Trans IMarE, Vol 103, pp 365-373

Expert scheduling and planned maintenance systems

P Alleyne, BSc, MSc, D Rhoden and D Williams, BSc, PhD
Lloyd's Register

SYNOPSIS

A major operational cost for a ship is that associated with maintaining it in a safe and seaworthy condition. Savings in this area can, therefore, have a significant effect on a ship's profitability. To this end, the production of effective plans which maximise operating time at minimum cost is an important task undertaken by Chief Engineers. In this paper a description is given of the way in which advanced information technology techniques can be utilised in a new generation of support systems for this task. These systems can produce maintenance plans which allow for the diverse factors that affect the timing of maintenance activities, including machinery condition information.

INTRODUCTION

To maintain a ship in a safe seaworthy condition requires execution of maintenance activities, actions which may involve inspection, repairs or replacements to machinery, electrical equipment or the hull. The timely and safe execution of these maintenance activities is one of the major tasks onboard a ship. Producing the most effective plans for these activities for modern vessels is a significant problem which involves consideration of many factors, eg minimising down time, stock control, classification restrictions, voyage details and personnel utilisation. This paper describes the way in which advanced information technology techniques can be used to support engineers in producing and maintaining plans that take these factors into account. Example user interface screens from such a system are given.

In the next section the requirements of modern maintenance planning systems are discussed. This is followed in the section on components of an EMS by a description of the main components that 'expert' maintenance systems need to possess in order to meet these requirements. In the section on use of expert knowledge within an EMS the various components of expert knowledge that have to be incorporated into an advance planning system are reviewed. The way in which engineers, the 'end users' of the system, can be provided with easy structured access to the expert knowledge and information generated by the system, is addressed in the section on user interaction with the EMS. The paper closes with conclusions on the development of expert planning systems.

P Alleyne gained his BSc in Applied Science in 1983 from Kingston Polytechnic. In 1986 he obtained an MSc in Intelligent Knowledge Based Systems from Essex University. From 1986 to 1989 he worked for AI Ltd as a technical consultant and systems developer on various projects ranging from discrete event simulation to concurrent extensions to common LISP. In 1989 he joined the Performance Technology Department of Lloyd's Register as a systems developer on the KBSSHIP project, where he has overall responsibility for the development of user interfaces.

D Rhoden served as an engineer in ocean-going ships from 1960 to 1969 when he joined the Department of Transport as a Surveyor, gaining his Extra-First Class Engineer's Certificate in 1971. From 1978 to 1987 he was employed by European Ferries as a member of their project team engaged in the design and supervision of construction of new ships. He was transferred to Three Quays Marine Services Ltd in 1988 for similar duties and in July 1990 he joined the Performance Technology Department of Lloyd's Register to assist with the development of ship performance monitoring, maintenance planning systems and related services.

Dr David Williams obtained his BSc in Engineering Science from Durham University, and a PhD in AI in engineering design from St Johns College, Cambridge. In 1982 he joined Sir Alexander Gibbs and Partners, Consulting Engineers, where he undertook design work. In 1984 he joined the Cambridge University Engineering Department where he produced design software and in 1986 headed a SERC research project on knowledge-based systems in control engineering design. In 1990 he joined the Performance Technology Department of Lloyd's Register where he leads the KBSSHIP project and works on design support systems.

BACKGROUND TO THE USE OF EXPERT MAINTENANCE SYSTEMS

In the past decade significant advances have been made in the development of computer based support systems for planning maintenance. These advances were instigated as a result of the increased complexity of the planning task and the need for greater savings in maintenance. More specifically the advances were made to satisfy the following major requirements[1]:

1. *Reduced repair costs and down time*. This is achieved by planning services of equipment before breakdown.
2. *Extended machine life*. This is achieved by systematically planning routine preventative maintenance.
3. *Control of spare parts/purchasing*. With the large numbers of spares required in maintenance there is a requirement to minimise ordering costs. This can be achieved by providing computerised stock control systems.

The types of system that have been developed to meet these requirements are called planned maintenance systems. With the ever increasing complexity of maintenance planning there is a need to further improve support systems for maintenance planning. This need can be transformed into the following requirements:

1. *Improved planning capabilities.* Factors that affect maintenance planning associated with other aspects of the operation of the ship should be taken into account, such as details of voyages, the weather, cargoes being carried and statutory regulations. For example, the maintenance plans produced should take into account the times when a ship is in port, so that maintenance that can only be carried out in port is scheduled for those times.
2. *Planning on the basis of condition information.* To fully exploit the savings that can accrue from the use of condition monitoring it is important that maintenance plans are continually updated to take into account the latest information on the condition of components.
3. *Communications with other computer systems onboard ship.* Planned maintenance systems (PMSs) that have been developed are self-contained units with internal databases, as shown in Fig 1. For efficient running of ships, communication between systems is becoming increasingly important. A diagrammatic representation of the potential requirements placed on maintenance systems with respect to information flows is shown in Fig 2. This shows, for example, a flow of maintenance history information to a diagnosis system. This system could use this information in its reasoning about which components' faults may be the cause of alarm conditions being detected.

Systems that can satisfy these requirements can be termed Expert Maintenance Systems (EMS).

Reference will be made in this paper to a prototype EMS which is being developed as part of the KBSSHIP project.[2,3] This project is sponsored by the European Commission as part of the ESPRIT II programme. Its aim is to design, implement and integrate onboard decision support systems for optimum operation of ships. At present the project comprises four task-solving systems which serve as decision-support tools for: voyage planning (expert voyage planner), alarm diagnosis and handling (expert diagnosis system), maintenance scheduling (expert maintenance system), and load planning (expert loading system). A system manager will supervise the communication and co-operation of the individual systems and will draw on the support of a system handling all the relevant regulations pertaining to the operation of a complex ship.

