Reliability and maintainability engine

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New product liability legislation, enhanced competition, and economizing on expenditures have lent increased importance to reliability and maintainability in a product design. A group of top Finnish industrial companies including Wärtsilä Corporation has participated in a research project to develop a computer supported probabilistic based method for enhancing the reliability and safety of products. Carried out by Tampere University of Technology, the project lasted nine years and was completed in February 2005.

A product's reliability and maintainability are quality characteristics to which customers attach great importance when forming an opinion of the product's overall quality. It is especially important to understand that these are precisely the characteristics whose design flaws cannot be fixed during manufacturing or operation. In fact it is in the product design phase where the fundamental decisions are made to set the product's maximum quality and minimum cost. A company that has good control of the reliability and maintenance performance of its products has a considerable competitive advantage both in the case of design and manufacturing consumer products and when negotiating availability contracts for large industrial systems.

The traditional and still dominant method of product design focuses on optimizing the technical performance of a product. However, although customer expectations are increasingly integrated as design requirements into the design process, the reliability aspects of the product are still today very poorly attached to it. The reason for this is simple: there is no easily available and comprehensive design method and software for integrating reliability aspects and their impacts into the product design.

In this article we first introduce the method developed to model and analyse failure logic as a qualitative investigation of reliability and safety. We then examine the specification and allocation of reliability and availability requirements set for the product and its design entities from the customer and manufacturer perspectives. Finally, we introduce the simulation and calculation methods developed for analysing the reliability, performance and maintenance costs of a design entity.

The general term 'design entity (DE)' can stand for function, system, equipment, mechanism, or any kind of part.

Modelling and analysis of failure logic

Modelling and analysing the causes and consequences of failures form a foundation for the quantitative investigation of the reliability, safety and risks related to a design entity. The objective is to identify all causes and their interconnected causalities that might lead to the DE not fulfilling its reliability and safety requirements.

In the method we developed, failure logic is divided into two types of tree: a 'cause tree' and a 'consequence tree'. The cause tree consists of such (well-defined) causes and interconnected causalities that can lead to the occurrence of a TOP event. Thus a cause tree structure forms a basis for a failure logic model of the design entity in question.

The consequence tree again describes the possible chains of consequences initiated from a TOP event. A consequence may further cause other consequences, either exclusively or independently. Finally, a combination of cause trees and a consequence tree, illustrated in Figure 1, will be called a 'cause-consequence tree'. A cause-consequence tree may for example contain several separate chains of events that lead to the same consequence. (Note the chains to consequences 1 and 2 in Figure 1).

During the research project, we developed an Event Logic Modelling and Analysis Software (ELMAS) tool. After identifying the events related to the TOP event, experts examine the generated event list one by one and indicate the event's cause and consequence connections with the other events. Based on the expert's decisions, ELMAS draws the logic diagram on the screen.

The same cause can occur in many places in the logic. On the computer screen the expert can drag and drop the events into the right position based on their best understanding of the logic. If the event is moved so that it leads to a loop in the tree, ELMAS gives a warning and rejects the choice. After the causes and consequences of events are determined, the types of gates are defined (Figure 2).

Modelling and analysing failure logic with ELMAS enables the designer to identify all potential component hardware failures, human errors, possible disturbances and deviations in the process,

