The use of technical condition indices in ship maintenance planning and the monitoring of the ship's safety condition

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Abstract

This paper describes a tool for technical condition monitoring (TeCoMan) and how that tool has been applied in various operational settings from long term condition monitoring, via continuous ship and fleet condition monitoring to on-line safety monitoring. The tool is based on a hierarchical aggregation of "Technical Condition Indices" (TCI). The concept allows a high level view of the overall condition of the system as well as the ability to track down any problem to the root cause. TeCoMan has also been used as the computing engine in an on-line safety monitoring system where the idea is to combine "slow varying" information from maintenance related measurements with on-line indications of ship performance and voyage requirements to generate indices for the ship's ability to perform operations that are critical for the ship's and crew's safety, particularly in degraded conditions. The online aspect is also of interest to IMO's current effort to review the Integrated Navigation System performance standard. A central part of this standard is the integrated alert handling. As the DSS_DC research already has pointed out, integrated alert handling may not be as critical to ship safety as a better tool to give a clear overview of the ship's actual ability to perform its critical functions on an integrated status display. The TCI system may be able to provide at least part of this capability.

Keywords

Technical condition; condition monitoring; performance monitoring; KPI; Status assessment; Alarm management;

1. Introduction and state of the art

A wide range of techniques are used in computer based condition monitoring. Very generally, they can be classified as in the following paragraphs.

Signal processing. Many systems monitor the condition of equipment by measuring certain physical parameters that are characteristic for degradation, such as increased vibrations, contamination of lubrication oil or increased temperature. This method is useful when the condition can be characterized by a known physical process.

Fussy logic (Zadeh 1968) has been used to incorporate the semi-quantitative reasoning of human operators in condition monitoring systems, see e.g., (Tessendorf, R.E., Hoffman, A.J., van der Merwe 2004). These systems will often combine signal processing with fuzzy reasoning.

Expert systems and related technologies, e.g., case based reasoning (Olsson, Funk, Xiong 2004), are similar to fuzzy logic in that they attempt to capture the logic of rule based human reasoning into a computer program. However, expert systems are even more oriented towards qualitative reasoning than fuzzy logic.

Neural networks have been used to automatically "learn" relationships between characteristic data or event patterns and a technical condition. This method is to a degree complimentary to the other techniques and can be used in combined systems (Tessendorf, R.E., Hoffman, A.J., van der Merwe 2004).

The above techniques are addressing the problem of converting one or more measurement into a technical condition measure for one component or process in a system. Some system level approaches are listed in the following.

Computerized Maintenance Management System (CMMS) is a tool to manage the maintenance of larger systems. Condition monitoring is part of this, but more important is general asset management, inventory control, management of work orders etc. Thus, the CMMS may not directly say something about the overall condition of the system or even components of it.

Key Performance Indicator (KPI) is closely related to the *balanced scorecard* (Kaplan, Norton 1992). KPIs are quantitative measurements that reflect strategic performance in an organization, which in turn may include maintenance and technical condition related metrics. KPIs are sometimes organized in hierarchies, particularly in large organizations where each division and department may have their own KPIs, see e.g., (Honeywell 2006). Technical condition related KPIs are normally measuring performance on a fairly high level, such as "Maintenance cost per produced unit" or "Failure frequency" (Smith 2006).

TeCoMan can be viewed as a combination of the above tools, although it has only a very small part of the functionality of the CMMS. It allows the embedding of signal processing and human knowledge into a calculator of technical condition measurements. In addition, it defines the concept of Technical Condition Index that can be aggregated in a tree structure to give condition indexes for whole systems or any aggregate component on any level of the system. On the higher levels, this can be used as a maintenance related KPI.

The concept of TCI and the use of a tool like TeCoMan allow the user to easily view the technical condition of complete systems as well as backtrack from top level anomalies to the root causes by traversing the tree from top to bottom. This means that the system to a certain degree also supports diagnosis in addition to technical condition monitoring. The diagnostic capabilities can be enhanced by adding informative annotations to the nodes and aggregation functions (see next chapter).

