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TITLE

Reliability Assessment of Crane Operations

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SUMMARY

This report gives an introduction to reliability assessment of crane operations. It defines the reliability of cranes, the reliability indices for cranes and their parts, as well as possible faults, failure and errors. Moreover, it describes the basic elements of crane configurations and the main components of crane safety systems. This involves error identification, error classification, error causes, reliability analysis, task analysis, event trees and fault tree analysis. Some standard analysis models are presented. The report focuses on the reliability of both physical cranes and crane operators. A systematic approach to error influence modelling is presented as well. Furthermore, some foundational aspects of failure interpretation are discussed.

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PREFACE

This report documents the results of a technical study sponsored by Liaoning Chemistry and Construction Industries. The study has been carried out at the Department of Production and Quality Engineering (IPK) at the Norwegian University of Science and Technology (NTNU) from November 2005 to November 2006.

The report consists of two main parts:

> Part 1: Guidelines for reliability analysis of cranes from the crane designer's perspective
>
> Part 2: Reliability assessment of crane driver operations

I would like to thank Marvin Rausand, Jørn Vatn and Trond Østerås from the Department of Production and Quality Engineering, NTNU for valuable advice during the project. My appreciation is also extended to the safety and reliability group at SINTEF, and especially Lars Bodsberg for supplying technical information and supporting the project.

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1. INTRODUCTION

Nowadays, cranes are widely applied in mechanical, chemical and construction industries all over the world. With the economic development and the increasing number of cranes, crane accidents become more frequent.

An ongoing challenge in crane manufacturing and usage is how to keep crane operation safe during a longer service period with limited maintenance budgets. Probabilistic methods provide tools to better assess the impact of uncertainties on component life and failure probabilities. Application of probabilistic tools to risk–based condition assessments and life prediction helps managers to make better risk–informed decisions regarding crane operations.

In addition to assessing crane reliability, probabilistic methods also provide information for analysing the costs of continuing operation based on risks and their possible financial consequences.

Hardware failures of cranes and human errors, separately or combined, are serious threats to crane operations. As a result, the Chinese government has drawn up norms for assessment of crane reliability (no international standards). But this is not sufficient, because human factors are also extremely important in crane usage. During the last years, hardware reliability of cranes and reliability of human operation were only studied separately. Nobody combined the physical reliability of cranes and the human reliability of crane drivers.

The objective of this report is to review key aspects of quantitative risk assessment related to crane components. Both the current engineering practice and new research developments are reviewed.

Another objective is to establish realistic operational procedures for crane operators according to the reliability assessment of crane operations.

The structure of this report is as follows:

Section 2: Crane description

Section 3: Basic concepts of reliability and human factors

Section 4: Regulations and guidelines for crane reliability

Section 5: Physical reliability assessment of cranes

Section 6: Application of reliability assessment to crane operations

Section 7: Conclusions and recommendations

2. CRANE DESCRIPTION

In this section the basic configuration of cranes is discussed, as well as relevant human factors and the reliability of cranes, operators and commanders.

A crane comprises four main subsystems: the structural, the mechanical, the electrical and the safety protection subsystem.

The structural subsystem of the crane includes a tower body, a pedestal, a tower top, a balancing boom, a hanging boom, a cab and a horizontal roof beam.

The mechanical subsystem consists of hoisting, returning changing scope, moving, and erecting and hydraulic pressure mechanisms.

The electrical subsystem includes a power supply, a control and protective panel, and a motor.

The safety protection subsystem includes an overload restrictor, a location restrictor, a movement restrictor, a buffer, a crushproof and windproof devices.

Tower cranes also comprise safety instrumented systems.

The basic configuration of a crane is illustrated in Figure 1.

The crane system life cycle is a term used to describe all the stages that a crane system passes through, from the initial installation of the system to its final dismantling and removal. It includes the following phases:

Concept → flow sheeting → preliminary design → detailed design → construction commissioning → operation and maintenance → decommissioning.

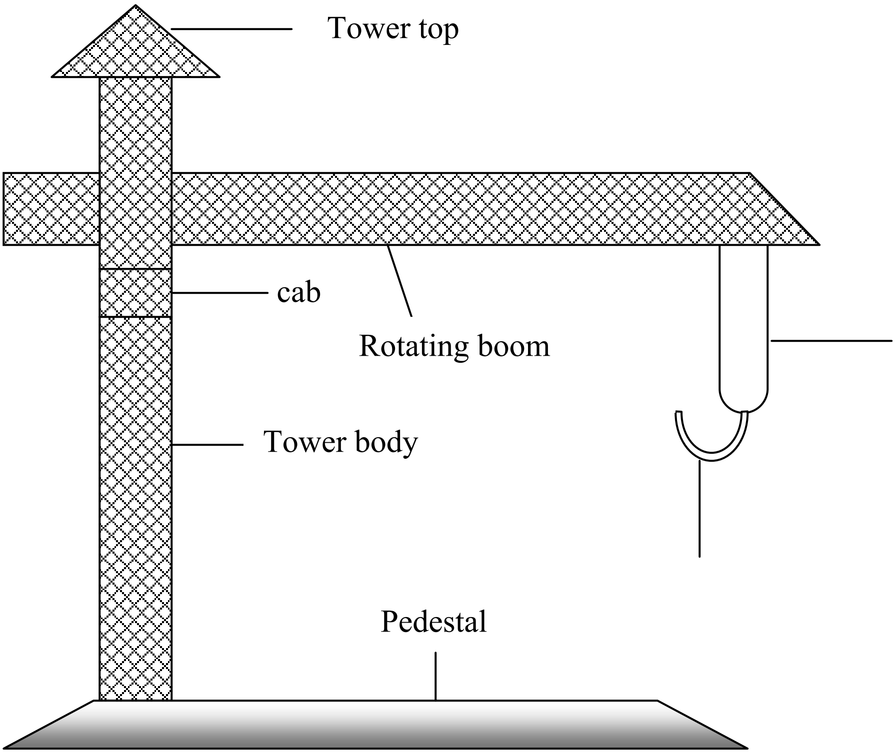

Figure 1: Basic configuration of a tower crane

3. BASIC CONCEPTS OF RELIABILITY AND HUMAN FACTORS

3.1 HUMAN FACTORS ISSUES

There are six major human factors issues that influence system success. Their adequacy can be evaluated and assessed using task analysis.

a. Function allocation

Function allocation takes place predominantly during the concept phase, and is concerned with the distribution of system functions between system equipment and human operators, as some tasks are best performed by machines and others by people. For example, a task requiring rapid, highly precise and repetitive actions will be best carried out by machines, whereas the task involving the ability to deal with unexpected effects will currently be best served by a human operator. If the human element is not considered properly during the function allocation stage, it may lead to the operator being asked to perform functions that are difficult to carry out reliably. These eventualities could lead to poor system operability and/or safety problems when the plant is commissioned and operated.

b. Personnel specification

A personnel specification details the characteristics needed by individual workers to perform their tasks. It can also usefully specify which requirements must be fulfilled at the recruitment stage and which will entail training. These characteristics include physical and mental capabilities, qualifications, personality traits and experience.

c. Staffing and job organisation

After determining which tasks will be performed by people and which tasks will be performed by machines, the number of people and their organisation will need to be defined. This will depend on the number and type of tasks, how long each task is likely to take, whether any tasks have to be done in parallel, and the available time to successfully perform tasks in terms of process requirements.