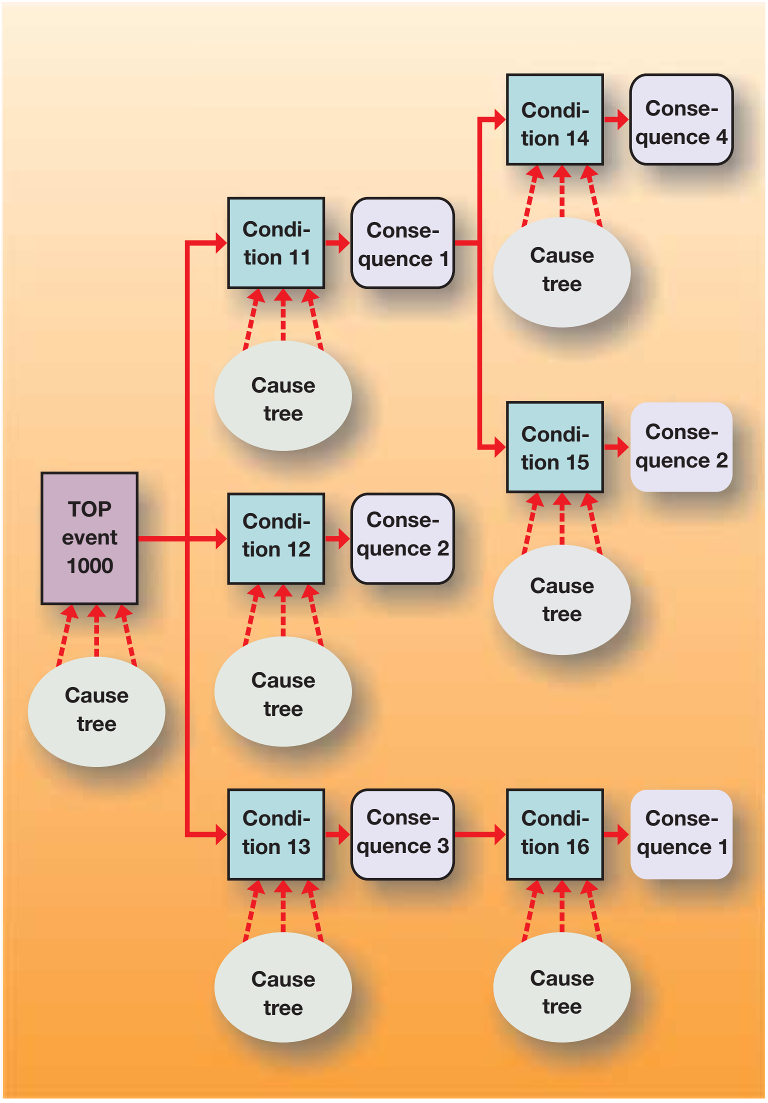

Fig. 1 – Structure of cause-consequence tree.

ering – a probabilistic approach

and environmental conditions related to the selected TOP event. The cause-consequence tree method makes it possible to precisely explain and describe the relations between the causes and consequences of failures.

The causes can be ranked from the probability and/or risk point of view. Results of the analysis help researchers to identify both the most probable causes and chains of causes leading to the TOP event, as well as the most significant consequences and chains of consequences. After ranking the causes, a more detailed root cause analysis can be performed by applying the event-cause-consequence method FMEA, which is integrated into ELMAS.

Specification and allocation of reliability and availability requirements

Our model and corresponding software (RAMalloc) for specification and allocation of requirements is based on a generalized fault tree approach (modelled by ELMAS), where the TOP represents the product to be designed. The other parts of the fault tree represent entities which essentially affect the failure tendency and the repair time of the product.

Relations between parts are modelled by two mechanisms. The 'gates' determine the partly logical and partly stochastic propagation of faults (primary states). The 'strategies' define other relations between TOP and the deepest entities. A consequence of the strategies is that two types of 'waiting' (secondary states) can occur because, for example, the DE cannot be repaired if TOP is running and/or DE is not running if TOP is not running.

The method forces the designer to work out which customer and manufacturer needs should be used to determine the product's quantitative reliability, availability and repair time goals, early in the design stage.

We assume that the customer product requirements for reliability and the number of failures can be concentrated in the following set of parameters:

Age at the end of the burn-in period .... t_a
Age at the end of the warranty period.......... t_b
Age at the end of the useful life period .... t_d
Length of age period (for Rel below) .... t_c
Reliability in age periods $(t, t+ t_c] \subseteq (t_a, t_d]$ .... Rel
A parameter for warranty period.......... s

The customer requirements are often described in terms of availability. For such cases, our model and software offer the following parameters:

Age at the end of the warranty period.......... t_b
Age at the end of the useful life period .... t_d
Average availability in age period $(0, t_b]$.......... A_b
Average availability in age period $(t_b, t_d]$ .... A_{bd}
Availability at age t = 0 .... A_0
Availability at age t = 2 t_b.......... A_m

Concerning repair time we assume the following model parameters can be extracted from the customer requirements:

Minimum repair time (0-quantile) .... t_{min}
Mean time to repair.......... m
Q-quantile (often Q=0.95).......... T(Q)

Rather detailed product-specific requirements can be modelled. With the mathematical models used for the critical customer data, there is from both the customer's and the manufacturer's perspective an opportunity to accept a different probability of failure during the burn-in phase than after it, or there is the possibility to accept different failure tendencies during the warranty and the post-warranty periods. The software allows the requirements to be allocated to functions, systems, mechanisms or any parts as the design work proceeds.