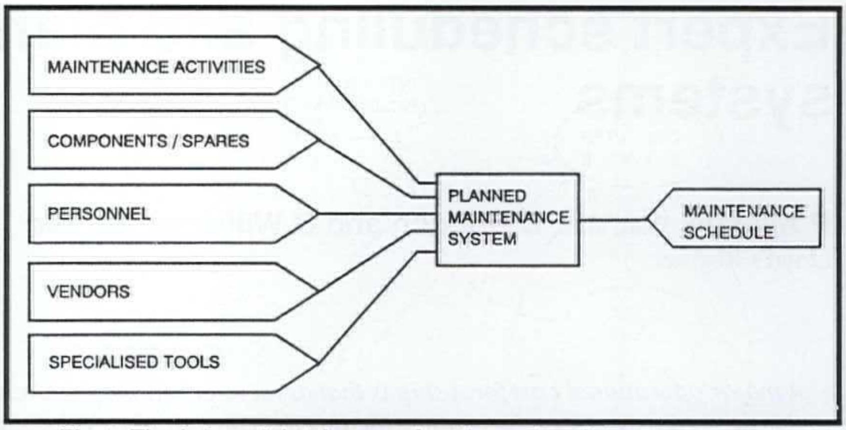


Fig 1: The internal databases of a planned maintenance system

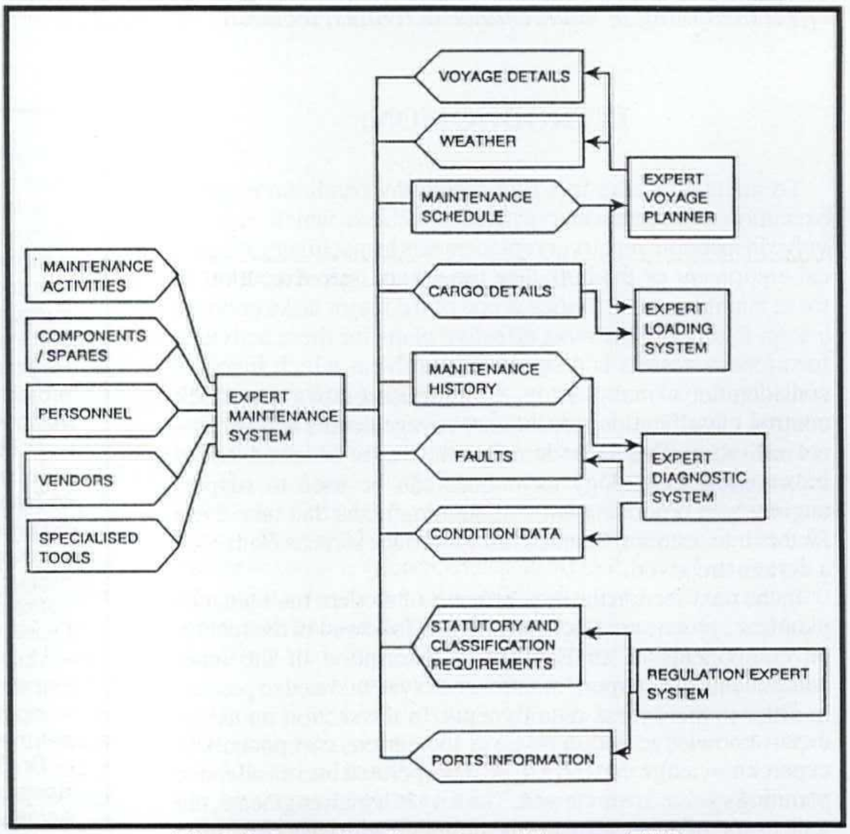


Fig 2: Information flows to and from an EMS

THE COMPONENTS OF AN EMS

To satisfy the enhanced requirements described in the last section an EMS must contain all the functionality of a PMS and must also contain an advanced planning component, capabilities for communicating with other systems, and interpreters of condition information. An abstract design of an EMS that combines these components is shown in Fig 3 and the components are now described in more detail.

The planning/scheduling component

Of central importance in any EMS is a planning component which assigns times and resources to maintenance activities

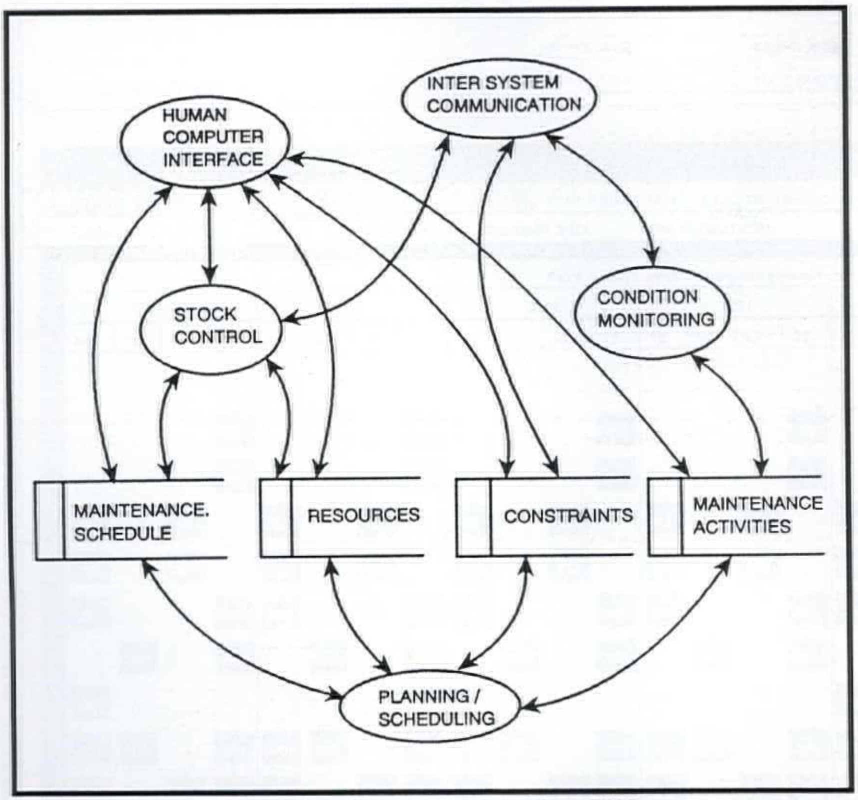


Fig 3: An abstract design of an EMS

whilst dynamically taking into account changes in any of the internal or external forms of information described in the last section. Assuming that the approximate time at which it is desired for a maintenance activity to be performed is available, the desired or goal state for a maintenance scheduler is to have all the maintenance activities whose desired time falls within a time period (specified by the user) actually scheduled within that period. The EMS scheduling problem can, therefore, be viewed in terms of a start state (current ship condition, manpower etc), and a set of goal states (numerous plans that detail when maintenance activities are to be carried out).