Staffing and job organisation aim to ensure that individuals are not overloaded or underloaded in terms of the demands of the allocated tasks.

As part of job organisation, communication between team members must also be assessed, as well as coordination of their activities. When designing a system, task analysis will help to identify the type of communication system that is needed.

d. Task and interface design

Task and interface design initially consider the types of information that personnel would need to be able to understand the current system status and its requirements.

e. Skills and knowledge acquisition

Skills and knowledge acquisition ensure that people within the system are capable of performing the tasks required of them. However, this is only possible if the right types of people are selected, if adequate supporting information is provided, and if personnel are adequately trained. If support is identified to be essential, then this should also be provided during training.

f. Performance assurance

This group of considerations is necessary to ensure that a system starts working correctly and continues to function as intended: operating safely. Four human factor approaches are relevant for the achievement of this goal: reliability assessment, management safety structure assessment, performance checking, and problem investigation.

The six issues discussed above are the major human factors concerns in a technical process. Each human factor issue should be addressed according to a specified schedule. For example, lifting performance assurance must be dealt with throughout the entire process.

The types of tasks analysed and assessed should cover the entire range of tasks that may be encountered, whether during normal operation, system abnormalities, or maintenance. Hence, they should include system start-up, shutdown, emergency tasks, communication, monitoring and supervision, administration, etceteras. Otherwise, system performance will only be maximised for a subset of the possible system task requirements.

3.2 RELIABILITY DEFINITIONS

Equipment under control (EUC)

Equipment, machinery, apparatus or plant used for manufacturing processes, transportation, medical or other activities

EUC control system

System that responds to input signals from the process and/or from an operator, and that generates output signals causing the EUC to operate in the desired manner. It includes input devices and final elements.

Error

Discrepancy between a computed, observed, or measured value or condition, and the true, specified, or theoretically correct value or condition.

Fault

Abnormal condition that causes a reduction or loss of the capability of a functional unit to perform a required function.

Failure

Termination of the ability of a functional unit to perform a required function.

Hazard

Potential source of harm.

Hazard event

Hazardous situation which results in harm.

Human error

Human action or inaction that can produce an unintended result.

Mode of operation

Way in which a safety-related system is intended to be used, with respect to the frequency of demands made upon it, which may be either:

> Low demand mode; where the frequency of demands for operation of a safety-related system is no greater than one per year and no greater than twice the proof-test frequency;
>
> High demand or continuous mode; where the frequency of demands for operation of a safety-related system is greater than one per year and/or greater than twice the proof-check frequency.

Primary safety critical function

A safety-critical function intended to control the direct hazards related to the operation of the system being analysed.

Random hardware failure

Physical failure where the supplied service deviates from the specified service due to physical degradation of the item. It can further be split into: aging failures and stress failures.

Reliability of cranes

The comprehensive characteristics of cranes quality; the possibility that a variety of parameters, representing the abilities of a crane, stay inside a specified range, under the intended usage conditions, during a certain period.

Safety-critical function

A function of a system whose malfunction would immediately increase the risk of injury or damage to health.

Safety function

Function to be implemented by an E/E/PE safety-related system, other technology safety-related system or external risk reduction facility, which is intended to achieve or maintain a safe state for the EUC, in case of a specific hazardous event.

Safety integrity level

Discrete level (one out of a possible four) for specifying the safety integrity requirements of the safety functions to be allocated to the E/E/PE safety-related system, where safety integrity level 4 has the highest level of safety integrity and safety integrity level 1 has the lowest.

Safety instrumented system

A safety-related system composed of sensors, logic solvers, and actuating items.

Safety instrumented function

A function that is implemented by a safety instrumented system and that is intended to achieve or maintain a safe state for the EUC with respect to a specific process demand.

Serviceability

Ability of a product to perform the specified functions.

Storage ability

A feature of the product to retain failure-free operation, durability and maintainability after proper storage and transportation.

Task analysis

Task analysis involves the study of what an operator (or team of operators) is required to do to achieve a system goal. The primary purpose of task analysis is to compare the demands of the system on the operator with the capabilities of the operator and, if necessary, to alter those demands, in order to reduce error and to achieve successful performance.

Useful life

Accumulated operating time of a product from the commencement of its usage or resumption after repair to the onset of the marginal condition.

Γ -percentile life

Accumulated operating time during which the product will not reach the marginal condition with a γ-probability expressed as a percentage.

4. REGULATIONS AND GUIDELINES FOR CRANE RELIABILITY

The regulations and guidelines for cranes are central resources in order to prepare the objectives and scope of reliability assessments of crane operations.

The regulatory system of the crane industry is very complex to understand. For example, the crane industry is subject to different regulations such as:

- Internationally agreed standards from ISO/TC96
- Regionally agreed regulations and national standards
- Classification rules of the individual classification societies
- Other technical standards

It is difficult to find suitable regulations for crane reliability assessment. ISO/TC96 (ISO11660-1) “Cranes-Access, guards and restraints” and “Cranes - Availability – Vocabulary” are the most important guidelines for crane reliability. Among the important regulations governing cranes are: Crane operator regulations; Crane and hoist safety 1065; Cal-OHSA crane certifier accreditation unit 15347; Chinese JB/SQI-87.

5. PHYSICAL RELIABILITY ASSESSMENT OF CRANES

5.1 DATA COLLECTION AND ANALYSIS

Reliability analysis requires several kinds of input data, such as design, operation and reliability data. Unfortunately, the crane industry completely lacks reliability data. Now, there is still no international standard for reliability assessment of cranes. For many applications, OREDA is frequently used as a data source for reliability data, but this data handbook does not contain data on cranes.

The Chinese government has established some crane norms. The Fuxin Institute of Boiler and Pressure Vessel Inspection, China, has collected and analysed reliability data of cranes since 1990. Data collection is based on observations and questionnaires.

Experience data from similar equipment, recommendations from manufacturers and expert judgements are helpful sources for reliability analysis of cranes.

Cranes are operated by drivers. Together, the driver and the crane constitute a human-machine system. The reliability of cranes is determined by the reliability of the human-machine system. This reliability can be split into the physical reliability of cranes and the reliability of human operation [2].

5.2 DEFINITION OF RELIABILITY INDICES OF CRANES

Reliability measures for cranes include the probability that no failures occur, durability, maintainability and the probability of preservation.

Reliability

A feature of a product which characterises the ability to perform, within specified limitations, required functions with failure-free operation, durability, maintainability, storage ability and transportability, or combination of these features.

Failure

An event causing the loss or reduction of the nominal serviceability of the product, which is “complete” if it results in total loss of serviceability of the product, or “partial” if it results in reduced serviceability.

No failure

A qualitative characteristic that cranes do not fail, and maintain a normal service during a certain usage period.

Durability

A feature of the product to retain the serviceability until a marginal condition is reached, with a predetermined system of maintenance and repair being used. This is a qualitative characteristic that cranes keep their normal working ability until the ultimate limit state is reached, under prescribed technical maintenance and repair conditions. The ultimate limit state means that cranes or parts reach a state that cannot be tolerated for further use, according to technical safety and economy.

Maintainability

A qualitative characteristic related to failure prevention, failure elimination and recovery of the normal working state. Maintenance is a set of procedures to ensure the serviceability of a product.

Probability of preservation

A qualitative characteristic that cranes keep their probability of non-failure, durability and maintainability.