The allocation of the failure tendency of a gate (entity) down to its input entities is guided by assessing 'importance' and 'complexity'. Importance takes into account customer's perspective while complexity represents the technical standpoint. The aim is that the more important an entity, the less it is allowed to fail, and the more complex an entity, the more it is allowed to fail. The repair time allocation again is based on a direct assessment of repair time ratios between the input entities. The failure tendency and the repair time of an entity can also be locked, in which case the designer can focus only on the unlocked entities.

Various and quite detailed requirements can be calculated for

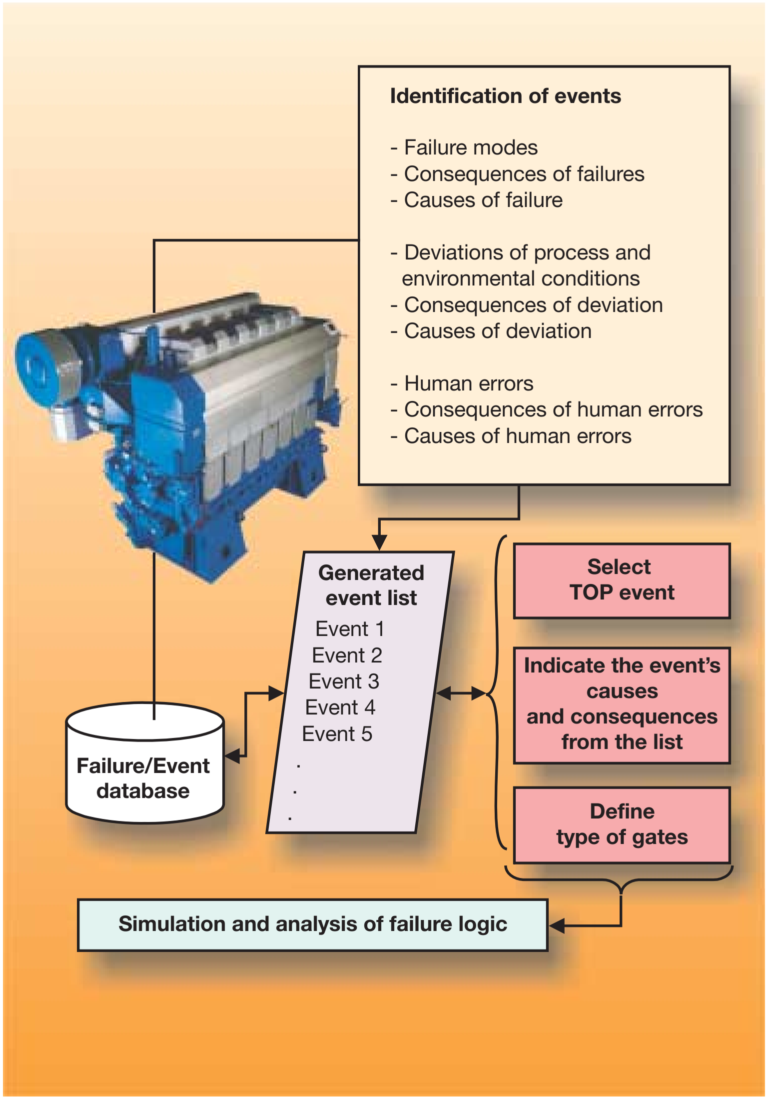

Fig. 2 – Principle of modelling the cause-consequence tree related to the selected TOP event with ELMAS.

the product (TOP) and its design entities (DE). RAMalloc software provides, for example, the following results:

(a) For TOP and DEs:

- Total operation time
- Total repair time
- Total number of failures
- Availability
- Mean time to failure (MTTF)
- Mean time to repair (MTTR)
- Time to repair (TTR, 95% quantile)

(b) For TOP or any DE, in a specified age interval:

- Number of failures
- Number of failures, 95% quantile
- Reliability
- Availability

These results are especially significant for certain DEs, since attention will be paid to these in a later design process concerning the technical solution. (Software has been developed for this purpose as well). The allocated requirements can be applied directly to the inquiry specification, which thus becomes criteria for the selection of vendors/suppliers.