The various factors that affect planning can be divided into those associated with resources and those associated with constraints. These can be defined as follows: a resource is a commodity that can be used (for example manpower and tools); a constraint is some limiting factor that influences whether a maintenance activity can in fact be performed or not (for example certain maintenance activities can only be scheduled if the ship is in port). It is recognised that a resource that is not available or already used could thus be thought of as a constraint. However, this is not how we use the terms; when a resource is not available it is an unavailable resource and not a constraint. This approach is adopted as it has proved a more natural way of discussing the problem with domain experts.

The required output from the scheduler is one or more plans. Each of these plans consists of a list of representations of activities which have been assigned times at which they should be carried out. These can be presented in the form of Gantt charts, an example of which is shown in Fig 4 and further details are given in the section on user interaction with the EMS. When setting the times on the activities the scheduler must ensure that sufficient manpower and tools are assigned to the activity and ensure that at the times at which it is scheduled none of its constraints are contravened in the environment.

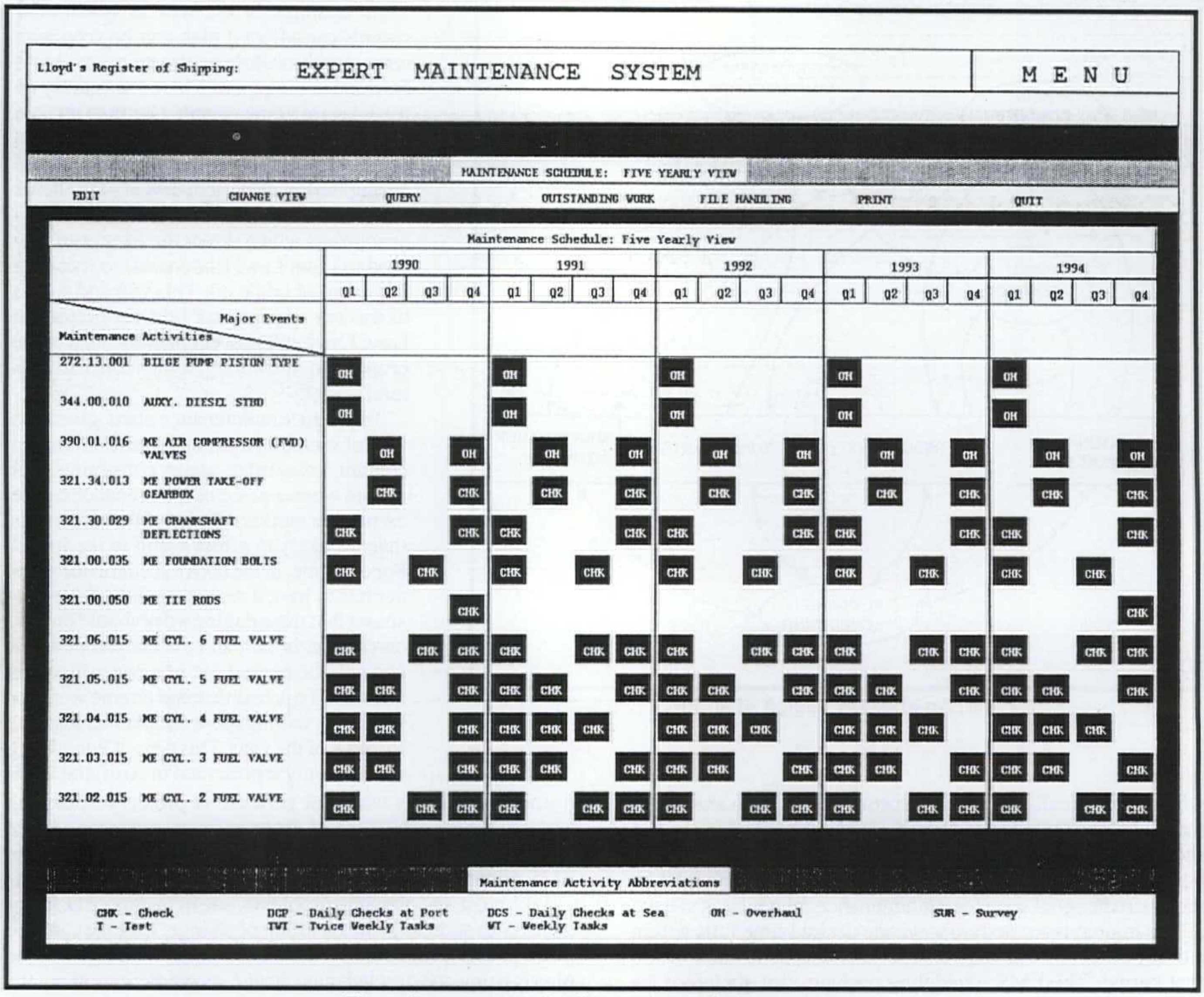
An example of the way in which constraints can affect a plan can be seen with respect to the following scenario: a tanker is en-route to Singapore where she is to lay up for 3 days at a tank cleaning berth to prepare for a cargo of white spirit. It is planned to carry out planned machinery maintenance during the lay up period. Twenty four hours before ETA Singapore, the ship receives new orders which direct the Master to proceed to Lawi Lawi (Indonesia) to receive a full cargo of crude oil. This will add 4 days to the sea voyage and Port restrictions at Lawi Lawi will prevent maintenance of the propulsion machinery in the immediate future.

To produce maintenance plans, given this type of scenario, a planner in an EMS has to contain knowledge about constraints that dictate when a piece of maintenance can be carried out and knowledge of the constraints that are likely to affect a ship in the future. For example, in the above scenario the planner has to have a representation of the constraint that main engine work should only be carried out in port and the constraint that it can only be carried out in a port where it is allowed. To schedule main engine work for the lay up in Singapore the planner also has to know of the visit. This type of knowledge is commonly represented in Artificial Intelligence systems as temporal periods. A prototype planning system that uses this type of representation and a state space search solution method have been implemented as part of the EMS system that is an integral part of the KBSSHIP project.