5.3 SPECIFICATIONS OF RELIABILITY MEASURES

In this section, it is assumed that the data set is complete. This means that the time from start-up until failure is recorded for all cranes. When this assumption applies, the following estimations may be used. When we have an incomplete data set, or when some cranes are still functioning at the end of the observation period or have been out of service due to some other reasons, we have to use more advanced estimators. See Meeker and Escobar (1998) for details.

I. MTTF- Mean time to failure

Average time until a failure of a system or device occurs. MTTF is a basic measure of reliability for non-repairable items, and is estimated by the total time in service of a population of similar items divided by the total number of failures within that population.

MTTF= $\frac{\sum t_i}{n}$, with

$\sum t_i$: the total time in service of cranes and their parts before first failure

n : number of failures of cranes or their parts.

MTTF is used for non-reparable parts.

II. MTBF- Mean time between failures

MTBF=$\frac{\sum ti}{N}$, with

$\sum t_i$: time during test or usage, the total time to work

N : number of failures of cranes (parts).

The scope of application: all kinds of cranes and repairable parts.

III. λ: failure rate

The probability of failure per time unit. It is the rate of occurrence of failures. A degraded failure rate is used for cranes and repairable parts; a critical failure rate is used for non-reparable parts.

IV. Reliability function (survivor function)

$$R_{(t)} = \int_{t}^{(x)} f_{(t)dt} \text{ or } R_{(t)} = \frac{N_{0(t)}}{N}\text{, with}$$

$f(_t)$: the density function of the time to failure

$N_{0(t)}$: normal cranes or parts number at time t

N : total number of cranes.

The reliability function is used for cranes or parts whose failure results in accidents.

V. Availability

$A = \frac{T_0}{T_0 + T_1}$, with

T_0: Time that cranes work

T_1: Time that cranes do not work, include repair and maintenance time.

The availability measure is used for cranes when failure consequences only lead to economic losses.

VI. Degree of reorganisation

$k_0 = kR_{(t)}$, k=$\frac{T_0}{T_0 + T_1^{'}}$,

Probability that cranes keep a good state during time t (does not include scheme ceasing time) and continue without failure after time t.

k: degree of reorganisation of cranes.

$T^{'}$: time that cranes do not work, except scheme ceasing time.

This measure is suitable for cranes or parts whose failure results in accidents.

VII. T-Mean life or overhaul life.

This represents the mean usage life when cranes reach their ultimate limit state. It is used for all kinds of cranes and parts.

VIII. γ-Lifespan.

T_r: indicates the usage life of cranes or parts while reliability is not less than γ. It is used for cranes or parts whose failure causes accidents.

IX. MTTR-Mean time to repair

MTTR=$\frac{\sum t_i}{N}$, with

t_i : the total accumulative time of cranes or parts to repair in statistical time.

N : number of repair actions in the population of cranes during the specified time period. It is suitable for all kinds of cranes or parts.

X. m - repair rate

The repair probability of cranes per time unit under the prescriptive repair conditions. It is suitable for all kinds of cranes or parts.

When we evaluate the reliability of cranes, the reliability of cranes can be divided into two types.

Type I is used in chemistry and metallurgy applications and for other cranes whose failure may lead to severe accidents because of operation interrupts. The appropriate reliability measure for such a type is R_t. Cranes that may cause serious accidents due to a bad technical state, or due to any sudden failure, belong to this type.

Type II is used when failures make operation ceasing, but when operation interrupts only entail certain economic losses. Only if failures do not last too long time, they do not have a strong influence on crane operations. The main reliability index of such a crane is the availability A.

The target value of reliability indices for cranes and their parts. The Chinese regulation JB/SQI-87 prescribes the reliability index of 16t-40t hydraulic pressure cranes with different quality grades, as shown in Table 1.

Table 1: Reliability indices of hydraulic pressure mobile cranes with quality grading [2]

Reliability index	**Quality of product grades**		
	Excellent	**Good**	**Pass**
Availability A (%)	95	91	88
MTBF (h)	150	100	50

In addition, this regulation prescribes reliability indices of currency overhead cranes and their criteria values. These are shown in Table 2.

Table 2: Reliability indices of currency overhead cranes [2]

index name	**estimate**	**index value**
MTTFF	MTTFF=$\frac{1}{r}(\sum_{i=1}^{r} t_i + \sum_{j=1}^{n} t_j)$ n-testing cranes number r-the cranes number that first appear failure. t_i-the total accumulative time to work of No.i crane. t_j the total accumulative time of No.j crane that does not appear failure in testing pause time.	≥250 h

MTBF	MTBF=$\frac{1}{N}\sum t_r$, N-the equivalent failure number of cranes in testing pause time. t_i -the accumulative time to work of No.i crane.	≥320 h
MTTR	MTTR=$\frac{1}{N_0}\sum_{i=1}^{N_0} t_i$, N_0 -the gross of all kinds of failures in testing ceasing time. t_i -time to repair No.i failure, include failure diagnosis, repair and testing time.	≤2 h
A_0	$A_0=\frac{\sum_{i=1}^{n} t_i}{\sum_{i=1}^{n}(t_i+t_i^{'})}$, $t_i^{'}$ -time to ceasing work of No.i crane ,including repair, preventing,	≥0.98

	safeguard and management time	

Failures are classified into four categories, as shown in Table 3.

Table 3: Failure categories and weighting [2]

Failure category	**Weighting**
Light	0.5
Common	1
Serious	4
Fatal	20

Reliability target values of cranes' elements are related to safety according to the degree of importance of the elements during operation. Elements of cranes are classified into two categories:

No. I: If elements are defect, this will cause serious and fatal accidents. Such as hook, axes, gear, wire rope (hoisting mechanism). [R]=0.9999

No. II: If elements are defect, this will not lead to accidents. For example, the driving elements for travelling and rotating. [R]=0.99

5.4 PREDICTION OF CRANE RELIABILITY

Cranes can be seen as series systems that consist of independent parts. A main characteristic of a series system is that if any subsystem or element does not work properly, this results in loss of function of the whole system.

The reliability of a series system is given by: $R_{s(t)} = \prod_{i=1}^{n} R_{i(t)}$ (1-1),

$R_{s(t)}$ --reliability of system in t time;

$R_{i(t)}$ --reliability of No.i subsystem or element in t time;

n--number of subsystems or elements.

A system that is constituted by subsystems or elements of different life-span and with different loss of function models, has an exponentially distributed failure probability function. If it is denoted by the failure rate λ or MTBF, formula (1-1) can be rewritten as

$\lambda_s = \sum_{i=1}^{n} \lambda_i$ or $\frac{1}{(MTBF)_s} = \sum_{i=1}^{n} \frac{1}{(MTBF)_i}$, (1-2).

$\lambda_s, (MTBF)_s$ respectively represent the failure rate of the system and the mean time to work without failure.

$\lambda_i, (MTBF)_i$ -respectively denote the failure rate of a subsystem or element and the mean time to work without failure.

A simple distributive way of cranes reliability is ARINC. If a complete machine or framework is constituted by n independent subsystems or elements, the failure probability obeys an exponential distribution. Given that the estimated value of the failure rate of each subsystem or element is $\hat{\lambda}_i$ (i=1, 2, 3…n). Then $[\lambda_s]$ is the permissible failure rate of the system. The failure rate of each subsystem or element is distributed as follows:

$$\hat{\lambda}_i = W_i\,[\lambda_s] \quad (i=1, 2, 3\ldots n) \qquad (1\text{-}3).$$

W_i: The comparative failure of coefficient of No.i subsystem or element.

$$W_i = \frac{\hat{\lambda}_i}{\sum_{i=1}^{n} \lambda_i} \qquad (1\text{-}4)$$

The distribution of failure, mean time to repair and life-span of cranes and their elements.