The effect of reliability, availability and repair time requirements defined by the customer and manufacturer on the known technical solution of a product can be demonstrated with the developed method and software. This connection is important in order to avoid promising something that cannot be achieved or something which is very expensive to achieve.

Simulation and calculation of reliability performance and maintenance costs

In this section we look at the method of assessing how a proposed design solution fulfils the numerical requirements set for its reliability, availability and maintainability (RAM).

The product under design is represented by a generalized fault tree (modelled by ELMAS), which describes how failures can propagate from one entity (part) to the modelled failure logic of product. The source data required for simulation have been selected to make assessment by the designers as easy and reliable as possible.

Our model provides 10 different methods to design the cumulative distribution function for repair time and average number of failures. The designed repair time often includes delays with external causes. The RAMoptim software also supports the separate adding of delays. Lack of repair staff can be one example. Further, lack of spare parts is another example, and the corresponding delay can be assessed with software (StockOptim) also developed in the research project. StockOptim software makes it possible to optimize the spare part stock to meet the technical and economic requirements set on the maintenance service supplier.

When using the developed method with corresponding software (RAMoptim), the designer can determine, early in the design stage, what level of reliability performance and maintenance costs can be attained using the design draft selected. The method can also be used to import expertise into the design process from areas that strongly affect the success of that process, namely the manufacture, testing, operation, and maintenance of the product. If the defined requirements have not been achieved, the expert must go back to the drawing board to consider other solutions for achieving the requirements (Fig. 3).

RAMoptim software also includes computer supported methods developed to quantify the effect of preventive maintenance (PM) on a part's failure tendency. With the help of this method, the effects of PM actions and PM interval

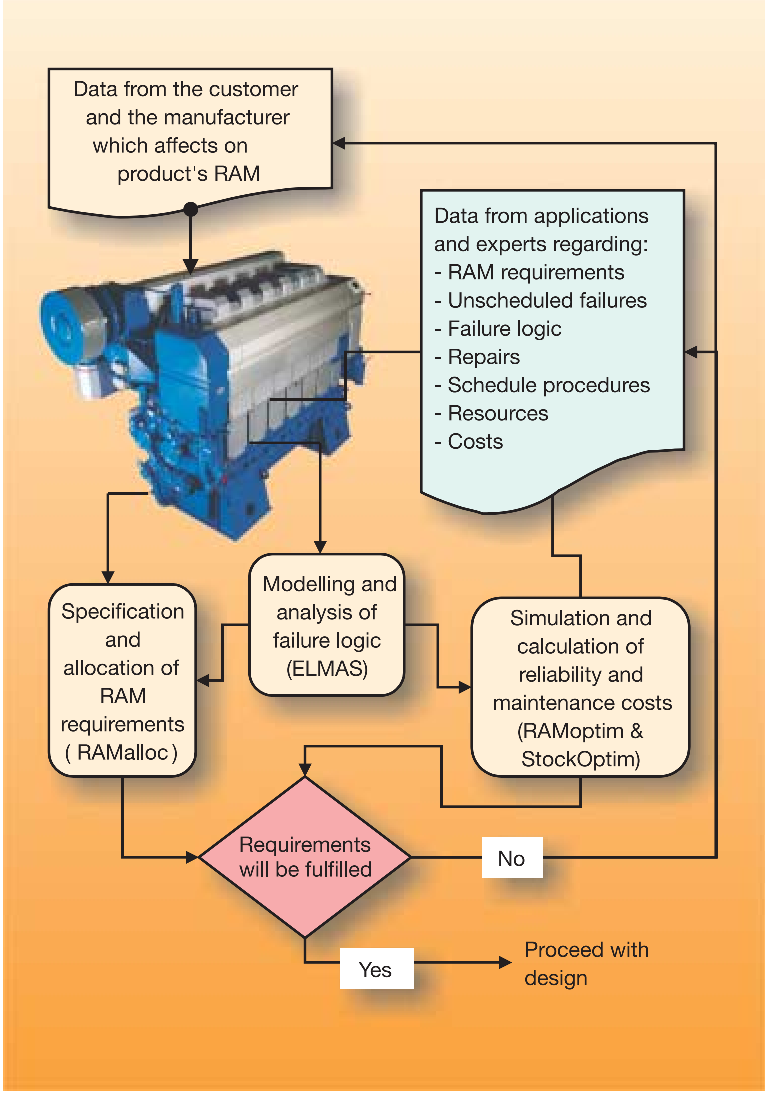

Fig. 3 – Probabilistic approach to defining RAM requirements to the product's DE and to assess that a proposed design solution fulfils the numerical requirements set for its RAM.

on failure tendency can be quantified in different phases of a product's lifecycle. Condition monitoring resources are included in preventive maintenance resources as well.

