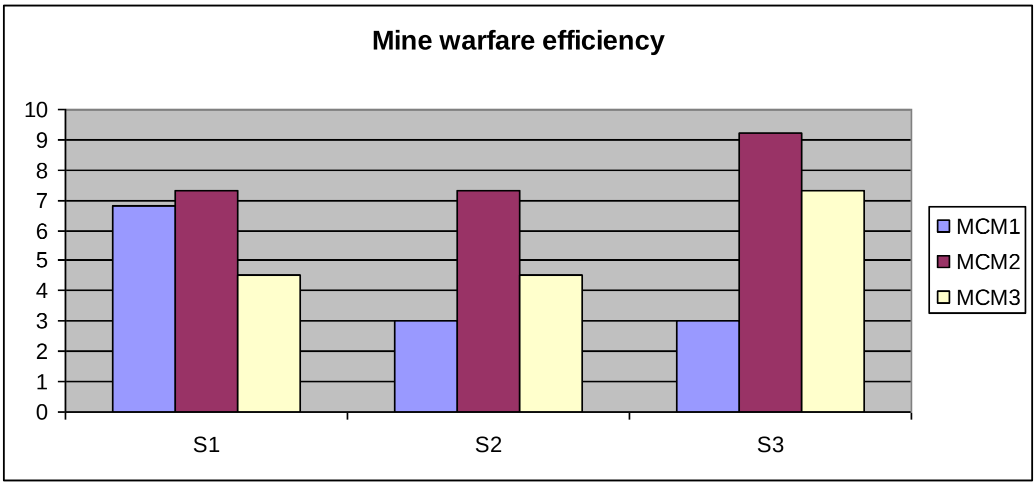

Figure 2: Mine warfare efficiency

We can see that for scenarios S2 and S3, MCM1 is the less efficient architecture. But for scenario S1, it is not the case. The analysis of the results shows that this is due to the fact that, in MCM2 and MCM3 architectures, there are more sensors that in MCM1. And in scenario S2 and S3, the covered area is large, so we need a lot of sensors. But in scenario S1 the area is much smaller, so the number of sensors is no longer the key parameter. The time to exploit the acquired data becomes the key parameter. So increasing the number of sensors is not always the best thing to do (even if we do not take into account the cost aspect!). In the case here, depending on the scenario, an optimization between the number of sensors, the number of operators, and the quality of the data treatment system has to be made.

This is an example of the kind of results we can obtain.

5. SECOND STEP: ASSESSMENT OF TECHNICAL SURVIVABILITY

The assessment is firstly made for each component with the assumption of the presence of threat in a danger zone. In this case, results do not depend on the overall architecture of the MCM system.

For the illustration, one single variant of each component is chosen and we suppose the low levels of signatures (compared to mine working logic) involve a maximal survivability for the AUV.

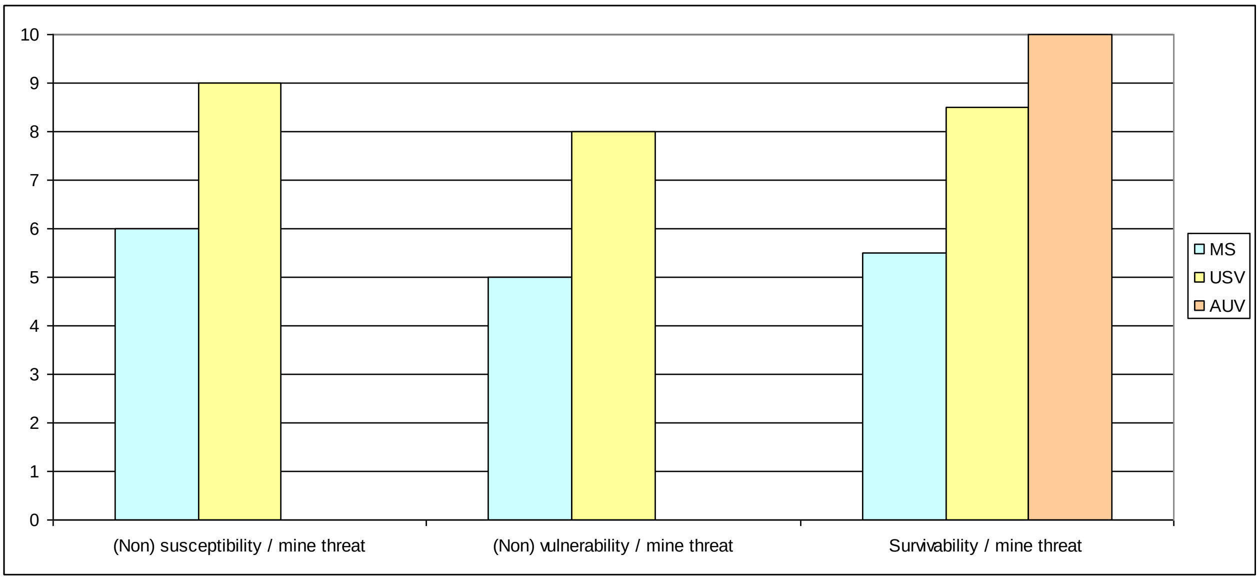

Figure 3: Technical survivability

The assessment is secondly made for the global system. In this case, results depend on the overall architecture of the MCM system.