Given that the MTBF is exponentially distributed, MTR obeys a Weibull distribution.

According to different types of breakage, the life-span of cranes or elements obeys respectively a Weibull, exponential, normal or normal logarithm (logarithmic) distribution.

Table 4 shows the distribution of failure, MRT, life-span of cranes and their elements.

Table 4: Distribution of failure, MRT, life-span of cranes and their elements [2]

distribution of failure, MRT and life-span		**distribution**			
		poisson	**weibull**	**exponential**	**normal**
failure number of cranes		+			
mean time to repair			+	+	
lifespan	hoisting wire rope			+	+
	wire rope of grab bucket		+		
	axes of reducer		+	+	
	gear		+		
	metal structure		+	+	

	element of electric equipment		+	+	
	grab		+	+	
	wheel		+		
	brake wheel		+		
	pin coupling		+		
	slew blocking		+		

6. APPLICATION OF RELIABILITY ASSESSMENT TO CRANE OPERATIONS

The reliability of a series systems is equal to the product of the reliability of each element (R_i). Since R<1, the reliability of one system is always less than the minimum value of the reliability of the crane elements. $R_s \le \min R_i$.

6.1 ASSESSMENT OF THE PHYSICAL RELIABILITY OF CRANES

When assessing the reliability of cranes, we must test, inspect and measure electric equipment and mechanical elements, to see whether they have the desired quality and reliability. In China, we have tested and recorded related data of overhead cranes in Fuxin, Liaoning.

We have reported and tested five cranes. Two of them appeared to have a failure during the observation time. The collected data is shown in Table 5 and Table 6.

Table 5: Measurement results of time parameters of cranes

No. of cranes	**Totally accumulative time to work(h)**
1	200
2	210
3	300
4	350
5	400

Table 6: Related failure data of two cranes

Elements of failure	**Weighting of failure**	**Repair time(h)**	**Safeguard and management time (h)**	**Time to ceasing work (h)**

wire rope	0.5	3	1	4
warning device	0.5	2.5	0.5	3

There were two failures during the observation time. These were, respectively, three steel wires outside wire rope were broken (No.1) and failed warning devices (No.2). Because these failures belong to the category of light accidents, both of their weightings are 0.5.

We may now perform the following calculations:

(1).MTTFF = $\frac{1}{2}[(\sum_{1}^{2} 200+210)+(\sum_{j=1}^{5} 300+350+400)]$ =830(h)>250h;

(2). N=0.5*2=1, MTBF = $\frac{(200+210)}{1}$ =420(h)>320h;

(3). N_0=2, Time to repair of the first failure is 3 hours, while time to repair of second failure is 2.5 hours.

Hence, MTTR$_{(1)}=\frac{1}{2}$*3=1.5(h); MTTR$_{(2)}=\frac{1}{2}$*2.5=1.25(h), both of them are less than 2h.

(4). For the first crane, time to ceasing work is 4h, $A_{0(1)}=\frac{200}{200+4}$=0.98; for second crane, time to ceasing work is 3h, since $A_{0(2)}=\frac{210}{210+3}$=0.98. The other cranes do not happen to have any failures, so they have higher reliabilities. As a result, five cranes have good reliability. The physical reliability of the cranes is excellent.

6.2 RELIABILITY ASSESSMENT OF CRANE DRIVER OPERATIONS

A. J. Bulter investigated 472 accidents involving construction-type cranes used in various activities as well as construction. The Division of Occupational Safety and Health reported a total of 158 accidents involving a crane, from 1 January 1997 through 31 December 1999. Over the three-year period, at least one crane accident has occurred in each three months of the three year period. The types of cranes involved in the 158 accidents are as shown in Table 7.

Table 7: The types and percentage of cranes accidents [4]

Crane type	**Count**	**Percentage (%)**
Mobile cranes	115	73
Bridge cranes	26	16
Gantry cranes	5	3

Tower cranes	4	3
Ship cranes	1	1
Not determined	7	4

Total injuries, serious and fatal, by type of worker:

(1). Cranes operator—1 fatal and 23 non-fatal injuries.

(2). Non-crane operator—12 fatal injuries and 79 non-fatal injuries.

These non-crane operators include occupations such as mechanics, ironworkers, and stevedores.

(3). Of the total of 13 fatalities for crane operators and non-crane operators, 4 were the result of falling loads. There were 3 fatalities from 14 electrical contact accidents.

The accident causation is shown in Table 8.

1). Instability

Instability accidents for mobile cranes generally resulted in either the crane tipping over, or the load falling off the hook or slings. Instability accidents were further broken down into separate categories.

2). Lack of communication

This was another major cause of accidents, because the point of operation is usually at some distance from the crane's operator station or not in full and direct view of the operator in operations involving mobile cranes.

75% of accidents caused by both “lack of communication” and “electrical contact” involved mobile cranes.

3). Lack of training

Although “lack of training” did not rank very high as a primary cause, it would have been ranked within the top three if a secondary were listed.

Table 8: The most frequent causes [4]

causes	**all crane types**	**mobile cranes**
1.instability	67	49
a. unsecured load	34	6
b. load capacity exceeded	0	29
c. ground not level/too soft	0	4
2. lack of communication	32	24

3. electrical contact	13	10
4.misc. in 14 categories	46	32

Of the mobile-crane accidents analysed by Buster, about 71% occurred due to overturning during operation and erection and dismantling. Human error and rope failures accounted for 9.7%; boom over cab for 3.2%.

Of the tower crane accidents, about 36% occurred during erection or dismantling, 18% were wind related, 10% were rope failures, and 49 % were due to human errors.

The above data were recorded several years ago and with current economical development, more and more cranes are manufactured and used. Therefore, according to crane experts' estimates, human errors weigh nowadays higher than before. Human errors are not only the major cause of crane accidents, but they also result in higher failure rates, lower availability and lower reliability of cranes in practical applications.

When crane drivers are not trained or do not have any practical experience, they would make some errors. So the reliability of driver operations cannot be ignored when assessing the reliability of crane operations. Human factors should be discussed as an important aspect. Human errors may cause systematic failures. This failure classification is illustrated in Figure 2.