Different types of functions (curves) for the product (TOP) can be calculated from the raw data from the simulation. Examples are the length of a single downtime or 'downtime period' (Fig. 4), the failure profile, which is the cumulative number of downtime periods (mean and 95 % quantile) during the design period (Fig. 5), a (smoothed) availability curve which is a useful combination of downtime and failure profile (Fig. 6), and cumulative distribution of total availability (Fig. 7).

Following figures are an example of results calculated for TOP's specified age interval e.g. 0....T, where T is the product's useful life period:

- Number of failures and corresponding deviation
- Frequencies for different numbers of failures
- Duration of repair time and corresponding deviation
- Duration of PM and corresponding deviation
- Unavailability caused by failures and PM (mean, deviation and distribution)
- Time dependent and independent repair costs and PM costs
- Loss caused by failure
- Number of persons needed for repairs and for preventive maintenance (PM)

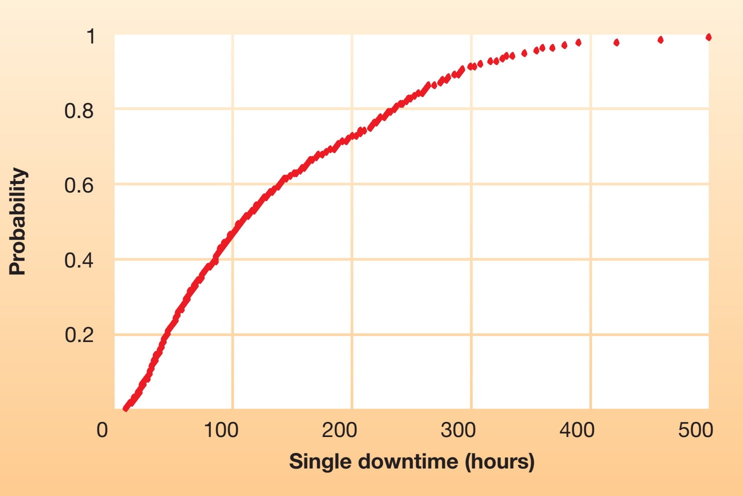

Fig. 4 – Single downtime. Mean 135.9, deviation 107.5.

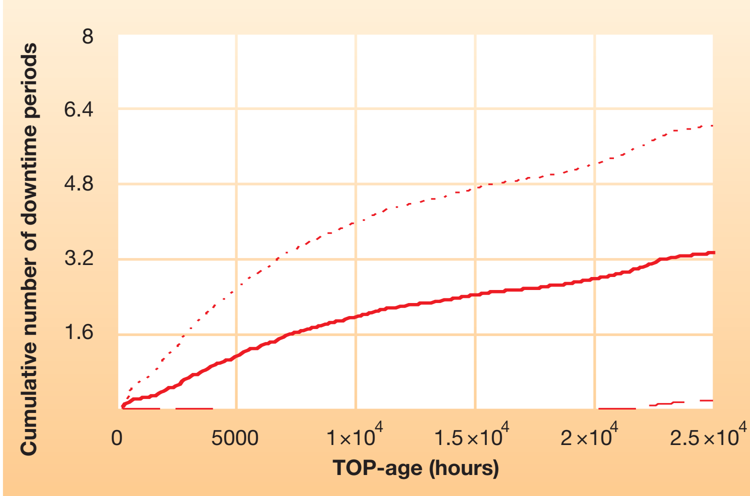

Fig. 5 – Failure profile. Total mean 3.318 with deviation 1.498.