For each critical event weights are associated with the components according to their influence on the global survivability:

- - weight 0: the component is not involved.
- - weight 1: the component is the single component involved.
- - 0<weight<1: weight depends on the seriousness of the loss of the component regarding the global system. Sum of the weights is equal to 1.

Critical events and Weights	MS	USV	AUV
MCM1			
To enter the mine field without knowing it	1	0	0
To be inside the mine field during MCM operation	0.90	0.05	0.05
To be close to residual mine threat	1	0	0
MCM2			
To enter the mine field without knowing it	1	0	0
To be inside the mine field during MCM operation	0	0.8	0.2
To be close to residual mine threat	1	0	0
MCM3			
To enter the mine field without knowing it	1	0	0
To be inside the mine field during MCM operation	0.90	0.08	0.02
To be close to residual mine threat	1	0	0

Occurrence of each critical event regarding mine threat has now to be evaluated.

Critical events	Occurrence	Comments
To enter the mine field without knowing it	0.3	Occurrence is the complement of probability of exact information about the starting point of the mine field (supposed equal to 0.7).
To be inside the mine field during MCM operation	1	This event is certain (at least for one component).
To be close to residual mine threat	**MCM1** S1:0.32 S2:0.7 S3:0.7 **MCM2** S1:0.27 S2:0.27 S3:0.08 **MCM3** S1:0.55 S2:0.55 S3:0.27	Occurrence is the complement of mine warfare efficiency

Figure 4 presents global technical survivability results:

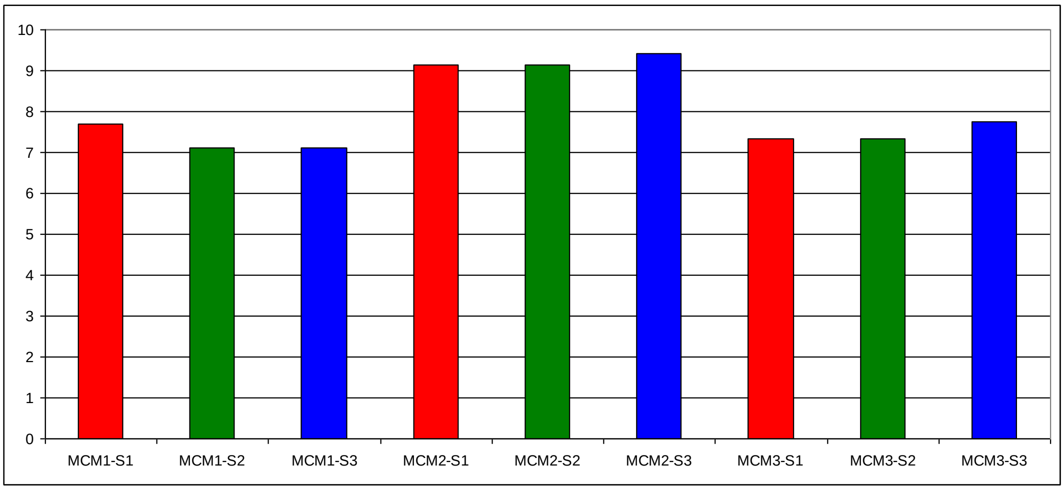

Figure 4: Global Technical survivability

We can see the following:

- MCM2 is the best architecture on a survivability point of view because the USV is the component which is close to the threat and the individual survivability of the USV is rather good.
- MCM1 has a slightly lower survivability than MCM3 because of its lower mine warfare efficiency (except for S1).

6. THIRD STEP: ASSESSMENT OF TACTICAL SURVIVABILITY

MS is the only component with human presence onboard. To evaluate the compliance with stand-off concept (man never close to the threat), we have thus to assess the presence of MS close to the mine threat using occurrences quantified above. Figure 5 presents tactical survivability results.