The system and the tool are also generic in the sense that they can be applied to other areas than technical monitoring, e.g., safety or efficiency monitoring or even as a business process KPI aggregation system.

2. Technical Condition Index

As results from the research project "Ageing Management" (1996-1999), MARINTEK published a new concept for supervising the technical condition of complex process plans (Steinebach, Sørlie, 1998). This system was based on a hierarchical aggregation of "*Technical Condition Index*" (TCI) from a set of initial measurement values. The principle is illustrated in Fig. 1.

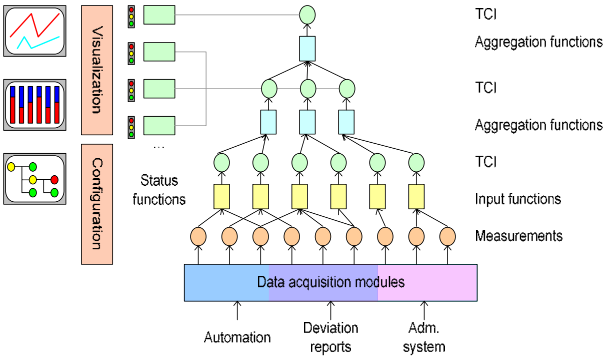

Fig. 1: General view of TCI aggregation

Different *data acquisition modules* collect data from online systems such as automation and monitoring, from deviation reports or from other administrative functions. The *Input functions* will convert these measurements into condition related index values (*TCI*). Input functions can use any of the methods outlined in Ch. 1, but will normally be relatively simple signal processing type algorithms.

The TCI can be aggregated in any number of levels through user configurable *aggregation functions*. Aggregation is often a weighted sum of lower level index values, but other transfer functions can be used. For application in technical systems, the aggregation usually follows the physical system breakdown. Thus, the first level may correspond to a cylinder or turbocharger condition index while the next level may reflect an engine's condition. Higher levels may include propulsion machinery as a whole and ship or fleet status at the top.

Visualization modules can be used to give "traffic light" type indications for selected systems or sub-systems, bar graphs showing how a degraded condition has been contributed to from different TCIs on lower levels or a trend over the development of one or more TCIs. In addition, a *configuration* module can be used to build or amend hierarchies or to change weighting factors and transfer functions.

In the current implementation, the range of the TCI is from 0 to 100 and is set to reflect the technical condition of the equipment or system compared to its condition as new. Other principles have been considered, e.g., making the value relative to the required functionality of the equipment or system. The former method was selected because it is easier to define a relatively causal relationship between the numeric value and the condition. The latter method would require a much more thorough analysis of how the equipment was used (Steinebach, Thorstensen 2002).

As will be discussed later in the paper, one can also use the system to indicate safety or efficiency. This will, however, require another interpretation of the value and, correspondingly, another way to construct the index values and the hierarchies. This issue will briefly be discussed in Ch. 4.

The benefit of the concept is that it allows a high level view of the overall condition of the system as well as the ability to track down any problem to the root cause by traversing the aggregation hierarchy. Thus, the TCI is mainly useful when supervising relatively complex systems where it is necessary to generate several levels of technical condition indicators.

As the TCI is dimensionless and mapped into a fixed value range (0 to 100), it can also – with careful design – be used to compare performance in different systems or sub-systems across different plants. This type of benchmarking can be used to quantitatively compare the effects of maintenance or operational procedures between companies or ships.

The TCI concept is currently used in two different applications. In one, the method is used to supervise a hydrocarbon gas compression plant with close to 5000 measurements. In the other, which will be described in Ch. 5, it is used to supervise a fleet of currently 30 ships.

3. The TCI and the KPI

The relationship between the KPI and the TCI was described in the two previous chapters. It is obvious that a TCI at some level can be used as a maintenance and technical condition related KPI. This may be used to complement the currently most common type of maintenance KPIs which are measuring the organizational aspects of maintenance (failures, maintenance cost, work orders etc.) rather than the actual technical condition (Smith 2006). The use of technical measurements is quite common in production planning and optimization through the use of Production Management Systems, but has to our knowledge had limited application in strategic maintenance management. Although condition monitoring and prediction is not without problems, one can assume that the use of this type of indicators may make the maintenance process more effective (Honkanen 2004).