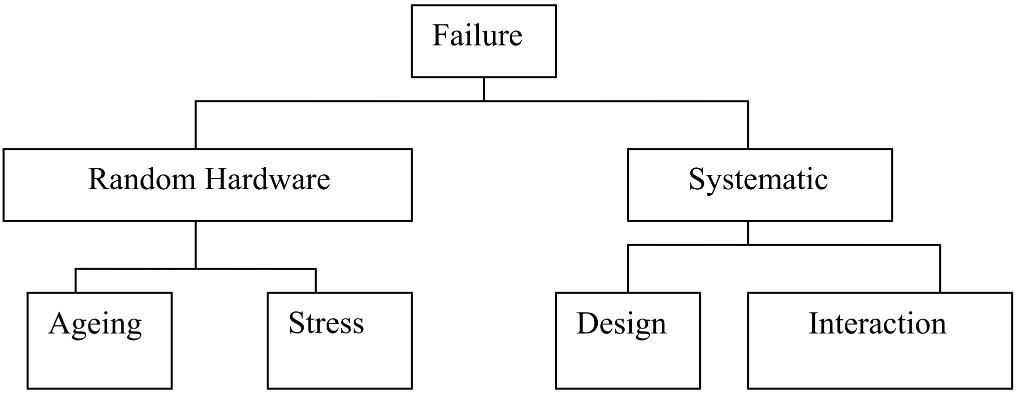

Figure 2: Loss of safety concepts and failure classification

Because a crane is very complex and dangerous, human actions during design, manufacturing, installation, operation, maintenance, commanding, modification and inspection of the crane, may lead to an unintended result. They are many different types of crane workers errors. Generally speaking, four different views on the causes of human errors may be distinguished:

(1) Individual factors

Different crane workers have different physical and mental capabilities, qualifications, personality, traits and experience. Operators who have been trained make less errors than new and untrained workers.

(2) Performance shaping factors

If workers are not well trained and do not seriously carry out their tasks as intended, they are likely to make errors during design and operation, and these errors may even cause serious accidents.

(3) Probability of Systematic Failure (PSF) factors

These failures are non-physical failures where the supplied service deviates from the specified service without any degradation of the item. If the revolving and lifting system of a crane fails while lifting a load, this may hurt people or damage the construction. However, if the operator cannot control the situation at all, this may result in an accident.

(4) Communication error factor

Generally speaking, communication between an operator and a commander is done by gestures or signals. If the commander has not been trained or if the operator cannot see the signal clearly, the operator may make errors, or even cause accidents.

The four factors mentioned above reflect the major causes of human errors in crane systems.

6.3 TASK ANALYSIS

The section introduces the basic concepts, purpose and application areas of task analysis. This is done by answering fundamental questions about what task analysis is and why it should be used, as well as when it should be used and by whom.

What is task analysis? [1]

Task analysis covers a range of techniques used by designers, operators and assessors to describe and in some cases evaluate the human-machine and human-human interactions in systems. Task analysis can be defined as the study of what an operator (or team of operators) is required to do, in terms of action and/or cognitive process, to achieve a system goal. Task analysis methods can also document the information and control facilities used to carry out the task.

Why use task analysis? [1]

It can be argued by managers, engineers and others involved in design that the human element within a system is already implicitly included in system designs. While this is to a large extent true, unless this is done systematically in an open manner which can be subject to careful scrutiny, it is unlikely that the human element will be optimised, or that the potential for error will be minimised. Usage of explicit task analysis approaches should therefore lead to more efficient and effective integration of the human element into system design and operations, in three principal areas:

(1) Safety

Systems must be safe in terms of staff and public safety, system integrity, and the impact on the environment. Task analysis can have an impact on safety in four ways. Firstly, it can be used to identify hazards to the operator in the workplace. Secondly, it aims to achieve a general level of system safety through the achievement of good design for human operation. Thirdly, it can contribute to the analysis of human errors in systems, or to human reliability assessments which can feed into quantitative risk assessment of systems. Fourthly, task analysis can be used in incident or accident investigation, to define what went wrong and to help identify remedial measures.

(2) Productivity

Task analysis can help in decisions about where to automate processes, how to determine staffing requirements and how to train staff and ensure efficiency. The identification and reduction of error potential will also enhance efficiency.

(3) Availability

Systems must be adequately maintained and run to keep downtime within acceptable limits. Task analysis can be used to identify maintenance demands and to define the need for maintenance support tools and systems of work. Optimal work design should also reduce errors that lead to unscheduled downtime.

Targeting task analysis

Task analysis can also be used to focus upon specific issues rather than examining the system as a whole. It can be used when:

a. safety is especially important

b. technology is vulnerable to human error

c. system changes have created a high level of uncertainty about system integrity

d. there are productivity/availability problems or a particularly high quality of product is required which depends on human performance

Therefore, it is possible to use task analysis to look at particular areas of concern to obtain specific benefits, as well as to apply more comprehensive task analysis programmes.

6.4 BARRIER AND WORK SAFETY ANALYSIS

Barrier analysis (Trost and Nertney, 1985) focuses on the transfer of harmful energy to vulnerable objects, establishing what barriers should have been in place to prevent the accident, or could be installed to increase safety.

Work safety analysis is “a systematic investigation of working methods, machines and working environments in order to find out direct accident potentials” (Suokas and Rouhiainen, 1984). Its primary goal is to identify potential hazards and to take appropriate protection measures.

The difference between them lies in their perspective: barrier analysis looks qualitatively and functionally at the barriers that should be present to prevent unwanted energy flows from reaching vulnerable targets (people); work safety analysis looks in detail at each step of the task to see what hazards could occur and to provide a rough quantitative calculation of their relative risks and hence what barriers are needed.

Barrier analysis of crane safety devices may be used to focus on human errors which may overcome barriers (e.g. if carrying out a human reliability analysis). In this case, after the barriers have been identified, it is possible to consider ways in which human errors, intentionally or unintentionally, could jeopardise the barriers’ effectiveness. An example of this approach, applied to a crane system safety investigation, is shown in Table 9.

Table 9: Example of the use of a barrier approach for error identification

Barrier		**Barrier failure**	
Function	**Type**	**Design features and assumptions**	**Human errors**
1.1 Overturned object protection (OOP)	Physical	Crane protective devices overturn out area Assumptions: securing of heavy equipment No design errors	Lifting and revolving equipment in unprotected areas Crane not constructed or installed as designed Crane not inspected and maintaining as designed Inspection errors(miss/false alarm) Maintenance errors Failure to secure heavy equipment leave OOP hatches open
1.2 Lifting and revolving	Physical	Hang hook Wire rope and rigging Gear and decelerator Assembly Pulley and drum Starting ,emergency shutdown and stopping Assumptions: No design errors	Manufacturing and inspection errors Test or inspection errors Operation or inspection errors Operation or inspection errors Operation errors
1.3 Safeguard crane safety	Physical	Location restrictor Buffer	Failure to limit rising or dropping barriers

		Load and movement restrictor Crashproof ,windproof Crawlproof devices Alarm Assumptions: No design errors	Maintenance and installation errors Failure to operation correctly Equipment not connected or installed according to design Not installed or installed in wrong location

Work safety analysis (WSA) of crane systems.

For WSA a list of the work steps involved in the crane operation is needed first. This can be obtained by carrying out a HTA. For each work step, potential hazards are identified. Each hazard is described in the WSA tabular representation (see Table 10) in a way which defines the consequences (e.g. crushed between cranes revolving booms). Causative factors are noted as well (i.e. factors which contribute to the hazards occurrence). We must then judge the severity of the consequences and the likelihood of the hazard. Subsequently, preventive and corrective measures are developed, according to the probability and severity of event.

Hazards and causative factors.

The potential hazards and causative factors associated with the crane work steps, its machinery, and auxiliary devices are noted. The aim is to find all hazards, whether they are caused by any of the following: the crane, the working method, working conditions, the operators, other operators working nearby the crane, or environmental variations (e.g. temperature variations) or disturbances (e.g. strong winds affecting worker operation). Additionally, variations in working methods often contribute to accidents (i.e. when the task is being carried out under abnormal conditions). While such conditions will be infrequent, the risk of accident may be significantly higher, making their overall contribution to risk relatively high. In particular, if the crane is less protected in a "maintenance mode" (i.e. usual protective systems are temporarily disabled), this may call for a thorough WSA investigation. Examples of hazards and causative factors are shown in Table 10.

