Assessing the Effectiveness of Maritime C2 Systems - Measures of Merit

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Abstract

This paper outlines a method for establishing appropriate measures of merit (MOMs) for quantitative assessment of the performance and effectiveness of maritime command and control (C2) systems in different scenarios. Focus is on the establishment of MOMs in order to measure quality and availability of information provided by the C2 system. The paper also presents examples of MOPs and MOEs and argue how they fulfil the beforementioned objective of studying quality and availability of information. One of the main challenges in such an analysis is to link MOPs to MOEs and to relate the MOMs to measurable/observable quantities. The paper outlines the method utilised to meet this challenge.

In summary this paper outlines a method for quantifying how alternative maritime C2 systems display desired properties like the capability of a C2 system to support the commander to achieve a high level of situation awareness, the capability of a C2 system to respond timely, and the availability of a C2 system.

1. Introduction

The Norwegian Defence Research Establishment (FFI) is involved in a project addressing the development of a future command and control (C2) system concept and a future C2 system for maritime operations. The objective of the project is to recommend guiding principles and ideas for the evolution of the maritime C2 system in the coming years and from these recommend a possible maritime C2 system plan. The recommendations are to be based on cost effectiveness analysis of alternative C2 systems. The framework of the cost effectiveness analysis is shown in figure 1.

The cost analysis part of the project, illustrated in the lower left part of the figure, is described in [Pedersen, 2000]. The right part of the figure illustrates the method concerning the effectiveness analysis [Malerud et al, 1998], and the shaded box in the figure indicates the main focus of the paper, namely system properties and Measures of Merit (MoMs).

In the literature there is consensus on desirable properties a C2 system should possess. These properties are typical general and high level, but scenario dependent. Often they are concerned with quality and timeliness of information provided to decision makers. Others are concerned with a C2 system’s “-ilities”. For instance, there is general agreement and strong evidence that the decision making performance is strongly correlated to the level of situation awareness. Thus, a C2 system should enable and facilitate the ability of a decision maker (DM) to reach a high level of situation awareness. A C2 system can achieve that by availability and quality of relevant information and appropriate presentation of that information. To be able to conduct an effectiveness analysis these general statements have to be made concrete such that alternative systems can be assessed and ranked quantitatively. Specifically, measures must be defined that relates quantities from simulation models to the capability of a C2 system to display the desired properties. The main objective of the paper is to describe how the MoMs can been derived and examples of actual MoMs utilised in the above-mentioned study at FFI.

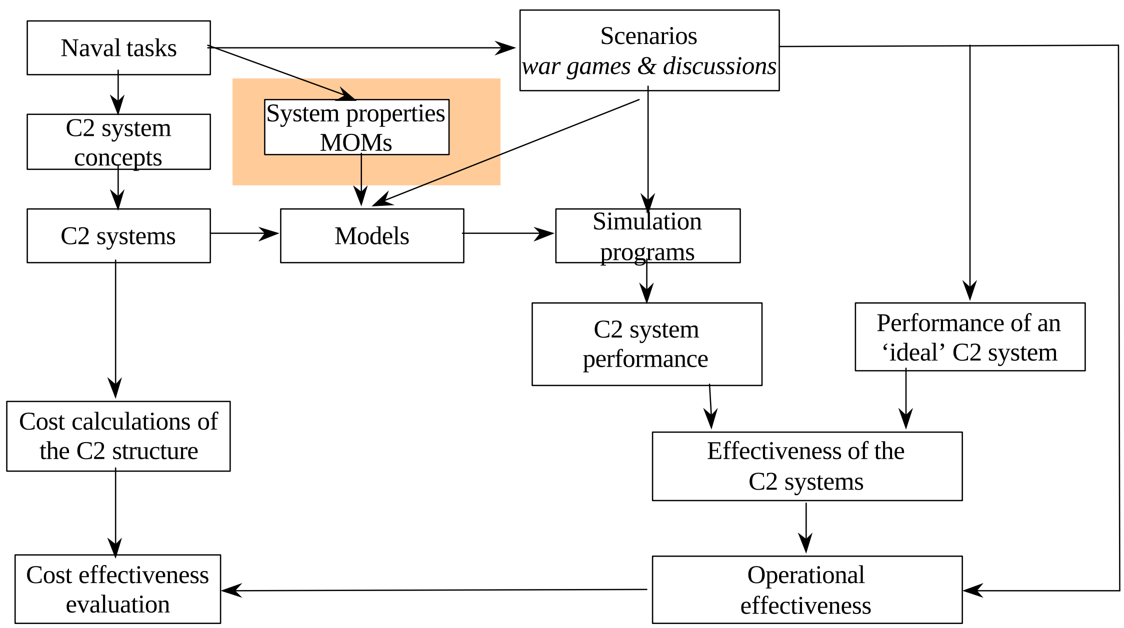

Figure 1. Framework for the cost effectiveness analysis

Sections 2, 3 and 4 give a brief overview of the method concerning effectiveness analysis and establishing MoMs, while section 5 gives examples of MoMs utilised in the project.