In the current applications of the TCI principle, the aggregation functions have used weighted sums in each level of the hierarchy. The weight factors are currently set manually by application experts based on their knowledge of the supervised process or system. It has not been attempted to use more formal approaches to assign weights, although such methods are available in the literature, see e.g. the "Analytic Hierarchy Process (Saaty 1980). Another possibility that has been considered, but not yet tested is to use fuzzy logic type aggregation. This may allow for a more flexible approach to capturing expert knowledge about consequences of technical problems in complex systems. In general, the TCI tool (see next chapter) does not put any restrictions on the aggregation functions in terms of algorithm and other principles may also be investigated.

In general, the TCI principle can obviously also be extended to other KPIs than those that are maintenance and technical condition related. In another project in cooperation with Intermanager[1], the TCI tool will be investigated as a means to implement a set of "Shipping KPIs" that shall cover also other aspects than technical condition, e.g., safety, efficiency and environmental impact. Intermanager has adopted the Conjoint Value Hierarchy (CVH) methodology (ICS 2005) as a means of generating KPIs for ship management companies and this method will be compared to the ones mentioned above and considered for implementation in the TCI tool.

4. Technical Condition Management Tool

To support the TCI method, a Technical Condition Management (TeCoMan) tool has been developed. It is a Java application that can be run via a web interface on a server or as a desktop application. As it uses a general purpose SQL database to store measurements and TCIs, it will in many cases be most useful as a web application with a centrally managed database.

The structure of the TeCoMan tool is roughly as illustrated in Fig. 1. The program on the lowest level consists of data acquisition modules for various interfaces, e.g., via OPC[2] directly from an automation system, as XML[3] input files via electronic mail or acquisition via access to an external database. Data is stored as measurements that are further transformed via input and aggregation functions into technical index values through several layers of aggregation in a tree structure.

The system supports asynchronous input and recalculates only the affected TCIs when new input arrives (Fig. 2).

This means that the system easily handles any combination of slow arriving data from monthly deviation reports to rapidly sampled data from an automation system. However, as TeCoMan is intended to aggregate relatively high level and thus slowly varying indexes, it is normally a limit to how fast one wants to sample input. Input functions can also implement functions over time, e.g., by picking out maximum values in a certain running period or by providing a running mean value.

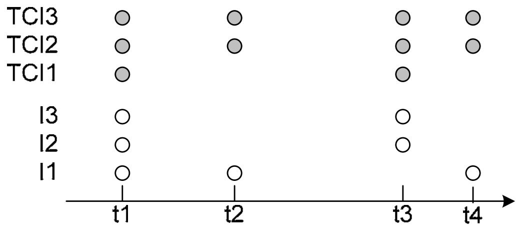

Fig. 2: Asynchronous input

Aggregation is by a selection of different aggregation functions. This includes linear weighted combinations, fuzzy logic type functions and others.

Final visualization can be as a trend over time of one or more TCIs, as a bar graph showing contributions from lower level TCIs and also visualization through a status function. It analyzes a time series of TCIs to define a traffic light status of good (green), alert (yellow) or alarm (red). The status can be calculated independently for each TCI-node in the system and at any level as needed or desired. Dedicated displays in TeCoMan allow the operator to view individual components' contribution to any degradation in system level TCIs (Fig. 3), also over time.

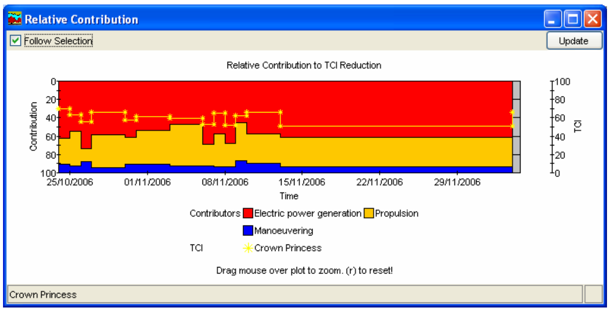

Fig. 3: Components' contribution to system TCI

TeCoMan defines two types of hierarchies: 1) One system hierarchy that defines the topology and the relationship between components, sub-systems and systems. 2) One or more functional hierarchies can be superimposed on the system hierarchy. This is done by selecting nodes and arcs from the system hierarchy and defining aggregation and transfer functions to suit the functional hierarchy one wants to implement. Any number of functional hierarchies with distinct mappings may be defined. In current implementations, the functional hierarchy is normally that of technical condition and the nodes represent TCIs.