Like most real planning problems, one of the major tasks for an EMS to address is the handling of change. Change can take place in two forms. Firstly, the environment within which the plan is being constructed may change, as predictions about the future received from outside the system alter. Such changes include changes to constraints (such as predicted weather), to resources (eg sickness of crew), and to the temporal environment within which the plan is constructed. In the above scenario a change occurs in the destination port. To take account of this the planning system has to know of the change to the destination. In addition, it has to be able to gain the knowledge that main engine work can not be carried out at the new port (Lawi Lawi). In a communicating system such as the one being developed in KBSSHIP this knowledge is gained directly from other systems. On the basis of the changed information the planner can make appropriate modifications to the plan.

In the second form of change, the goal state itself may alter. For example, when a fault or change in fuel quality causes the condition assessment elements of the EMS to identify a change to the desired time to execution of certain maintenance activities, then the scheduled times of those activities should be changed. The EMS planner must also be able to respond to situations where maintenance has not been completed. In this case the system should be capable of including the unfinished work in the future plan.

The majority of the work performed by the planning component will be the re-scheduling of existing plans. In these situations an important requirement is that the change to the plan should be minimised, so that disruption to the mainte-



Maintenance Schedule: Five Yearly View

Major Events / Maintenance Activities	1990				1991				1992				1993				1994			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
272.13.001 BILGE PUMP PISTON TYPE	OH				OH				OH				OH				OH			
344.00.010 AUXY. DIESEL STBD	OH				OH				OH				OH				OH			
390.01.016 ME AIR COMPRESSOR (FWD) VALVES		OH		OH		OH		OH		OH		OH		OH		OH		OH		OH
321.34.013 ME POWER TAKE-OFF GEARBOX		CHK		CHK		CHK		CHK		CHK		CHK		CHK		CHK		CHK		CHK
321.30.029 ME CRANKSHAFT DEFLECTIONS	CHK			CHK	CHK			CHK	CHK			CHK	CHK			CHK	CHK			CHK
321.00.035 ME FOUNDATION BOLTS	CHK		CHK		CHK		CHK		CHK		CHK		CHK		CHK		CHK		CHK	
321.00.050 ME TIE RODS				CHK																CHK
321.06.015 ME CYL. 6 FUEL VALVE	CHK		CHK	CHK	CHK		CHK	CHK	CHK		CHK	CHK	CHK		CHK	CHK	CHK		CHK	CHK
321.05.015 ME CYL. 5 FUEL VALVE	CHK	CHK		CHK	CHK	CHK		CHK	CHK	CHK		CHK	CHK	CHK		CHK	CHK	CHK		CHK
321.04.015 ME CYL. 4 FUEL VALVE	CHK	CHK		CHK	CHK	CHK	CHK		CHK	CHK	CHK		CHK	CHK	CHK		CHK	CHK	CHK	
321.03.015 ME CYL. 3 FUEL VALVE	CHK	CHK		CHK	CHK	CHK		CHK	CHK	CHK		CHK	CHK	CHK		CHK	CHK	CHK		CHK
321.02.015 ME CYL. 2 FUEL VALVE	CHK		CHK	CHK	CHK		CHK	CHK	CHK		CHK	CHK	CHK		CHK	CHK	CHK		CHK	CHK

Maintenance Activity Abbreviations

CHK - Check
T - Test
DCP - Daily Checks at Port
TWT - Twice Weekly Tasks
DCS - Daily Checks at Sea
WT - Weekly Tasks
OH - Overhaul
SUR - Survey

Fig 4: An example of a five yearly maintenance plan

nance crew is minimised. This can be achieved by using the state space approach to planning.

The condition monitoring component

The aim of maintenance operations onboard ships is to achieve maximum operating time at minimum cost. This aim can more nearly be obtained if an EMS is capable of automatically taking into account sensor information indicating the condition of components. It can use this information to generate predictions as to when a component may enter its corrective maintenance zone. These predictions can then be used as the basis for producing the maintenance schedules, leading to possible extensions between maintenance work on that component and reductions in failures.

Condition monitoring has been applied with some success in a number of areas, eg by using vibration measurement on rotating machinery and shock-pulse measurement on rolling bearings. The condition monitoring component of an EMS should be capable of using this information to generate automatically times for next maintenance.