2. Effectiveness analysis

In [Thorsen et al, 1999], experiments and models used in an effectiveness analysis of a C2 system are separated into three levels:

- The operational level
- The C2 system level
- The C2 sub system level

This division originates from the common organisation of MoMs in a three level hierarchy consisting of Measures of Force Effectiveness (MoFEs), Measures of Effectiveness (MoEs) and Measures of Performance (MoPs) [MORS, 1986]. These are described as:

- MOFEs measure how well the force of which the system is a part performs the mission
- MOEs measure how well a C2 system performs its functions within a given operational environment
- MOPs measure attributes of system behaviour

To quantify the performance two simulation models are implemented on the basis of formal models of the C2 system. Input to the simulation models is parameters representing the performance of sub systems within the C2 system. Simulations are performed to quantify the responses of the C2 systems to the course of events generated by the scenarios. Events occurring during execution of a mission trigger processes and generate load on the C2 system. In this way scenarios represent the environment to the C2 system. The simulation model calculates how a particular C2 system accomplish C2 related tasks by assigning values to the MOPs.

A procedure has been developed to determine the effectiveness of C2 system alternatives, see figure 2. The procedure compares the calculated performance to the performance of an 'ideal' C2 system. The performance of an 'ideal' C2 system is established by analysing the results of scenario discussions and war games [Malerud et al, 1998]. By looking at the discrepancies between actual and 'ideal' performance it is possible to calculate the C2 system effectiveness.

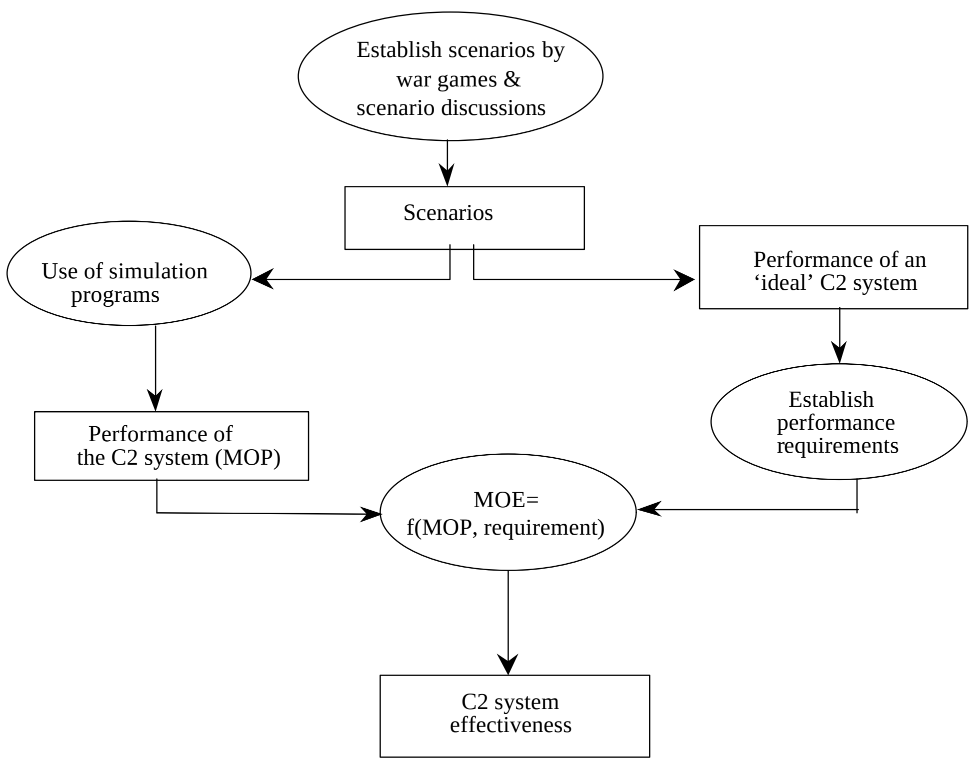

Figure 2. A procedure for determining effectiveness of C2 systems.

3. Method for establishing MOMs

Several methods for establishing MoMs have been proposed in the literature, e.g. [Jones et al, 1997], [Giard, 1989] and [Wheatly and Stein, 1998]. Our work is based on the method advocated in [Bouthonnier and Levis, 1994] and [MORS, 1986]. A brief outline of the method is given below.