It is also possibly to define functional hierarchies based on, e.g., safety or efficiency. However, this has not yet been tested in large scale implementations so it is not clear how well this will work. One problem for other functions than technical condition is that the function may require both technical and process oriented hierarchies, which it may be difficult to capture in one system hierarchy. One example is safety. Safety indexes may require mapping of the technical system, the control and monitoring system as well as the more process oriented aspects onto the system hierarchy. This issue will be

[1] http://www.intermanager.org/
[2] Open Process Control (www.opcfoundation.org)
[3] eXtensible Markup Language (www.w3c.org)

investigated in ongoing research.

There are many possible approaches to establishing the system hierarchy. The easiest approach for smaller systems is a strict technical system breakdown to the desired level of detail. It is typically established by answering the question: "What parts does this equipment consist of?" In other cases it may make more sense to look at groups of a specific equipment types, such as all valves, piping or instrumentation. It is also possible to use a functional breakdown. However, this is practical only if the equipment under consideration provides one distinct function. If equipment provides several functions it will appear more than once in a functional hierarchy, thus making the hierarchy more difficult to manage. Also, most existing equipment tag systems, such as used for maintenance planning and/or condition monitoring, mostly follows a hierarchical and physical system breakdown philosophy. Personnel are used to this method for tagging components and systems and will have less difficulty in getting accustomed to the TCI system hierarchy when it follows or is similar to the tag structure.

TeCoMan is today used in two live applications. One is TOCC, which will be described in the next chapter, and the other is a gas export compression plant in Norway. In this plant about 5000 measurements are integrated in TeCoMan, including a large number of different deviation report types, imported from SAP[4].

5. Technical Operations Competence Centre

TeCoMan will normally run in a mixed batch and interactive mode. Incoming data or a timer triggers the batch processing of measurements into TCIs and the interactive mode is for visualization of the results.

In the last two years the TeCoMan tool has been adapted to be used in a "Technical Operation Competence Centre" (TOCC[5]) for fleet management, superintendents and chief engineers. TOCC uses TeCoMan to give automatic feedback on critical ship TCIs based on monthly engine reports. More detailed analysis of the reasons for any irregular values can be performed by the receivers of the report or by consultation by on-shore experts.

The chief engineer onboard the ship fills is periodic (usually monthly) reports on various parameters related to the engine's performance and sends these data as an XML file to TOCC. TeCoMan stores the data in its database and automatically generates a summary report on the engines performance (in PDF[6]) and sends this back to the ship and the superintendent in the manager's or owner's office. This is illustrated in Fig. 4.

It is also possible for the superintendent (or, in principle, also for the chief engineer) to access TeCoMan directly via the web interface if this should be necessary. However, the PDF report contains the summary TCI status as well as selected information from those nodes that contribute to any non-normal result. This can be used by the receiver to detect and address technical problems that can be detected by the TCIs. If necessary, they can also get help from the expert team that is developing and improving TOCC. These experts come from MARINTEK as well as from the Norwegian University of Technology and Science (NTNU). This has already resulted in significantly improved performance for some of the ships.

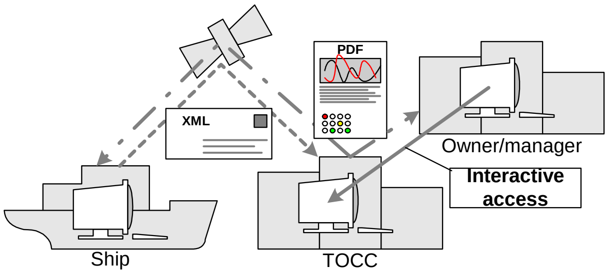

Fig. 4: TOCC information flow

Approximately 30 ships currently use the service to systematically control and improve main engine performance. Solutions to control performance of auxiliary engines, hull and propellers are currently being evaluated. A new measure to follow up environmental performance will be developed in 2007. TOCC solutions give vessel operators and crews a better overview and validation of ship performance. TOCC also increases the capability for better centralized views of the resources needed and benefits obtained in the course of reaching the performance goals.