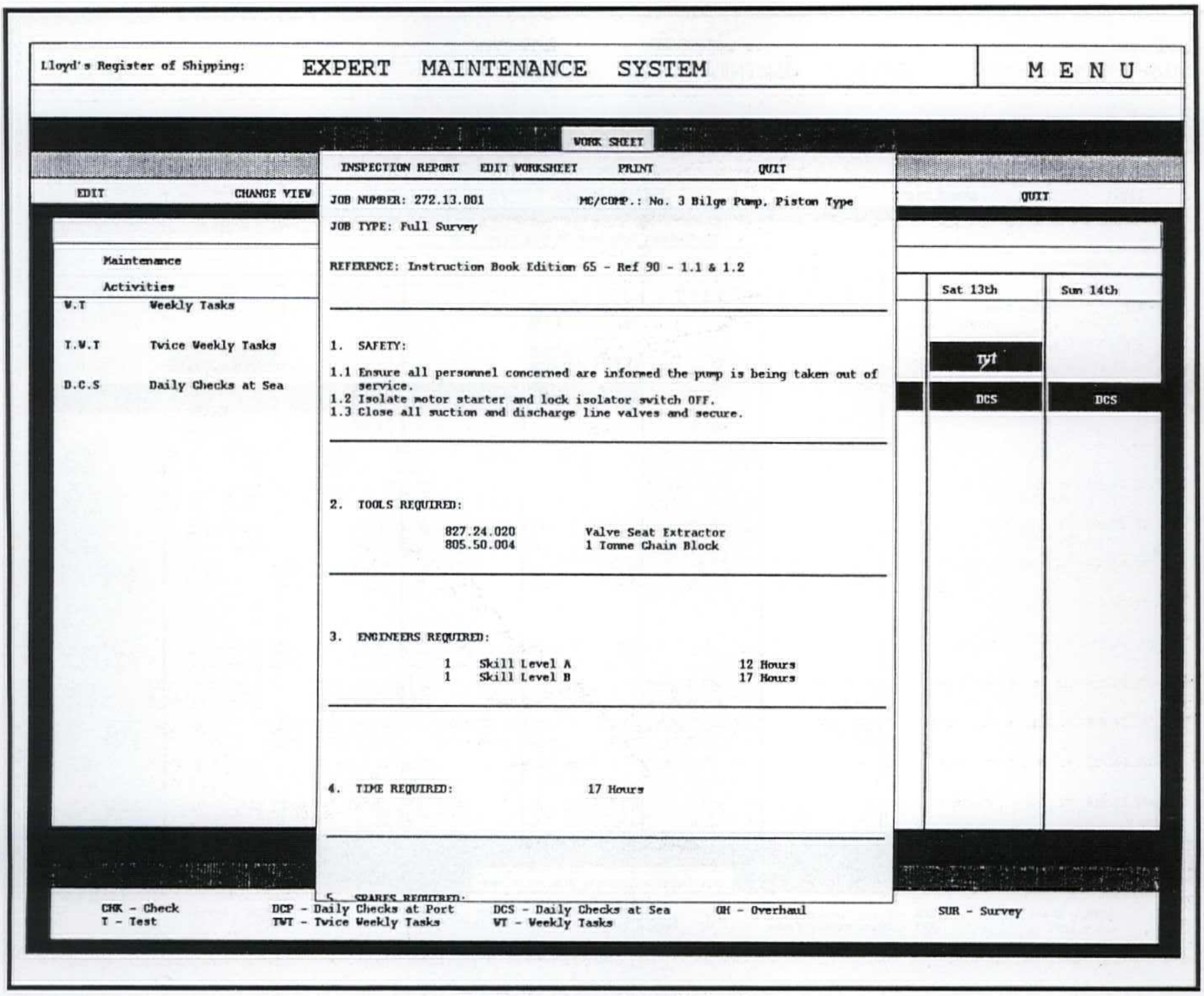
Other techniques for automatically setting times to next maintenance on the basis of sensor information are less well developed. The problems are similar to those faced by performance optimisation systems, such as MAN/B&W's Computer Aided Performance Analysis (CAPA) system,[4] and by failure diagnosis systems, such as those developed as part of the Condition/Performance Monitoring and Predictive Systems (CPMPS) projects.[5,6] The on-line data acquisition systems that are now being developed as part of integrated ship monitoring and control systems that facilitate the above types of diagnosis could well be used for wear condition monitoring. Projects to investigate these possibilities are still under way and others are being proposed.

The communication component

Carrying out maintenance in an efficient manner is dependent on integrating maintenance work with the other operational concerns of the ship. In the past the communications necessary for this integration have been carried out by engineering personnel, because any computer based support systems for engineers have been isolated from the other systems. The ability to handle this communication is a vital component of an EMS.

This component must be able to:

1. Carry out the basic task of passing and receiving information to and from other systems.
2. Update the EMS internal information store based on



```
JOB NUMBER: 272.13.001                    MC/COMP.: No. 3 Bilge Pump, Piston Type

JOB TYPE: Full Survey

REFERENCE: Instruction Book Edition 65 - Ref 90 - 1.1 & 1.2

1.  SAFETY:

1.1 Ensure all personnel concerned are informed the pump is being taken out of
    service.
1.2 Isolate motor starter and lock isolator switch OFF.
1.3 Close all suction and discharge line valves and secure.

2.  TOOLS REQUIRED:

            827.24.020          Valve Seat Extractor
            805.50.004          1 Tonne Chain Block

3.  ENGINEERS REQUIRED:

            1    Skill Level A                        12 Hours
            1    Skill Level B                        17 Hours

4.  TIME REQUIRED:                  17 Hours

5.  SPARES REQUIRED:
```

```
W.T       Weekly Tasks
T.W.T     Twice Weekly Tasks
D.C.S     Daily Checks at Sea
```

```
CHK - Check      DCP - Daily Checks at Port     DCS - Daily Checks at Sea     OH - Overhaul     SUR - Survey
T - Test         TWT - Twice Weekly Tasks       WT - Weekly Tasks
```

Fig 5: An example worksheet

information it has received, eg update its representations of constraints.

3. Interpret requests for information from other systems and send replies.
4. Perform housekeeping associated with communications, eg informing other systems of the availability of EMS, when it is booted up.