The first step is to define high level desired properties of the C2 system. These properties are qualitative and defined by a top-down approach. The starting point for the definition of these desired properties is the missions, doctrines and the operational concept giving broad statements about the maritime operations and how they are to be performed by the forces available. The main relationship between the planning and performance of operations and the C2 system is the sequence of decisions made by the commanders based on the information, services and support provided by the C2 system. Thus, the desired properties should be defined such that they express aspects of the C2 system that are significant in enabling good and timely decisions such that mission objectives are achieved. We do not attempt to model and measure the effectiveness of the decisions themselves. That is outside the scope of our analysis. Thus, our analysis is restricted to the measuring and assessment of properties of alternative C2 systems that facilitate and enable good and timely decisions. There are several reasons why the decisions themselves are left out of the quantitative part of the analysis. First, it is hard to define what a good decision sequence for a particular operation is – several decision sequences can reach the same end state. Secondly, modelling of decisions involves models of human cognitive processes, which have not met a level of maturity for the kind of analysis we are engaged in. The desired C2 system properties, which we have defined in our study, are described below.

The next step is to outline MOPs that can be used to quantify the selected properties. MOPs refer to the actual performance of a particular C2 system. To define MOPs, first, concepts that are relevant and characterise the defined properties are selected. Examples of such concepts are accuracy, timeliness, completeness, correctness, etc, expressed in a specific context. Then variables that quantify the concepts are defined. To these MOP variables functions are associated that map these variables to directly measured or inferred observables of the C2 system. In this way figures can be obtained that quantify to what extent the desired properties are displayed through concepts that are relevant and characterise them. There can be several concepts and likewise several MOPs for a given property and MOPs can be combined to form more aggregated MOPs. Examples of MOPs utilised in our study are given below.

While MOPs are related to the C2 systems themselves, MOEs refer to the effectiveness independent of how C2 systems are realised. In other words, MOEs define standards against which performance of a C2 system may be judged to determine to what extent user requirements are met [Sproles, 2000]. A MOE is thus established by defining a function of MOPs and requirements. Requirements are mission and scenario dependent and are established by scenario analysis. Associated to the MOEs are criteria that provide the limits within which the values of MOEs for a particular C2 system must lie to be judged acceptable. How the requirements are established in our study is outlined below. Likewise, MOEs defined and utilised in our study are also outlined below.

The last step in a method to establish MoMs is to define the MOFEs. MOFEs may be established in the same way as MOEs by defining a function of MOEs and requirements. However, these requirements are operational (i. e. in a SLOC operation: Ships must arrive at destination port in five days without loss) and performance, as noted earlier, are related to decision sequences. Since trying to define quantitatively the performance of decision sequences is particularly difficult and since models of decision making are not included in our simulation models and hence not observables, we do not define MOFEs in the same structured way as the other MoMs. Our quantitative effectiveness analysis ends with the effectiveness of the C2 system. A C2 system's contribution to the operational effectiveness is analysed by military and analyst judgement. In our study senior grade officers and analysts of our project team assess qualitatively the consequences on the performance of an operation of effectiveness values not meeting defined criteria.

4. Use of Operational Information Exchange Requirements in an Effectiveness Analysis

One of the main objectives of a C2 system is to support the DM in making good and timely decisions. In order to reach this objective the C2 system must be able to provide the DM with relevant information of high quality in a timely manner. Information entity types in the C2 domain are e.g. orders, requests, warnings, status reports, and situation pictures (tracks). The demand for information depends on the situation where it is utilised and the decisions to be made. The quality of the decisions depends upon the situation awareness of the DM, which among other factors depends on the information available to the DM when the decision is to be made. By analysing the results of scenario discussions it is possible to establish operational information exchange requirements (OIER). The OIER comprises information needed to make actual decisions.