Each identified hazard must then be classified to derive an appreciation of its relative risk. The relative probability is rated on a five point scale as follows:

0-Hazard eliminated

1-Very improbable (once in 10 years)

2-Improbable (once in 10 years)

3-Slightly probable (once a year)

4-Rather probable (once a year)

5-Very serious (several/many times a year)

The consequences are categorised as follows:

1-Insignificant (only first aid required)

2-Little (1-2 days of disability)

3-Considerable (3-21 days of disability)

4-Serious (22-300 days of disability)

5-Very serious (over 300 days of disability)

The relative risk (R) is then calculated by multiplying the probability with the consequences, as shown in the example in Table 10.

Table 10: Work safety analysis of lifting a roll

Work step **Machine component** **Auxiliary device**	**Hazard**	**Causative factors**	**Classification** **Before** **P C R**	 **After** **P C R**	**Corrective actions**
lifting the roll	a worker may get squeezed between the roll and machine	the crane is not exactly vertical with the roll	3 5 15	1 5 5	a marking on the machine surface enabling the identification of the right position of crane
moving the roll with crane	a worker may fall down	the worker have to climb on machine to protect the roll with planks	3 3 9	0 3 0	stationary pads are set on the roll, which case the plank control and falling between rolls are avoided
break of the lifting wire	the roll may fall down	wire ropes are broken	2 3 6	0 3 0	replace new wire ropes

ropes					
cleaning the lower surface of the roll	litter ma get into worker's eyes	compressed air makes litter fly around	3 2 6	1 2 2	safety glasses are used
setting down the roll on trestles on the floor	the floor may give may	the roll is set down in a wrong place	2 3 6	0 3 0	the proper place for the roll to set down is marked on the floor
turn on safety protective device	the crane is damaged or injury other persons near the crane	not inspected or inspection and maintenance errors	3 5 15	1 5 5	periodically ,inspecting ,maintenance and modification
commanding of lifting load ,revolving	it may be hit other workers and machines in workshop	can not communicate clearly with each other	2 4 8	1 4 4	crane operators and commander must be trained

Corrective actions

Ways to reduce or eliminate risk are identified mostly during the investigation itself (e.g. by asking the operators how the system could be made safer). The types of corrective actions that are feasible will generally fall into the same categories as for barrier analysis.

Once corrective actions have been identified, their effectiveness must be checked, and if they are complex, it will be necessary to review the work steps to see if new hazards have been introduced by the corrective actions themselves. Lastly, if new operating methods have been introduced, these must be checked after their initial introductory period, to see if workers still use them. Maintaining safety is a continuous process.

6.5 EVENT TREES

Although the event tree technique was originally developed for the analysis of system reliability, event trees can be effectively used to study human reliability. Event trees show the relative importance of different tasks and errors, indicating their upon crane system safety and reliability.

The errors that have severe consequences can often be identified by individual inspection of the event tree. This can often be supplemented by quantitative assessment in which the probability of each sequence is assessed. The overall probability of a particular sequence occurring, can be estimated by multiplying the probabilities of the constituent steps along an event “path” through the tree. Simple checks on accuracy can be made by ensuring that these probabilities always add up to unity. So in the example in Figure 3: Probability (B1) + Probability (B2) + Probability (B3) = 1.0

The relative likelihood of the different sequences can be investigated and, in this way, the most significant errors can be identified. The effect of various changes, such as improved design, can be measured by re-assessing the probabilities of the errors and recalculating the sequence probabilities. Event trees are used to depict graphically the different permutations of operator behaviour that may occur during a procedure and to identify the various outcomes that are possible.

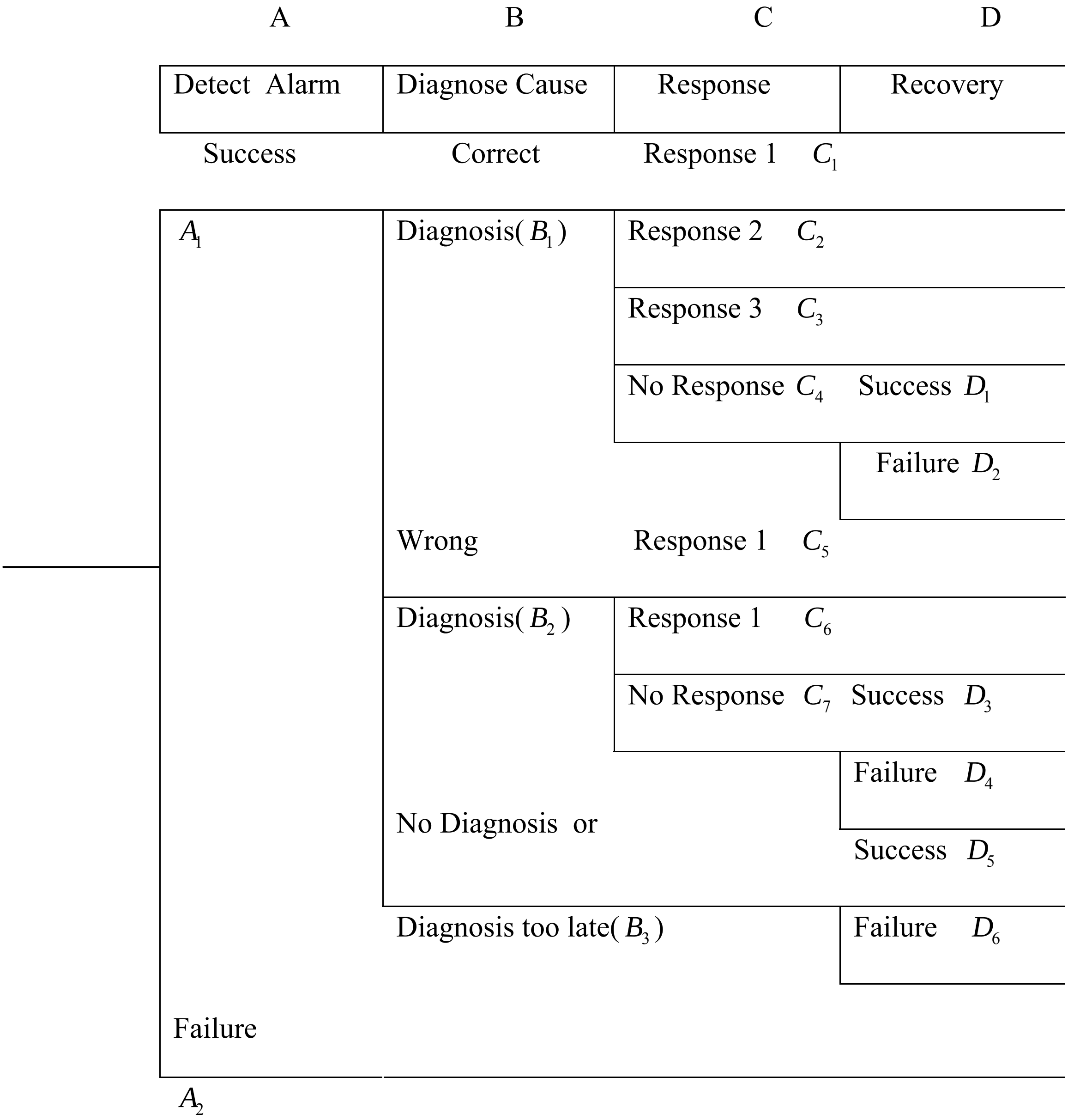

Figure 3: Example of an event tree

Identification of the initiating event

The initiating event is usually defined as the first significant deviation from the normal situation that may lead to a system failure or an accident. The initiating event may be a technical failure or some human error and may have been identified by other risk analysis techniques like FMECA, preliminary hazard analysis (PHA), or hazard and operability analysis (HAZOP). To be of interest for further analysis, it must give rise to a number of consequence sequences.