Thus, TOCC develops solutions that use data from technical operations in shipping to systematically improve performance with respect to fuel consumption, maintenance, off-hire and environmental impact. It is essential that relevant information is presented to vessel operators and crews in a way that best offers intelligent guidance.

Recent developments in legislation and reporting requirements also offer new challenges to the documentation of good management and performance in ship operations. Systematic and reliable actions initiated by calibrated technical performance measures, before effects on economics and the environment can be observed, will be essential in future shipping operations.

6. On-line decision support

The TeCoMan tool as used in TOCC generates summary reports based on standard machinery registrations from the ships. The reports can show the overall technical condition on fleet level or ship level as well as give an indication of where any highlighted problems may originate from. The process that TeCoMan analyzes is relatively slow and data is acquired with a "sampling rate" of about once a month.

TeCoMan has also been experimentally used as the computing engine in an on-line safety monitoring tool developed in the EU project DSS_DC. The idea is to combine "slow varying" information from maintenance

[4] SAP AG, see www.sap.com.
[5] See www.tocc.no
[6] Portable Document Format, see www.adobe.com

related measurements with on-line indications of ship performance and voyage requirements. This can be used to generate indices for the ships ability to perform operations that are critical for the ship's and crews' safety, particularly in degraded conditions. The tool can give an at a glance overview of the ship's technical condition and the safety implications of any problems deriving from degraded condition.

In addition to the calculation of TCIs for critical technical systems, DSS_DC focused on making this information available to the crew as operationally useful data.

Thus, the presentation had to satisfy two different criteria: 1) It needed to be continuously updated so that any "catastrophic" change in system status was immediately visible in the status display and; 2) It needed to take the long term developments into consideration so that an more accurate assessment of the maintenance status of components and systems could be assessed.

These two criteria has been satisfied with a minor change in TeCoMan by which aggregation can be done in "real time" without storing all rapidly varying TCIs in the database. TCIs and corresponding measurements is only stored one a day or even rarer if desired. This means that one can look at the actual status, both taking historical data and current data into consideration.

To provide a more intuitive display to operational crew, a new display type has been added to TeCoMan that can overlay the TCI values on a graphic drawing or picture – either as a process diagram (Fig 5) or as a geographic representation of the actual system (Fig. 6).

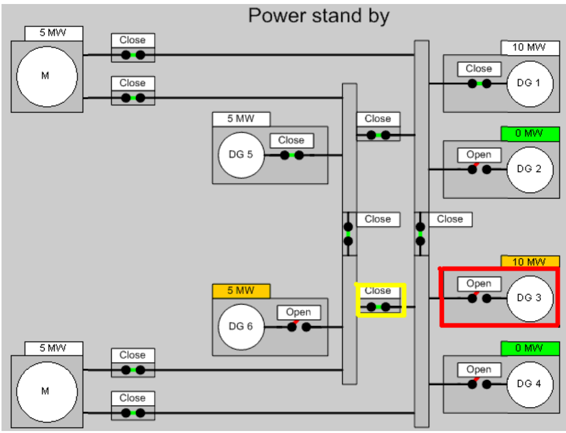

Fig. 5: Process type display

The process type display will give a clear indication of the functional consequences of problems as it directly represents one aspect of the systems functionality. This display type is normally the one that is most informative to the crew. This particular figure shows the power generation plant with four main engines and generators, two auxiliary engines and generators and two of the motors of a cruise ship.

The geographic type diagram is very efficient as a means to show the spatial relationship between any indicated problem and components of the system. This type of display can be used when consequences of fires, flooding or structural damage needs to be assessed, but it is less relevant in typical TeCoMan applications. This particular figure is a part of the engine room with some of the same components as are shown in the process diagram in Fig. 5.