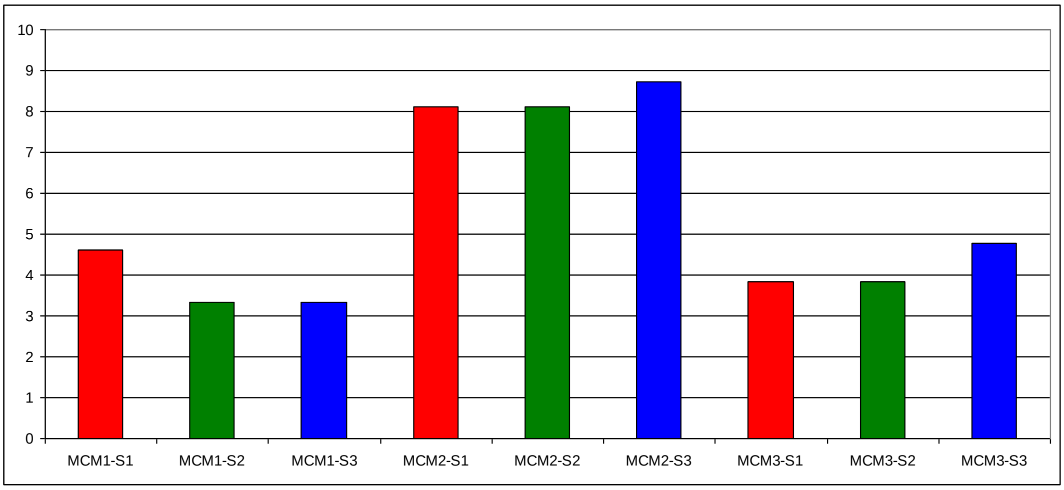

Figure 5: Tactical survivability

We can see MCM2 offers the best tactical survivability results.

7. COST AND TRL ASSESS

The following step is to put the above results with regard to cost and TRL aspects. For the illustration only TRL criterion and mine warfare efficiency are taken into account (Figure 6). The mine warfare efficiency is the average value obtained with the 3 scenarios. For TRL, the TRL of each component has been evaluated. Then a global TRL is computed for each architecture as the average value of all the components.

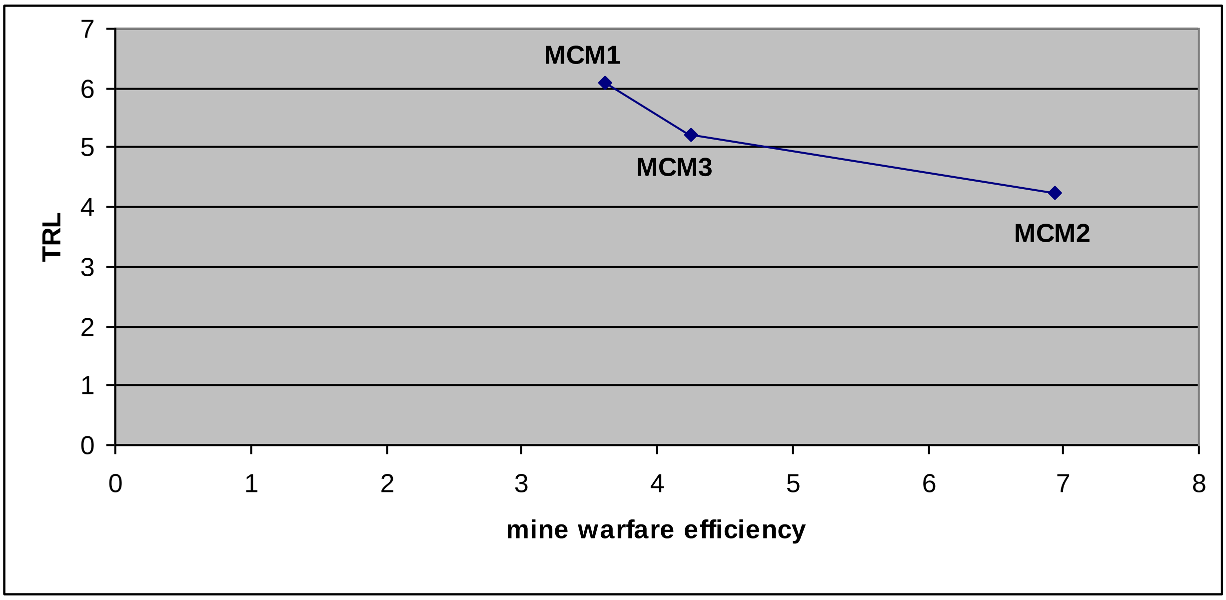

Figure 6: TRL versus mine warfare efficiency

The same kind of analysis can be done with cost in a relative way. An objective cost is defined and the given prices are compared to this given cost to obtain an indicator between 0 and 10, indicator which can be compared to the mine warfare efficiency or to the survivability aspects.

8. CONCLUSION

A methodology of global evaluation of a system of systems has been presented through the case of mine counter-measure system.

This method, adapted to early design phases, enables us to classify the different alternatives according to different criteria. It can be used for various systems of systems in naval domain and also in land or aerial domains.

This method does not replace a simulation. With this method we are at a macroscopic level which is very useful to have a synthesis view of the different possibilities. In later phases, simulation is needed for a better assessment of the performances and to take into account the dynamic aspect.

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