The initiating event is normally identified and anticipated as possible critical event already in the design phase. In such cases, barriers and safety functions are usually introduced to deal with the event.

Identification of barriers and safety functions

The safety functions (barriers, safety system, procedures, operator actions, etc.) that respond to the initiating event can be thought of as the system's defence against the occurrence of the initiating event. These safety functions include:

> Safety systems that automatically respond to the initiating event (e.g. automatic shutdown systems, automatic crane protection systems)
>
> Alarms that alert the operator when the initiating event occurs (e.g. ESD alarm systems, alarms in the crane control room)
>
> Operator procedures following an alarm (e.g. procedures how to contact crane and worker on the ground in an emergency situation)

Barriers or containment methods that are intended to limit the effects of the initiating event

Construction of the event tree

The event tree displays the chronological development of states or events, beginning with the initiating event and proceeding through success and/or failures of the safety functions that respond to the initiating event. The consequences are clearly defined outcomes of the initiating event.

The diagram of the initiating event starts on the left-hand side of a page with the symbol for the initiating event. It expands at each safety function, illustrated by the barrier symbol for the function. Within the barrier symbol the safety function is formulated as a question. To obtain a systematic diagram which is easy to read, the questions should be formulated such that the most critical output is obtained when a question is answered with “NO”. The output from a barrier symbol may lead to another barrier symbol.

The development is continued to the resulting consequences, illustrated by consequence symbols. If we adopt the convention that the “NO” branches (barrier fails to hold) correspond to the lower branches from the barrier symbol, the most severe consequences will be located at the bottom right corner of the consequence spectrum. The “NO”-output from a barrier symbol (failure of a barrier/safety function) is often analysed by a fault tree to identify the cause of the failure. This may graphically be accomplished by linking a fault tree to the “NO”-output. An example of a very simple cause consequence diagram is shown in Figure 4.

The last step is to describe the different event sequences arising from the initiating event. One or more of the sequences may represent a safe recovery and a return to normal operation or an orderly shutdown. The sequences of importance, from a safety point of view, are those that result in accidents.

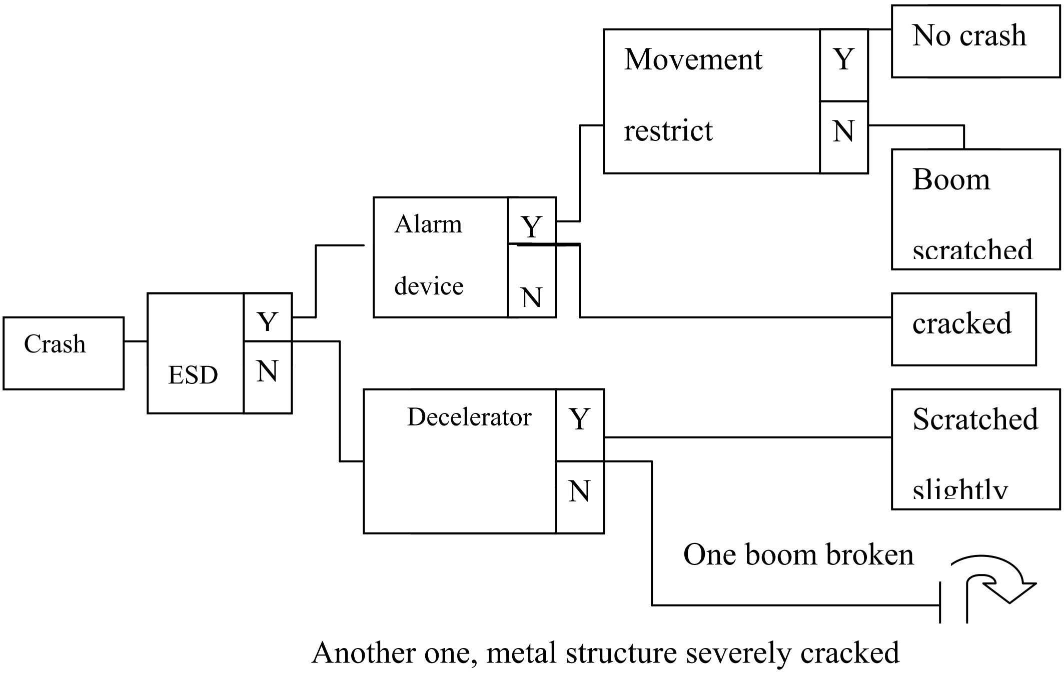

Figure 4: Example of a crane crash event

Quantitative analysis

If relevant reliability data is available for the initiating event and all the activated safety functions, a quantitative analysis of the event tree may be performed to obtain the probabilities or frequencies of the resulting consequences.

For the initiating event we usually specify the frequency of occurrence of the event with the expected number of occurrences per time unit. For the various barriers or safety functions we have to specify the probability that these barriers or safety functions fail to hold when activated. To assess this probability we normally have to estimate the failure rates of each of the components comprising the barrier or safety function. We also have to know how the various components are linked together, as well as the possible maintenance strategies. The assessment may then be carried out by a fault tree analysis.

If we assume that all the barriers or safety functions are statistically independent, it is a rather simple procedure to combine the data to obtain the consequence probabilities or frequencies. These are obtained by multiplying the frequency of the initiating event with the probabilities of the relevant barrier symbol\ along the event sequence.

We need the frequency of the initiating event, and the barrier probabilities. During construction of the event tree, we enter the probability that the barriers fails (i.e. the "NO" results). For each barrier i , we enter:

q_i = probability that barrier i fails ("NO")

$p_i = 1 - q_i$ = probability that i functions as intended ("YES").

In addition to the barrier probabilities, we enter the frequency of the initiating event:

f = frequency of initiating event

When establishing the barrier probabilities and the frequency of the initiating event, it might be necessary to perform separate analyses.

To calculate the frequencies of the various consequences we may multiply the frequency of the initiating event with the barrier probabilities of each barrier along the path leading to the actual consequence.

Consider consequence C_j, and assume that S is the set of barriers in the path leading to consequence C_j and that represents "success" of barrier (YES-branches), and further that F is the set of those barriers on the path leading to the consequence representing "barrier fails" (NO-branches). Then the frequency of the consequence C_j is given by:

$$F_j = f * \prod_{i=1}^{m} p_i * \prod_{i=1}^{n} q_i$$

To solve the equation we multiply the following three factors:

a. The frequency of the initiating event;

b. $\prod_{i=1}^{n} p_i$ = the product of success probabilities for barriers with a "YES" branch

c. $\prod_{i=1}^{n} q_i$ = the product of failure probabilities for barriers with a "NO" branch

Application to crane related problems

Examples of initiating events leading to the crash of two cranes may be:

Signalling error (commander errors or red light instead of green)

Safety distance between two cranes is too small (installed mistakes)

Operator fails to recognise the control button or movement restrictor failure.