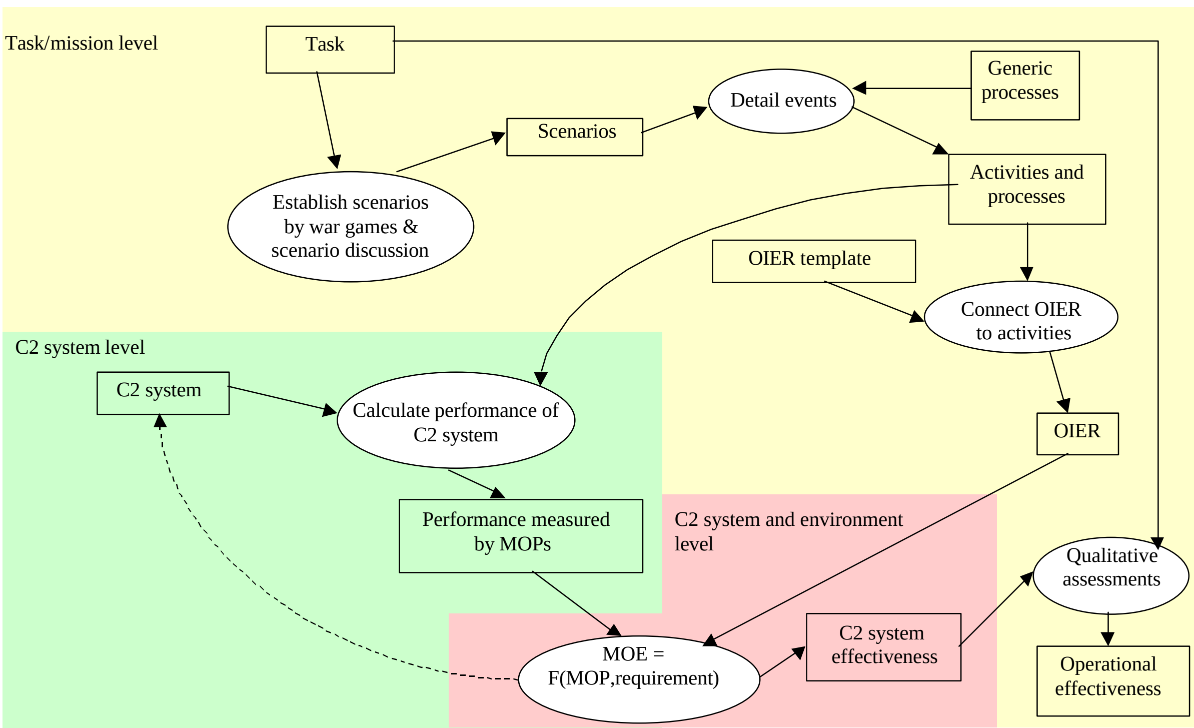

Figure 3. Method for establishing OIER and the use of OIER in the effectiveness analysis.

Figure 3 gives an overview of the method for establishing OIERs and how the OIERs are applied in order to calculate effectiveness. The starting point of the method is scenarios describing the naval tasks [Thorsen et al, 1999]. War games and scenario discussions are carried out to determine the most 'challenging' events with respect to command and control. The selected events are further analysed to determine the C2 processes and the flow of information related to the C2 processes.

In order to establish OIER it is necessary to construct an OIER template [Sharp and Bateman, 1999]. The OIER template defines a baseline set of data types for use in the analysis. An OIER template is given in table 1.

By comparing the actual information flow determined by simulations to the OIER, the effectiveness of the C2 system in providing the DM with relevant information in a timely manner may be assessed.

Data types	**Explanation**
Source	Source of information
Source Activity	Activity producing the information
Time	Time when the information is disseminated
Distribution	Number of destinations the information is sent to
Destination/recipient	The destination(s) that should receive the information
Destination activity	Activity requiring the information
Information type	Description of information content
Time requirements	Time when information has to be at the destination
Size	Size of information entity
Priority	Priority of the information entity
Security	Security of the information entity

Table 1. Example of an OIER template

5. MOMs utilised in the Effectiveness Analysis

The method for establishing MOMs, outlined in section 3, assumes that it is possible to derive a set of 'desired' C2 system properties. These properties are the starting point for establishing MOMs and they are established in a top–down approach. In this way the C2 system properties become certain high level requirements to the C2 system.

The main objective of a C2 system is to support the DM in direction of maritime operations. In this context direction is to take timely decisions in connection with the planning and execution of operations.

In modern operational concepts relying on manoeuvre warfare and indirect operations, features such as speed of operations and the capability to respond faster then an opponent are of vital importance. A C2 system supporting a DM in direction of operations within this context should enable for fast decision making and dissemination of missions/orders in a timely manner at the necessary level of security. The capability to make fast decisions depends among other factors on the performance of the C2 processes (OODA–loop), which is governed by how well the staff are organised, the workload, the number of staff resources available, the adaptability of the staff to tasks, and how the C2 processes are organised and synchronised. Other important factors contributing to reduced response time are the capability of the C2 system to acquire information to enable timely decision making, and the capability of the C2 system to disseminate decisions to lower level commanders in order to conduct missions.

The ability to take good decisions in a timely manner relies on the DM's situation awareness, i.e. his understanding of the actual situation. Thus, one of the most important properties of a C2 system is its capability to support DMs in achieving high level of situation awareness by providing relevant information of high quality in a timely manner.

The management philosophy most often associated with manoeuvre warfare is mission oriented direction of operations. This philosophy implies that decision authority is delegated to DMs at lower levels in the organisation. A common understanding of the situation is required to ensure that lower level commanders act in accordance with the intentions of higher level commanders. This demands consistency between the situation pictures at the different levels in the organisation.