The stock control/supplier's information component

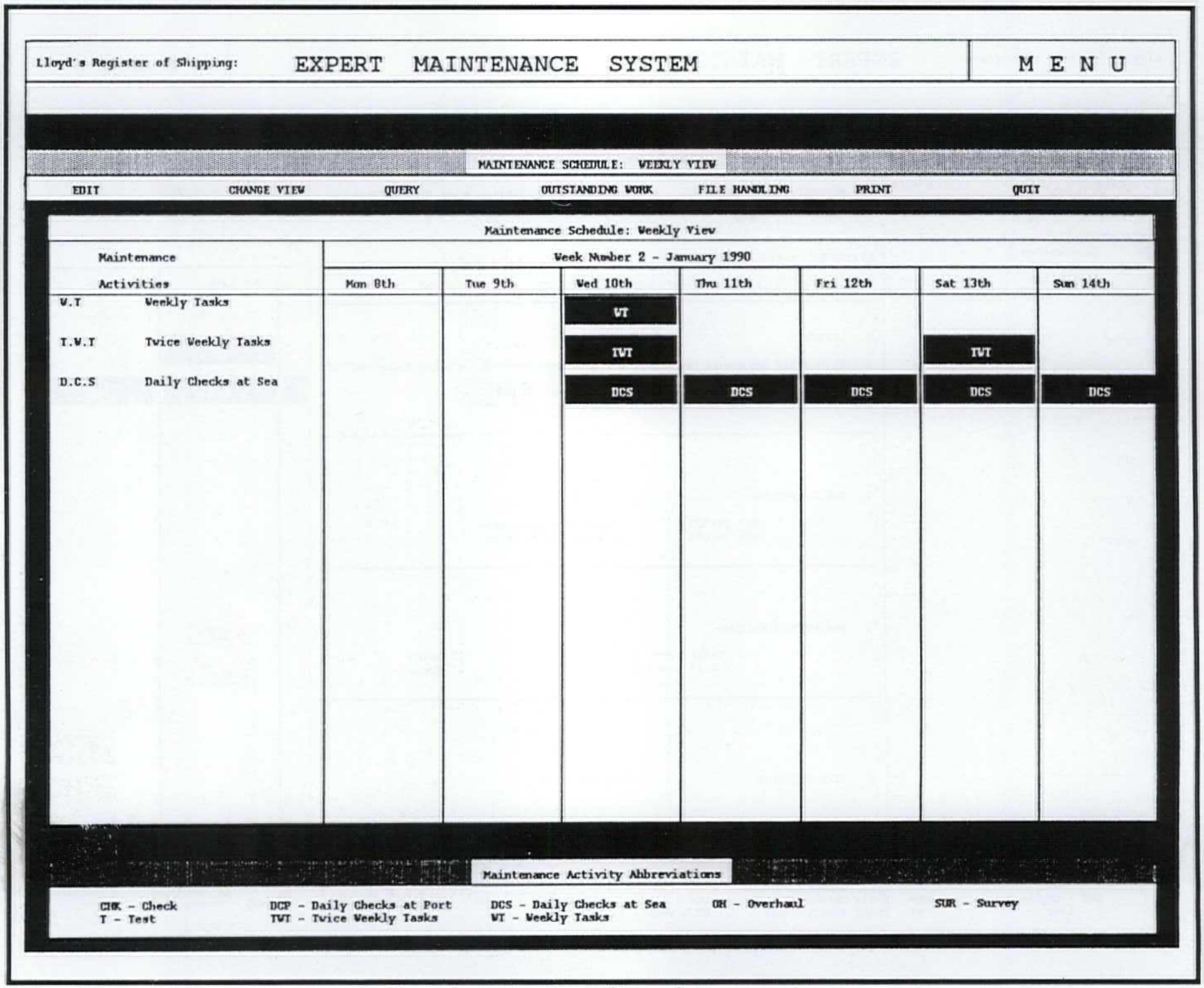
Of vital importance to the efficient running of maintenance operations onboard a ship is an integrated stock control system. Some form of stock control is available in many PMSs. These systems can greatly improve the accuracy of orders by removing the need for the transfer of written requests and by storing relevant manufacturers' numbers, thus decreasing errors in transcription.

An important capability of an EMS is that it should ensure that the spares required for scheduled maintenance are available. There are two aspects to this. The first is that the stock control component can automatically generate orders on the basis of the projected requirements dictated by the maintenance plan. Given an EMS which is an integral part of the kind of information technology environment described in the last section, the orders produced can prescribe delivery locations based on the voyage details available to the EMS.

The second aspect is that, using its advanced planning capabilities, an EMS can take into account information about the availability of components when producing plans. For instance, if for some reason the stock control system knows that a part required for a particular piece of maintenance cannot be obtained, then the planner will not schedule the maintenance until it can be.

THE USE OF EXPERT KNOWLEDGE WITHIN AN EMS

As with a PMS an EMS contains a great deal of expert knowledge on the components that make up the ship, and the maintenance activities that are carried out on those components. In the case of an EMS this knowledge has to be more extensive and much of it has to be in a form that can be understood by the computer. The expert knowledge can be



Maintenance Schedule: Weekly View

Maintenance	Week Number 2 - January 1990						
Activities	Mon 8th	Tue 9th	Wed 10th	Thu 11th	Fri 12th	Sat 13th	Sun 14th
W.T Weekly Tasks			WT				
T.W.T Twice Weekly Tasks			TWT			TWT	
D.C.S Daily Checks at Sea			DCS	DCS	DCS	DCS	DCS

Maintenance Activity Abbreviations

CHK - Check
T - Test
DCP - Daily Checks at Port
TWT - Twice Weekly Tasks
DCS - Daily Checks at Sea
WT - Weekly Tasks
OH - Overhaul
SUR - Survey

Fig 6: An example weekly maintenance plan

incorporated into the system whilst it is being set up, but engineers can be provided with facilities to modify it in the light of their experience.

The description of maintenance activities

The fundamental knowledge required is that of running hours intervals between maintenance for activities on particular components. This is used by the planner to schedule activities. Added flexibility is provided to allow the onboard expertise of the ship's staff to influence the basic plan by increasing planned maintenance intervals if they consider this can safely be done, or by reducing them if this is likely to reduce the risk of breakdown or excessively costly repairs. The hours of components under condition based maintenance can be adjusted on the basis of this information.

Information on each survey and maintenance activity should be individually described in detail on a worksheet which can be displayed on screen and printed out for the use of the maintenance engineer. The worksheets are arranged in sections designed to lead the user through the planned task in a logical order, as shown in Fig 5 and outlined as follows:

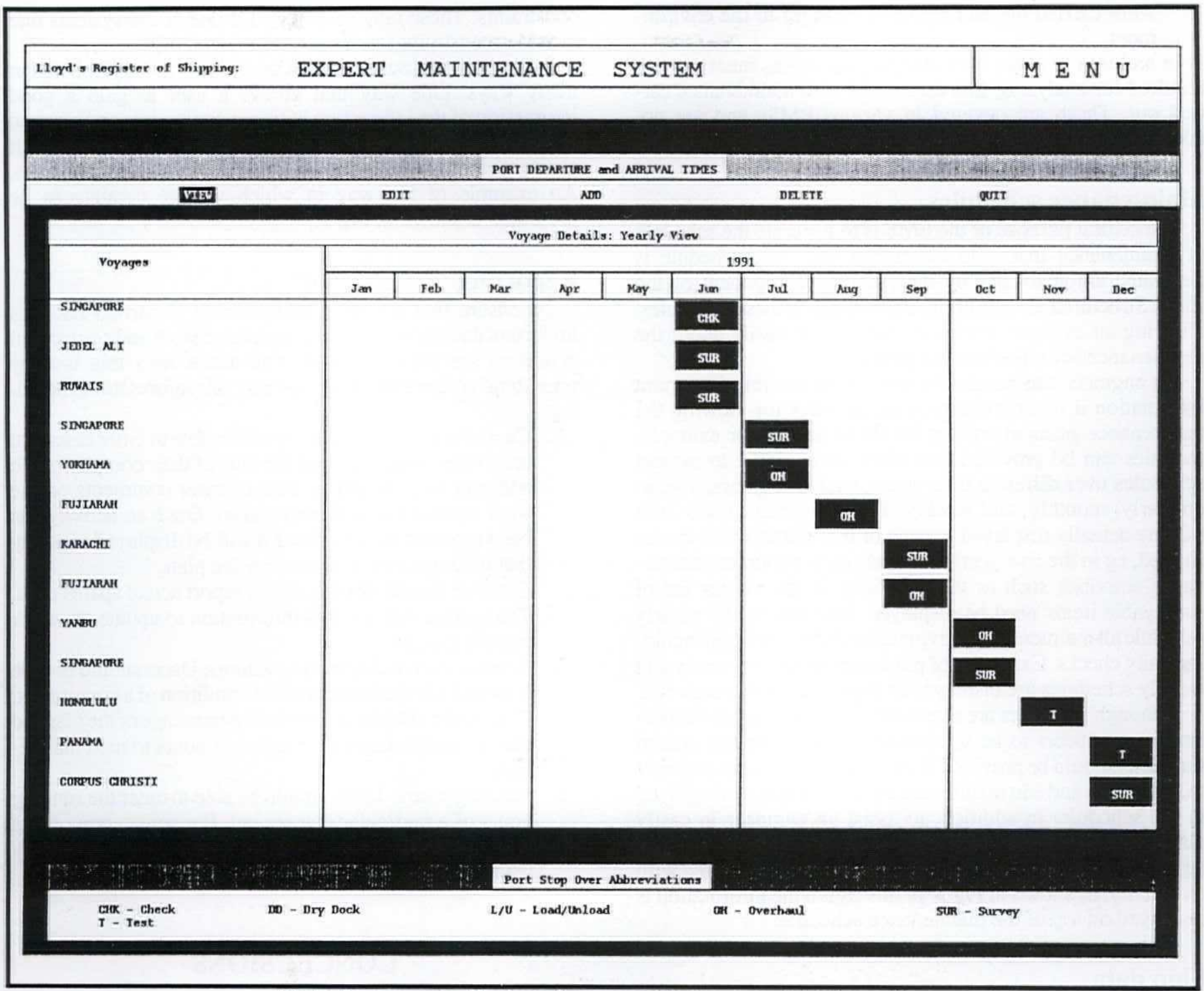
1. safety precautions;
2. tools required;
3. men and hours required;
4. time required;
5. spare parts required;
6. overhaul procedure;
7. constraints on the activity.

These items have to be stored in a form that can be interpreted by the planning component, so that their values can be taken into account when plans are being produced.

In addition to the information shown facilities should be provided for inspection reports and special notes, including measurements and calibrations, spares actually used and notes of any abnormality found or any inspection requirement or feature requiring special attention. This section can be brought up to date upon completion of the task and the information entered will then be available in the worksheet for the maintenance engineer and planner on the next occasion when that task is to be done.

The activity and component numbering system

The key to a maintenance system is an indexing system which enables the computer to obtain access to the stored



Voyages	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	1991											
SINGAPORE						CHK						
JEBEL ALI						SUR						
RUWAIS						SUR						
SINGAPORE							SUR					
YOKOHAMA							OH					
FUJIARAH								OH				
KARACHI									SUR			
FUJIARAH									OH			
YANBU										OH		
SINGAPORE										SUR		
HONOLULU											T	
PANAMA												T
CORPUS CHRISTI												SUR

Port Stop Over Abbreviations

CHK - Check
T - Test
DD - Dry Dock
L/U - Load/Unload
OH - Overhaul
SUR - Survey

Fig 7: An example display of voyage detail constraint information

information about individual machines, survey and maintenance tasks, components and maintenance records. One scheme that is being used in the KBSSHIP project is a system of unique identification codes intended to enable every survey and maintenance task and every machine and component part of a ship, including tools and consumables, to be identified.

As will be seen from the examples provided, each code number comprises three number groups of 3, 2 and 3 digits respectively. The first digit of the first group defines the main category in the ship and the second and third digits define a main element within that category, for example:

3XX = Machinery

321 = Main Propulsion Engine No 1

The second group of two digits defines a main component, for example:

321.02 = Main Engine No 1, Cylinder Unit No 2

If between 001 and 009, the final group of three digits defines the survey task, for example:

321.02.003 ME No1, No 2 Unit, Crankpin bearing and webs – survey

If between 0.011 and 0.049, a maintenance task is defined, for example:

321.02.019 ME No1, No2 Unit, Exhaust valve overhaul.

Subsequent numbers between 050 and 099 are for instrumentation and controls and numbers from 100 to 999 are for component parts.

USER INTERACTION WITH THE EMS

The success of an EMS, as with all computer based support systems, is dependent on how easy it is to use. Great care must be taken, therefore, in the design and implementation of the facilities for providing engineers with access to the information it contains.

The interactions that an engineer requires to have with an EMS can be divided into the following areas:

1. *Maintenance schedules*. Functions associated with viewing and editing maintenance schedules.
2. *Ship data*. Functions for editing and inspecting data pertaining to shipboard machinery (including stock information), manpower, vendors and specialised tools.
3. *Constraints*. Functions for editing and inspecting factors that influence the generation of a maintenance schedule.
4. *Reporting*. Functions for keeping the system updated on

work carried out and reporting changes to the environment.

In addition to these user interface facilities, functions are required for analysing data associated with maintenance carried out. These are covered in various PMSs and are not addressed here.

Maintenance schedules

The central purpose of the EMS is to generate the schedule of maintenance that is to be carried out. This schedule is generated automatically by the planning component of the EMS. Structured access should be provided to these schedules, allowing an engineer to obtain information easily about the maintenance activities that are planned.