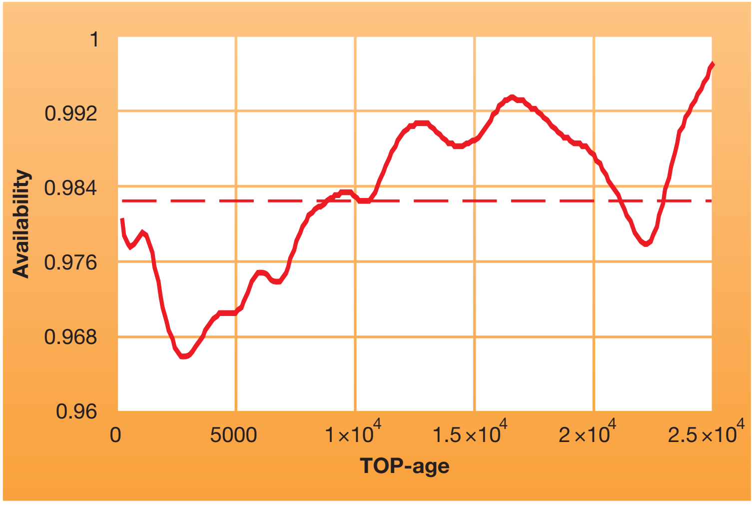

Fig. 6 – Point wise availability. Mean 0.9823.

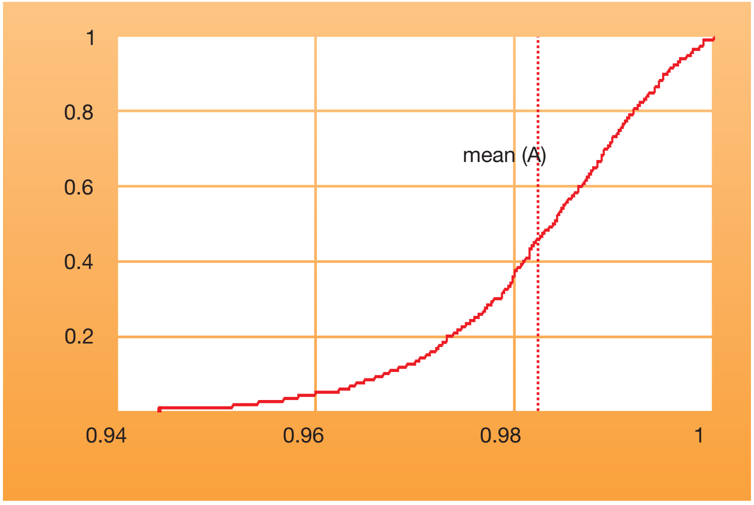

Fig. 7 – Cumulative distribution of total availability.

- Frequencies for different numbers of needed persons (= how many hours a certain number of persons is needed simultaneously)
- Mean time to first failure (MTFF) and corresponding deviation
- Mean time to failure (MTTF) and corresponding deviation
- Mean time to repair (MTTR)
- Max time to repair (TTR, 95% quantile)
- Probability distribution for failure and repair time
- Failure probability in a specified age interval
- Lists of the most critical parts from TOP's reliability, availability and risk point of view

Conclusions

The applicability of the developed methods and software has been tested in the companies participating in the research project. These companies are both manufacturers and users in the metal, energy, process and electronics industries. Their products and systems have to correspond to high safety and reliability demands. Most of the participating companies have started to apply the proposed methods and software in the design of their products' and systems' reliability, availability and safety.

Based on experience, and with the help of the methods and corresponding software, it is possible to identify those problem areas during the design stage which can delay product development and/or reduce safety and reliability. Artekus Oy (www.artekus.fi) is responsible for commercializing, marketing and supplying technical support for the developed computer software.

The application of the developed methods into the product design and development process requires companies to invest more resources in reliability and maintainability engineering and to increase the knowledge of their engineers in the area of reliability and maintainability engineering. The companies should also develop RAM related data collection methods in order to serve the product design and development process.

Biographies

Seppo Virtanen received his BSc, MSc and DSc Tech. degrees from Helsinki University of Technology, Finland. He is currently a Professor in the Machine Design and Operation Laboratory at the Tampere University of Technology. His research and teaching interests includes reliability and maintainability engineering and risk management within a product and system design process. Professor Virtanen has over 15 years of industry experience in the field of reliability engineering and maintenance, which includes three years in the energy, pulp and paper industry in the USA and two years in the offshore industry in Norway. ■