Another important factor influencing the capability of the C2 system to support good and timely decision is the availability of C2 processes/functions, relevant information, and communication in the C2 system.

Based on the above discussion, our analysis is focusing on three main C2 system properties. These are:

- Capability of the C2 system to support the achievement of a high level of situation awareness
- Capability of the C2 system to respond in a timely manner
- Availability of the C2 system, i.e. availability of C2 processes/functions, information, and communication

In the literature [NATO, 1994], [Bjorklund, 1995], [NATO, 1998] other C2 system properties are discussed. However, due to the top–down approach applied in our analysis the three properties listed above are considered to be the most important. In the following sections MOMs are derived in order to quantify to what extent a C2 systems display the first two properties listed above. The third property "Availability of the C2 system" is measured by use of the MOMs derived from the two first properties, i.e. different degree of availability influences the capability of the C2 system to support the achievement of a high level of situation awareness and the capability of the C2 system to respond in a timely manner.

5.1 *Capability of the C2 system to support the achievement of a high level of situation awareness*

In [Endsley, 1995] Endsleys provide the following definition of situation awareness:

The perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in near future.

According to Endsley the first external issue influencing situation awareness is the degree to which a C2 system acquires the needed information from the environment. The second major issue involves the display interface for presenting information to the DM. The MOMs established in order to quantify the capability of C2 systems to support the achievement of situation awareness focus on the first external issue, that is the situation picture available to the DM. The second issue is also recognised as important. However, this is best assessed by human factors evaluation of a prototype and is outside the scope of the analysis described in this paper.

The situation picture comprises the track information available to the DM. The information could be provided and processed by an information system or it could be obtained directly from sensors/senses. Independent of the sources of information it is necessary that the information of the situation picture is relevant for the actual situation.

The capability of a C2 system to support the achievement of a high level of situation awareness is determined by the type of information it manages to obtain about the environment, the quality of the information, and the capability to disseminate the right information to the right place in a timely manner. Important concepts related to quality and availability of information are: relevancy, correctness, accuracy, precision, completeness, consistency between situation pictures at different levels in the organisation, and timeliness of the information. Table 2 gives an explanation of these concepts.

Concept	Explanation
Accuracy	Accuracy describes measurement errors or estimation errors of physical state variables or continuous variables. E.g. estimation errors can be expressed by a covariance matrix.
Precision	Precision describes the level of detail in the information. E.g. frigate is a more precise description of a vessel than surface vessel.
Uncertainty	Uncertainty describes the confidence in the determination of a discrete variable. E.g. uncertainty can be expressed by a confidence level.
Completeness	Completeness describes the degree to which the information includes every entity of interest. E.g. situation picture completeness describes the degree of ground truth of an area of interest covered by the information of a picture.
Redundancy	Redundancy describes the degree of information that is overlapping. Note that redundant information can be used to increase accuracy and certainty.
Consistency	Consistency describes to what degree information entities are not in conflict.
Relevancy	Relevancy describes the value of information to task performance.
Correctness	Correctness describes whether the estimate of a discrete quantity/variable is right or wrong.

Table 2. Concepts related to quality and availability of information

MOPs for each of these concepts are outlined in the following sections.

5.1.1 *MOPs related to quality and availability of information*

In this section MOPs will be established in order to measure to what extent C2 systems display the property “Capability to support the achievement of a high level of situation awareness”. The aim is to derive a set of MOPs that are quantifiable by following the approach outlined in section 3. Table 3 presents the set of MOPs utilised in the analysis. The first column presents MOP concepts. These concepts are the foundation for judging to what extent the actual C2 system displays the actual property. The second column comprises the MOP variables, which are variables derived to quantify the concepts. In the third column the functions of the MOP variables are described. These functions comprise system variables/parameters that are measurable/observable. Column four presents the system variables.

Table 3 explains the MOPs, but "the precision of the information in the situation picture" and "the correctness and completeness of the situation picture" remain to be explained. The situation picture available to a DM will always include inaccuracies caused by misjudgement of the values of the attributes describing tracks, e.g. age of information may cause inaccuracies in the estimate of the kinematic variables. A MOP variable related to the precision of information should therefore be a function of the accuracy of the information compared to a reference error, which may be the desired degree of detail. According to table 2 precision is related to the degree of details in the information. The MOP may then be expressed as:

$$\text{Precision} = \frac{\text{ref. error}}{\text{accuracy}}$$

<table>
<tr><th>MOP concept</th><th>MOP variable</th><th>MOP function</th><th>System variables</th></tr>
<tr><td>Accuracy of the situation picture</td><td>Mean accuracy of the state variables (the kinematic variables) of the tracks of the situation picture</td><td>Function to calculate the mean accuracy from kinematic variables of the tracks</td><td>Accuracy of the estimated kinematic variables (e.g. position, course, and speed)</td></tr>
<tr><td>Precision of the situation picture</td><td colspan="3">Explained in the text after this table</td></tr>
<tr><td>Correctness of information in the situation picture</td><td>Mean correctness of tracks contained in the situation picture</td><td>Function to calculate the mean correctness from the discrete variables of the tracks</td><td>Uncertainty in the estimation of the discrete variables (e.g. classification, identity)</td></tr>
<tr><td>Completeness of the situation picture</td><td>Mean completeness of tracks presented in the situation picture. (Some of the attributes describing the tracks may not be assigned a value)</td><td>Function to calculate the mean completeness of the tracks (kinematic and discrete variables)</td><td>Kinematic variables such as speed, course, and position.
Discrete variables such as identity, track type, and classification</td></tr>
<tr><td>Correctness of the situation picture</td><td colspan="3" rowspan="2">Explained in the text after this table</td></tr>
<tr><td>Completeness of situation picture</td></tr>
<tr><td>Consistency between situation pictures at different C2 nodes</td><td>Consistency between the tracks of situation pictures at different C2 nodes</td><td>Function that calculates the consistency of situation pictures by accounting for differences in precision, accuracy, correctness, and completeness[1]</td><td>Use of the system variables in the rows above</td></tr>
<tr><td>Age of information</td><td>Latency in dissemination of information</td><td>Function that calculates the time from an event is observed to information about the event is available to the DM
$(t_{DM} - t_{observe})$</td><td>t_{DM} = point in time when DM receives the information
$t_{observe}$ = point in time when an event is observed</td></tr>
</table>

Table 3. MOPs related to quality and availability of information

The MOPs correctness and completeness of the situation picture are illustrated in the Venn diagram of figure 3. Tracks of a situation picture ($A_{picture}$) are of two different types; real tracks and false tracks. The set of false tracks is denoted A_{false}. The set of real tracks in the real world is denoted A_{real}.

Thus, completeness is the ratio between the number of real tracks in the situation picture and the actual number of real tracks in the area of interest. The completeness of the situation picture may then be expressed by:

$$P_{comp} = \frac{|A_{picture} \cap A_{real}|}{|A_{real}|}$$

[1] It is important to underline that consistency between situation pictures does not mean that they need to be equal. There may be different requirements on the degree of detail, the accuracy, and completeness of the situation picture dependent on the level in the organisation.

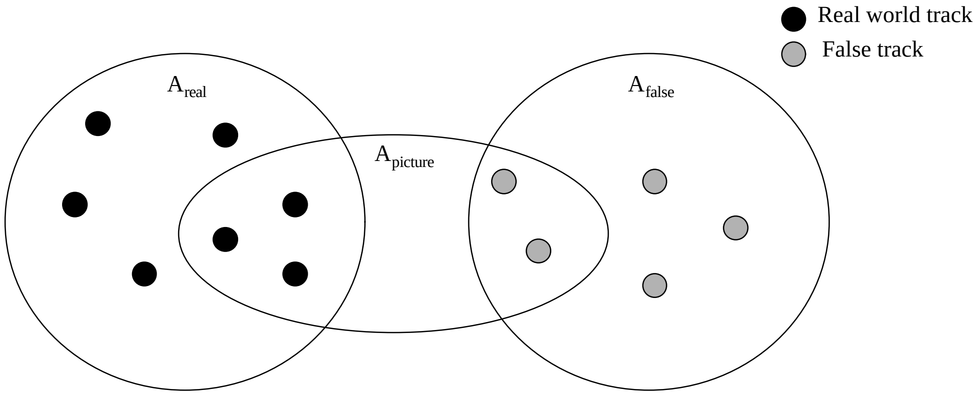

Figure 3. Venn diagram illustrating real world tracks and false tracks of a situation picture compared to actual tracks in the real world.

If the situation picture is complete $P_{comp} = 1$. Correctness as a MOP comprises a larger set of tracks because it includes false tracks, which may occur in the situation picture. The correctness of the situation picture may then be expressed as:

$$P_{corr} = \frac{|A_{picture} \cap A_{real}|}{|(A_{picture} \cap A_{real}) \cup (A_{picture} \cap A_{false})|}$$

If the information in the situation picture are correct (no false contacts) $P_{corr} = 1$.

Latency in dissemination of information is only one example of a MOP variable related to the MOP concept "Age of information". Other relevant MOP variables are; latency of information collection, and latency in the processing of information.

It is possible to define a composite MOP made up by the MOPs in table 3. One candidate MOP could be an overall quality measure comprising accuracy, precision, correctness, and completeness of the situation picture.