Examples of barriers are:

Switch off current by control room

Emergency shut down system

Decelerator and movement restrictor

When presenting the results, we typically include:

Listing of all identified consequences;

Ranking of the various consequences;

Description of the event sequences for the most severe consequences;

The frequency of occurrence of each consequence;

Evaluation of any dependencies between the barriers;

Suggestions for improvement in terms of additional safety functions, or strengthening of weak barriers

6.6 FAULT TREES

Fault trees are used in human error analysis to analyse the causes of human error, and in systems analysis to assess the impact of operator errors on system reliability. Fault trees can also be used to assess the likelihood of an undesirable event or accident scenario, and typically a fault tree considers hardware faults, environmental stressors or events, and human errors as potential accident causes. Fault trees are a powerful means to graphically represent the relationships between the potential causes of accidents, and when quantified, to yield the frequency or probability of accidents. Sensitivity analysis of the fault tree can determine the relative importance of each contributor to an accident. Essentially, analysis involves defining one undesirable event at the top of the tree, the "top event", and deciding what can cause it, either alone, or in combination with other events, errors, etc. For each of these causes or intermediate events underneath the top event, the question of what could cause them is asked again. This reduction process can often be assessed quantitatively. Basic events related to human errors are quantified as a probability, called human error probability.

Construction and analysis of fault trees

The logic of fault trees centres around the top-down nature of the approach and its use of AND gates and OR gates, which denote the relationship between an event and those events immediately below it and joined to it via the gate. An OR gate means that any of the events underneath that gate can, on their own, cause the event above the gate. An AND gate, in contrast, means that the event above the gate will only occur if all the events below the gate occur. As most events in a fault tree usually are independent, it can be seen that an event above an OR gate is much more likely to occur than an event above an AND gate, provided that the basic events underneath each of the gates have the same likelihoods.

To analyse a fault tree, a logical mathematical expression must be derived for the top event, based on those events lower in the line which contribute to the top event. Two simple rules are followed, namely:

> The output of an AND gate is equal to the product of its input probabilities;
>
> The output of an OR gate is approximately equal to the sum of its input probabilities; (NB this approximation only holds if the probabilities are small –i.e. significantly less that 0.1)

This expression is then reduced using the standard rules of Boolean algebra (see Henley and Kumamoto,1981). The basic Boolean expression for the top event can for example be B + C + (G + H +F) * (A + E + D) + D + (A + E + F + G) *(H + I + J). This identifies base events B, C and D as being potentially important, because the occurrence of any one of these alone, will lead directly to the top event. Other contributors (e.g. A, E, F, G, H, I and J) cannot cause the top event alone; instead they must occur simultaneously with another basic event.

7. CONCLUSIONS AND RECOMMENDATIONS

Because $R_{s(t)} = R_{d(i)} * R_{m(t)}$ (with $R_{d(i)}$ --the reliability of drivers operation in t time; $R_{m(t)}$ --the physical reliability of cranes), the reliability of crane systems can only be improved if both the physical reliability of cranes and the quality and ability of operators, reduce mistakes during operation, are improved.

We can learn from equation (1-1) for the reliability of a series system, that if a crane system consists of fewer elements, it has higher reliability.

For example, topless tower cranes have higher reliability than normal tower ones. Because they do not have tops of towers and tie bar blocking, the number of metal components is reduced and, hence, these cranes are safer and more reliable than normal tower cranes.

Character of the parallel connection system in reliability technology

When all of the parallel connection elements lose their effectiveness, so does the entire system. The reliability of a parallel system is higher than the reliability of any parallel connection element: $R_s > \max R_i$.

If elements of lower reliability are broken and these elements are replaced by the same type of elements in a serial connection, the reliability of the system will remain at the original level or will be less than before. On the other hand, if elements are replaced by the same type of elements in a parallel connection, the reliability of the system will increase. The reliability of the crane will then be higher than before.

During operation of cranes, the practical hoisting capacity and lifting moment are always lower than the maximum specified value and hence, the reliability of cranes is higher. Because of lower load and higher safety storage, the failure rate is effectively lowered, enhancing the reliability of the system. In case of increasing storage intensity of parts, such as the power storage of the prime mover, the capacity storage of hydraulic pressure or electric elements, and the kinetic energy storage of the frame movement, this will lower the failure rate of cranes and improve the reliability of the entire system.

If a crane is equipped with safety devices with higher quality, it can be operated agilely, and it has higher reliability. Because safe devices can reduce or avoid hidden troubles, the number of accidents is reduced and safety in operation is improved.

The probabilistic analysis methods of cranes are broadly used to evaluate the reliability of cranes. However, these methods are merely tools that assess whether the cranes themselves are reliable or not. Reliability analysis of crane operations is considerably complex. If a crane of higher reliability is not operated correctly or maintained carefully, its reliability will gradually decrease. As a result, when assessing the reliability of crane operations, it is not sufficient to evaluate only the cranes themselves. One must consider both cranes and human factors.

There are nearly 10 million cranes in operation today worldwide [9]. Therefore, it is hardly surprising that cranes that have not been tested and unqualified products flow into the market. Their number is increasing gradually year by year. Therefore, tasks of departments for crane inspection become more arduous and significant. Every inspector must be responsible for the safety and reliability of cranes that have been tested. Supervision departments must also supervise crane builders and users seriously, to check whether better, higher qualified products should be used.

To obtain cranes of higher reliability, which can keep their stable reliability during the entire usage period, we recommend to take the following steps:

1. Choose proper preventive maintenance routines. Choosing proper preventive maintenance routines is extremely important. Good measures can increase the reliability of equipment and their performance during crane operations.

2. Enterprises should engage qualified crane specialists. Crane specialists can find and eliminate safety-related faults in time, by using a mandatory historical database of defects, combined with inspections and repairs.
3. Strengthen the education and training of crane drivers Crane operator errors lie at the root of 73% all crane accidents [9]. Companies should engage operators of higher qualification and specify qualification requirements for operators. In addition, crane specialists should train crane drivers and commanders. In this way, safety and reliability of cranes will be improved significantly.

Only by applying the recommendations above, the reliability of crane operations can be ensured and improved. One should keep in mind that the reliability of crane operations is not solely determined by crane hardware, but also by human factors.

ABBREVIATIONS

A	Availability (validity)
EUC	Equipment under Control
FTA	Fault Tree Analysis
ETA	Event Tree Analysis
HAZOP	Hazard and Operability Study
HSE	Health, Safety and Environment
K_0	Reorganisation Degree
m	Repair Rate
MORT	Management Oversight Risk Tree
MTBF	Mean Time between non-failures
MTTF	Mean Time to failure
MTTFF	Mean Time to Work before First Failure
MTTR	Mean Time to Repair
OREDA	Offshore Reliability Data
PFD	Probability of Failure on Demand
RBD	Reliability Block Diagram
RHF	Random Hardware Failure
RIF	Risk Influencing Factor
$R(t)$	Reliability

SCF	Safety Critical Function
SIF	Safety Instrumented Function
SIL	Safety Integrity Level
SIS	Safety instrumented system
HRA	Human reliability analysis
T	Mean life or overhaul life
TC	Technical Committee
Tr	Life-span of cranes
TA	Task analysis
λ	Malfunction rate

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