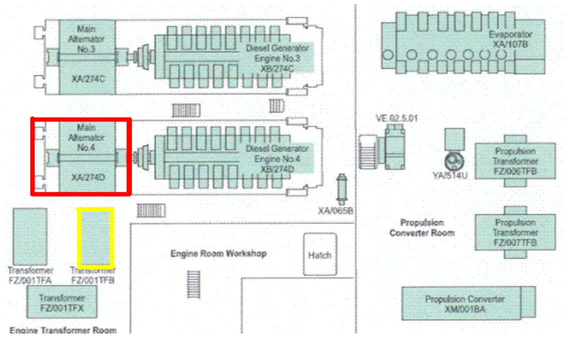

Fig. 6: Geographic type display

TeCoMan handles both display types as graphic file that can be overlaid with certain status information as indicated in the examples above. The size and placement of the status symbols must be configured into TeCoMan.

The intention of developing this system was to give bridge officers information about the technical condition of selected ship systems that were important for safe operation of the ship. This would be valuable information in a degraded ship condition where only parts of the ship systems were available. In such cases one could use this information to assess the operational margins of the ship and also to take this into consideration when making plans for getting the ship and passengers to a safe heaven.

7. Alarm management

The advanced and complex systems onboard modern ships can give rise to a large number of alarms. A study done on board a shuttle tanker and a selection of cruise ships showed alarm rates of up to 9 alarms per hour from the automation systems even under normal operation (Rødseth et. al., 2006a). The distribution of these alarms is shown in Fig. 7. Note that this histogram does not include navigational alarms that are presented on the bridge alone.

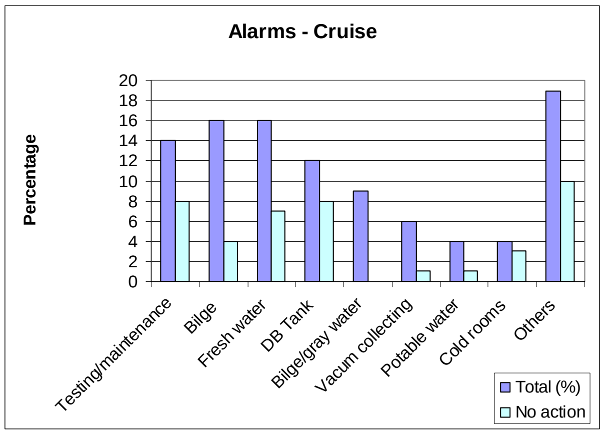

Fig. 7: Alarms on a cruise ship

Many of these alarms are technical, i.e., they show a deficiency in a system or component that may or may not have any influence on the operation of the ship. A typical example is a technical failure in one of two redundant systems: These alarms have no functional consequence and is more or less an annoyance for the bridge team because they cannot do anything about it. They have to inform the engineers of the problems and the engineers will take action as soon as they can.

Alarms of this type should in principle be routed away from the bridge and sent directly to the engineers to reduce disturbances on the bridge. However, the degradation in technical condition should be brought to the officers' attention as it may cause problems in the future, e.g., if the second system also develops problems.

This means that a status assessment system similar to that presented in Ch. 6 could be used to aggregate information about technical condition as well as alarms and show it as degradation of certain components or systems. If this was combined with purely technical alarms being routed to engineers and just functional alarms being presented on the bridge, it would enable a significant reduction of bridge alarms.

8. Impacts on ship safety and efficiency

The initial research and development on TCIs and TeCoMan was focused on creating a more efficient way to monitor the condition of large industrial plants with several thousand measurement points. The project was successful and the system is still in operation on one of the plants. It is obviously costly to do the required engineering work for such plants and it is not yet clear if it is commercially viable as a general concept. However, work continues also in this area.

The TOCC concept described in Ch. 5 is more promising as a commercially viable system. The technical systems onboard modern ships are increasingly getting more complex while crew is reduced and also has less experience with such systems. It also becomes more difficult for the superintendents to monitor and pinpoint condition related problems. While some system manufacturers also supply services related to remote monitoring of their equipment, TOCC can provide a holistic view of a fleet with the potential to cover most or all technical systems onboard. The commercial potential of TOCC is currently being investigated by Det Norske Veritas (DNV 2005).