The MOPs presented so far are related to the quality of the situation picture and the track information. However, in order to assess the availability of information it is necessary to take into account other types of information entities, such as orders, requests, status reports, and warnings. Availability of this type of information is determined by looking at the flow of information in the C2 system.

Having defined the MOPs, the next section describes the corresponding MOEs.

5.1.2 *MOEs related to quality and availability of information*

MOEs are functions of MOPs and requirements to C2 system performance. Requirements related to accuracy, precision, correctness, and completeness of the situation picture depend on an actual situation and are closely connected to the basis needed to enable good and timely decisions. In table 4 some examples of MOEs are given.

A composite MOP measuring quality of the situation picture becomes a MOE by establishing quality requirements. A MOE of specific importance in our analysis is related to the information flow in the C2 system. This MOE is established from OIER as described above.

MOE	MOP	Requirement	MOE function
Age of a situation picture compared to update requirements	Age of the tracks of a situation picture	The tracks must be updated at certain time intervals	Function to calculate the mean delay of track update
Accuracy of the situation picture compared to accuracy requirements	Accuracy of the information in the situation picture	Accuracy requirements	Function to calculate the mean differences between the accuracy of the kinematic track variables and the accuracy requirements

Table 4. Examples of MOEs related to a C2 system's ability to support the achievement of situation awareness.

Figure 4 illustrates how the MOP associated with the information flow and the MOE based on the OIER are established..

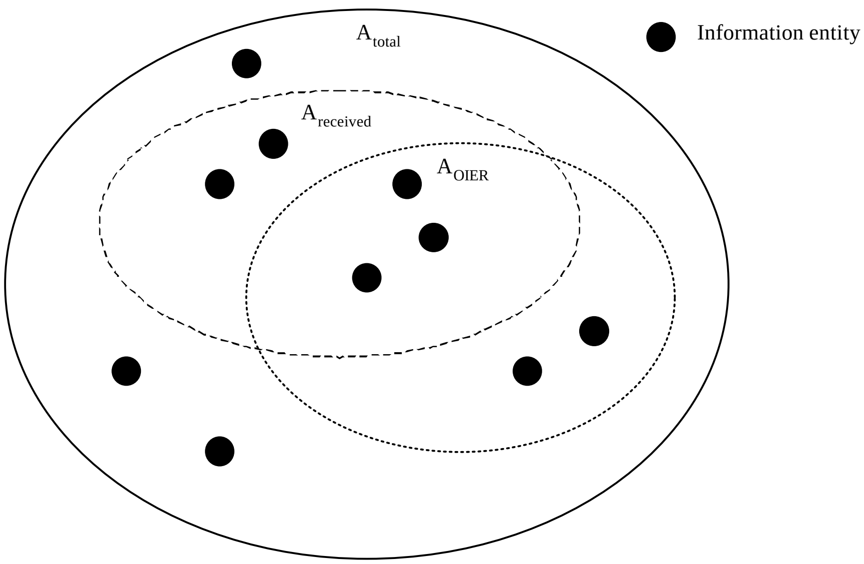

Figure 4. Establishment of a MOP measuring the information flow and a MOE based on OIER.

A MOP measuring the actual information exchange in the C2 system may be expressed as the proportion of the information entities received by a certain DM. Thus,

$$P_{DM} = \frac{|A_{received}|}{|A_{total}|}$$

where A_{total} is the set of information entities sent and $A_{received}$ is the set of information entities received by the recipient DM. By comparing the actual information exchange (measured by information flow MOPs) with the set of OIER, A_{OIER} it is possible to quantify the capability of the C2 system to produce and disseminate information as required. This is done by measuring the proportion of OIER satisfied:

$$P_{OIER} = \frac{|A_{received} \cap A_{OIER}|}{|A_{OIER}|}$$

P_{OIER} = 1 if all the information entities received by the recipient DM are OIER. It is important to note that the MOE expression is a function of time.

5.2 *MOMs related to the C2 System's capability to support decision processes at high speed*

Capability to respond timely is recognised as an important feature of a C2 system which should support a DM in making decisions and disseminate information in a rapid changing environment. In order to take advantage of favourable situations/"windows of opportunities" it is necessary that the C2 system support fast decision making.

It is important to note that the response time is not independent of the situation awareness. A common situation is that a DM has to decide if he should make a decision based on the current situation picture, which may be incomplete, or wait for more information to be available, which may result in a late decision. On the other hand, making a decision based on incomplete or incorrect information may increase the probability of making a "wrong" decision.

5.2.1 *MOPs related to the C2 system's capability to respond timely*

The MOPs established to measure the capability of the C2 system to respond timely is related to the decision and planning processes illustrated in figure 5.