An engineer can be greatly assisted in locating important information if he is provided with facilities for viewing the maintenance plans at various levels of detail. For example, facilities can be provided that allow an engineer to inspect schedules over different time spans, such as 5 years, 1 year, quarterly, monthly, and weekly. The maintenance activities that are actually displayed in each of these time spans can be filtered, eg in the five yearly schedule only important maintenance activities such as those defined in the master list of surveyable items need be displayed, whereas on the weekly schedule all maintenance activities should be displayed including daily checks. Examples of presentations of five yearly and weekly schedules are displayed in Figs 4 and 6 respectively.

Although schedules are automatically generated it is important for engineers to be in ultimate control. For this reason functions should be provided in an EMS that allow an engineer to add, delete and edit maintenance activities that are displayed in the schedule. In addition, to assist an engineer in easily obtaining information on maintenance activities, facilities can be provided for displaying all the information associated with an activity, as shown in Fig 5. In this figure the information is displayed on top of the maintenance schedule.

Ship data

When using an EMS an engineer has to have access to all the data used by the planner when constructing schedules. A large portion of that information can be considered to be associated with the ship. The following facilities associated with this information are required:

1. *Maintenance activity details.* Functions for inspecting and editing details of maintenance activities.
2. *Component details.* Functions for inspecting and editing details of machinery and associated components.
3. *Stock control.* Functions for inspecting and editing details of machinery parts stock.
4. *Crew.* Functions for inspecting and editing crew details.
5. *Specialised tools.* Functions for inspecting and editing details of the specialised tools that are available on the ship.

Constraints

In an EMS, information on the constraints that affect a plan will mostly be supplied by other systems. An engineer does, however, need access to this information. The reason for this is that he needs to be able to inspect the factors that are influencing the generation of schedules. This is particularly important in situations where the planning component is unable to generate a schedule that includes all the maintenance to be carried out if all the constraints are to be satisfied.

Facilities have to be provided for entering and editing constraints. These may be required if one of the systems that provides constraint information is unavailable.

Information associated with constraints can be presented in many ways. One way that allows a user to gain a good impression of the interaction between constraints and planned activities is by providing the information in the form of Gantt charts at various levels of detail as with maintenance schedules. An example of the way in which voyage details can be presented is shown in Fig 7.

Reporting

To ensure that effective maintenance is carried out it is important that accurate logs of completed work and component condition are kept. An EMS can assist with this task by providing facilities for easily entering this information, including:

1. *Completed work.* A user should be able to enter tasks that have been completed and the time of their completion. In addition they should be able to enter comments on the work carried out and hours taken. Once an activity has been reported as completed it will be displayed in a way that distinguishes it as such on the plan.
   The user should also be able to report actual spares used. The system will use this information to update the stock control system.
2. *Component condition observations.* Users should be able to enter their assessment of the condition of a component. This can be entered in terms of a percentage of the planned time to maintenance or in terms of hours to next maintenance.
3. *Running hours.* Users should be able to enter the running hours of a particular component. For some components this information can be made available automatically by using sensor data.

CONCLUSIONS

Expert maintenance systems can now be implemented which can provide much greater support to chief engineers when developing maintenance plans for ships. In this paper the requirements for these systems, a high level design that meets those requirements, the knowledge involved and the human computer interface facilities required have been described. These have been illustrated with examples from a system that is currently being implemented as part of the KBSSHIP project.

At the core of this new type of 'Expert Maintenance System' is the use of advanced planning techniques that have been developed in work on Artificial Intelligence. These techniques provide the power required to produce much more accurate plans, which take into account information that may affect the smooth carrying out of maintenance plans, such as voyage details. They also permit easy incremental updating of the plans to take account of changes in constraints or other influencing factors.

The planning capabilities of such a system allow ready use of condition information to produce revised plans. Even trends generated from sensor data can be used to automatically revise the planned 'time to maintenance' interval. By such means maintenance plans can take precise account of component condition and thus ensure necessary maintenance is done and unnecessary maintenance is avoided.

Powerful management tools, with easy to use and flexible methods for access and control of information, can now be developed using advanced computing techniques. These techniques have been applied in the production of a prototype EMS. This system indicates the potential cost savings inherent in this particular application and the practical benefits to ship's engineers and hence their ships.

ACKNOWLEDGEMENTS

The authors are pleased to acknowledge with thanks the support of the KBSSHIP Project Partners, particularly the Institute Superior Technico of Lisbon for their valuable contribution to the planning component.

The provision of engine maintenance and associated manuals by MAN/B&W have enabled real technical information to be used in the prototype EMS and the authors are also pleased to record their thanks for this assistance.

REFERENCES

1. M MacLeod, 'Computerised maintenance system', IMarE Conference on Maritime Communications and Control, London, UK (1988).
2. Aa Damsgard, 'Shipboard installation of knowledge-based systems: design and implementation', Information processing systems; Results and progress of ESPRIT project in 1989, pp 123–132, DG XIII (November 1989).
3. M B Abbot, L Bardis, C P W Hornsby, P Katsoulakos, M Lind and T Wittig, 'An architecture for a shipboard knowledge-based system', ESPRIT '88, pp 780–795, North-Holland (1988).
4. MAN/B&W, 'CAPA performance 1.30 – users manual', MAN/B&W Diesel A/S, Stamholmen 161, DK–2650 Hvidovre, Copenhagen, Denmark (1989).
5. P S Katsoulakos, C P W Hornsby and R Zanconato, 'DEEDS; the Diesel engine expert diagnosis system', IMarE Conference on Maritime Communications and Control, London, UK (1988).
6. C Elliott and K Banisoleiman, 'Advanced health monitoring systems for marine medium speed diesel engines – A naval and a merchant view', IMarE Conference on Maritime Systems Integrity, Newcastle, UK (1990).

GLOSSARY

Booted up:	To start or restart a computer system by reading instructions from a storage device into the computers memory.
Domain expert:	An individual who has a good working knowledge of a particular problem area.
EMS:	Expert Maintenance System.
ESPRIT II:	A programme of research projects funded by the CEC.
ETA:	Estimated time of arrival.
KBSSHIP:	An ESPRIT II project, whose aim is to design, implement and integrate onboard decision support systems for optimum operation of ships.
PMS	Planned maintenance system.
State space search:	The representation of a problem as a set of attributes, called a state, and the ordered search through those states to find one that matches a predefined goal state.
System manager:	A computer system responsible for communication between individual expert systems.
Temporal periods:	A time interval.