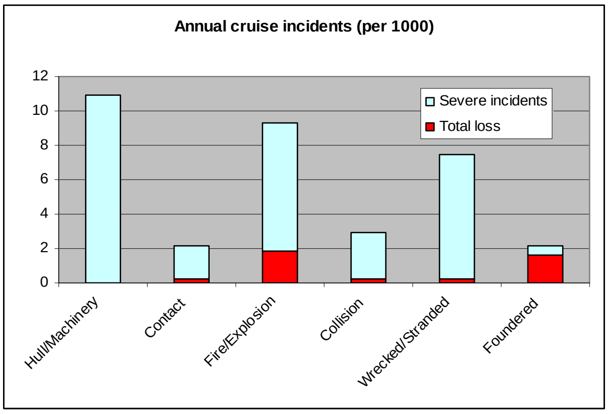

Fig. 8: Annual cruise ship incidents

Focusing on technical condition in ship safety makes sense. A general damage statistics for passenger ships above 4,000 GRT is presented in Fig. 8. This is based on data from Lloyds/Fairplay accident database in the years 1990 to 2004 inclusive, where 131 severe incidents were reported for this group of vessels. A mean fleet size of 250 such ships has been used in the vertical axes (Rødseth 2005).

As one can see, technical problems with hull or machinery accounts for about 30% of all serious incidents for this type of ship and has also the potential to severely aggravate other types of incidents.

On line decision support as described in Ch. 6 is also an interesting concept, but still not tried out in an operational setting. As maintenance of modern ships is becoming more complex it is also getting more difficult to understand the operational consequences of degradation in technical systems. As a significant portion of accidents are related to technical problems (see, e.g., Fig. 8), it is highly probable that better condition monitoring will have an impact on ship safety.

Finally, the issue of alarm management is central for increasing ship safety. Many accidents happen because some alarms where overlooked or because it was not clear what operational consequences the alarm had. As can be seen from Fig. 7, a significant number of alarms require no action from the operator. These are typically "technical alarms" that indicate a problem with a sensor or a system that has no immediate operational consequence, but that needs technical maintenance at some time. If these alarms could be transferred to a maintenance management system and only be displayed to the user as a potential technical condition problem as in Fig. 5 or 6, this could immediately reduce the number of alarms with about 30% in this example.

All in all, one can expect that further research and developments in this area will have a significant impact both on efficiency and safety in modern shipping.

9. Conclusions

This paper has shown some ways technical condition monitoring can be integrated with ship operations, both on board and on shore.

The hierarchical principle implemented by TeCoMan has proven to be a reliable mechanism for supervising the technical condition for large plants and for fleets of ships. Due to the cost of engineering the hierarchy, it may also be more applicable to the problem of supervising systems that consist of a number of more or less identical sub-systems which is the case both for the gas processing plant (6 compressor trains) and TOCC (30 ships).

Some of the potential of the TCI method has already been validated through the TOCC project. It has been in operation now for about one year and the feedback is positive although many practical problems have had to be solved along the way. In particular, the problem of getting correct and reliable information from the ships has proven more difficult than expected. However, in the near future with steadily fewer experienced sailors available both as engineers or superintendents and as system complexity steadily increases in all areas onboard, it may very well become an operational necessity to have systems of this type both on the ship and in the fleet manager's office.

The extension of the technical condition management system to also be an on-line system with decision support functions for the deck officers is also an interesting possibility. Its application as a purely technical condition display system may not add that much value to current ship systems. However, integrated with alarm filtering mechanisms, it has significantly greater potential. Ship bridges with less crew and more systems to supervise will require new innovations to keep it manageable by the bridge team.

The concept of TCI is also being investigated in other areas, e.g., for integration with key performance indicators (KPI) and for more flexible calculation and follow up of time charter party claims.

10. Acknowledgements

The work described in this paper has partly been funded by the European Commission through the research project "Decision Support System for Ship in Degraded Condition" - DSS_DC, Contract number TCT3-CT-2003-506354.

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