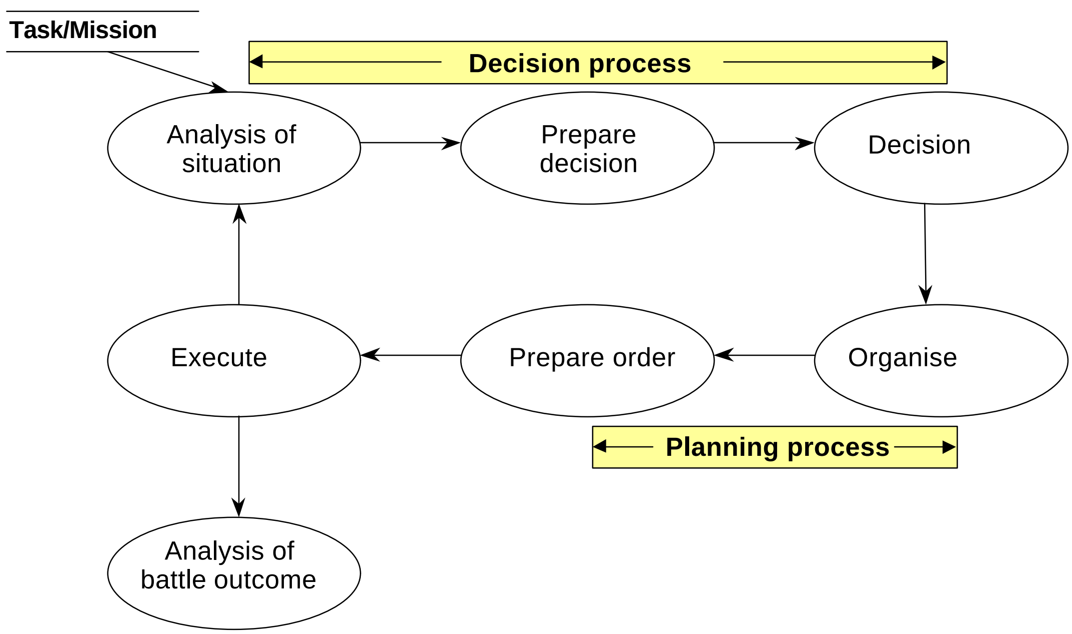

Figure 5. C2 process

The MOPs utilised in the analysis is presented in table 5.

MOP concept	**MOP variable**	**MOP function**	**System variables**
Speed of the decision process	Latency	Latency = $(t_{decision} - t_{mission})$	$t_{decision}$ = point in time when decision is made $t_{mission}$ = point in time when DM receives the mission
Speed of planning process	Latency	Latency = $(t_{order} - t_{decision})$	t_{order} = time when an order is disseminated $t_{decision}$

Table 5. MOPs related to the C2 system's capability to accomplish decision processes at high speed.

The most important MOP related to the capability of the C2 system to respond timely, is the response time, which is the time from an event occur until it is possible to take action. The response time is a composite measure comprising the time the C2 system needs to collect information about the event, the time to send the information to the DM, the time to make a decision, the time to plan, the time to disseminate an order, and the time to reallocate forces. However, we concentrate on the time spent on decision and planning processes in our analysis.

5.2.2 *MOEs related to the C2 system's capability to respond timely*

MOEs are established by making requirements to the C2 system performance. As explained in section 5.2.1 the response time is an aggregate MOP. Thus, it is natural to use this as a MOE by stating response time requirements. The MOE becomes:

- Timeliness of response

The response time requirements are established by analysing events occuring in scenarios. The MOE measures to what extent the performance of the C2 system meets the response time requirements.

6. Conclusion

This paper presents MOMs enabling a quantitative analysis of C2 systems. C2 systems are known to be rather difficult to analyse quantitatively, because of the large number of sub systems involved, and because it includes humans. The cognitive aspects related to humans are not easily quantifiable. A method is applied to obtain a set of relevant and quantifiable performance (MOP) and effectiveness (MOE) measures. This method is outlined in the paper as well. It involves deducing certain 'desirable' C2 system properties based on a top–down approach starting with the naval tasks, operational concept of maritime operations, and doctrines. In the paper it is argued for the following C2 system properties:

- Capability of the C2 system to support the achievement of a high level of situation awareness
- Capability of the C2 system to respond in a timely manner
- Availability of the C2 system, i.e. availability of C2 processes/functions, information, and communication

These properties are in a way high level requirements of the C2 system performance and effectiveness. MOPs and MOEs are established in order to measure to what extent the C2 systems display these properties.

The focal point in our analysis is the property "Capability of the C2 system to support the achievement of a high level of situation awareness", and MOMs established are related to quality and availability of information, which is of fundamental importance for the DM to achieve a high level of situation awareness and decision making performance.

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