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LIFE CYCLE COST (LCC) ANALYSIS IN OIL AND CHEMICAL PROCESS INDUSTRIES

Yoshio Kawauchi and Marvin Rausand

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ABSTRACT

This report presents brief history and a state-of-the-art survey of Life Cycle Cost (LCC) analysis, in particular LCC analysis in oil and chemical industries, based on a detailed literature survey, internet-web browsing, and interviews with experts. A main objective of the LCC analysis is to quantify the total cost of ownership of a product throughout its full life cycle, which includes research and development, construction, operation and maintenance, and disposal. The predicted LCC is useful information for decision making in purchasing a product, in optimizing design, in scheduling maintenance, or in planning revamping. This report presents an LCC procedure consisting of six steps, which are "Problems definition", "Cost elements definition", "System modeling", "Data collection", "Cost profile development", and "Evaluation". Sub-activities to be encompassed in the six steps procedure are described. This report also presents codes and standards related to LCC analysis, and software tools for LCC analysis. Appendices include a list of references, samples of cost breakdown structure, and descriptions of software tools for RAM analysis.

Keyword ENGLISH	Keyword NORWEGIAN
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COST BREAKDOWN STRUCTURE	KOSTNADSNEDBRYTING
SYSTEM MODELING	SYSTEMMODELLERING
CODES AND STANDARDS	RETNINGSLINJER OG STANDARDER
SOFTWARE TOOLS	PROGRAMVARE

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1. Introduction

This report presents a general introduction to Life Cycle Cost (LCC) analysis, in particular LCC analysis applied in oil and chemical process industries. Most of the content in this report is based on a literature survey and interviews with experts within LCC analysis and reliability engineering.

Life Cycle Cost (LCC) analysis is a collective term comprising many kinds of analysis, e.g., reliability-availability-maintainability (RAM) analysis, economic analysis, risk analysis, and so on. A main objective of the LCC analysis is to quantify the total cost of ownership of a product throughout its full life cycle, which includes research and development, construction, operation and maintenance, and disposal. The predicted LCC is useful information for decision making in purchasing a product, in optimizing design, in scheduling maintenance, or in planning revamping.

LCC analysis may be applied for[(1)][1]:

- evaluation and comparison of alternative design;
- assessment of economic viability of projects/products;
- identification of cost drivers and cost effective improvements;
- evaluation and comparison of alternative strategies for product use, operation, test, inspection, maintenance, etc.;
- evaluation and comparison of different approaches for replacement, rehabilitation/life extension or disposal of aging facilities;
- optimal allocation of available funds to activities in a process for product development /improvement;
- assessment of product assurance criteria through verification tests and their trade-offs;
- long term financial planning.

[1] The numbers in superscript specify references listed in APPENDIX A of this report.

It is easily understood that the total cost of a product through its life cycle comprises not only “acquisition costs”, but also many other cost categories such as “ownership costs”, like operation costs, maintenance costs, logistics costs, etc. As shown in Fig.1-1, the ownership costs may be higher than the acquisition costs. It is believed that a typical range of the ownership costs is 60 percent to 80 percent of the total LCC. For instance, according to a standard of LCC analysis, the ownership costs of a fighter aircraft are 53 % of the total LCC, and the ownership costs of a basic trainer aircraft occupies 91 % of the total LCC(5). If we do not care about the ownership costs at purchasing a product, it is likely that we get surprised by the growing ownership costs after the purchase. It is consequently important to try to minimize the LCC at an early phase of the product life cycle.

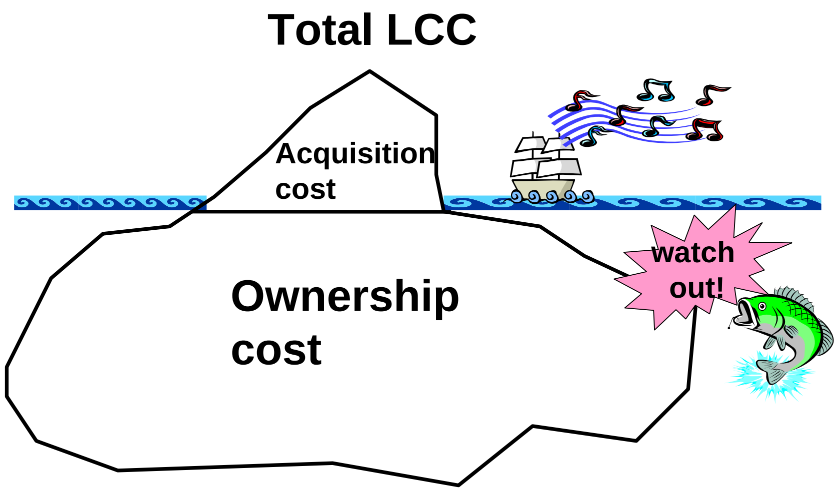

Figure 1-1: Life cycle cost consisting of acquisition costs and ownership costs(81)

2. Definitions

Life cycle

Time interval between a product's conception and its disposal[1].

Life cycle cost (LCC)

Cumulative cost of a product over its life cycle[1].

Life cycle costing

Process of economic analysis to assess the life cycle cost of a product over its life cycle or a portion thereof[1].

Cost driver

LCC element which has a major impact on the LCC[1].

Cost profile

Graphical or tabular representation showing the distribution of costs over the life cycle (or portion thereof) of a product[1].

Life cycle cost breakdown structure

Ordered breakdown of the elements of cost to arrive at a product's total life cycle[1].

Availability

The ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided[25].

(It is assumed that Availability depends on the following three system performance measures:. Reliability, Maintainability, and Maintenance support performance)

Reliability

The probability that an item can perform a required function under given conditions for a given time interval (t_1, t_2)[25].

Maintainability

The probability that a given active maintenance action for an item under given conditions of use can be carried out within a stated time interval, when the maintenance is performed under stated conditions and using stated procedures and resources(25).

Maintenance support performance

The ability of a maintenance organization, under given conditions, to provide upon demand, the resources required to maintain an item, under a given maintenance policy(25).

Corrective maintenance

The maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function(1).

Preventive maintenance

The maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item(1).

Logistics support

The materials and services required to operate, maintain, and repair a system. Logistics support includes the identification, selection, procurement, scheduling, stocking, and distribution of spares, repair parts, facilities, support equipment, and so on(31).

Supportability

Inherent characteristics of design and installation that enable the effective and efficient maintenance and support of the system throughout its planned life cycle(30).

3. Brief History of LCC analysis

We find one of the roots of LCC analysis in some US-Department of Defense (DOD) programs(27,33,81). DOD has incorporated optimization of LCC into their activities such as logistics, operation, and acquisition. For instance, the concept of minimization of LCC is found in a process named "Integrated Logistics Support (ILS)"(81), a program called "Acquisition Category One (ACAT I)"(33) and in the "Design-to-Cost (DTC)"(30) procedure.

ILS is defined as " a composite of elements necessary to assure the effective and economical support of a system or equipment at all levels of maintenance for its programmed life cycle" in DOD Directive (DODD) 4100.35 issued in Nov. of 1968 (81). The ILS has some derived programs such as NAVMAT, BUPERS, NAVFAC, and other systems commands.

ACAT I is a program for major weapon systems, and details a policy basis for weapon system acquisition processes. The policy is interpreted into DOD Directive (DODD) 5000.1 which is implemented by DOD Instruction (DODI) 5000.2, "Defense Acquisition Program Procedure" DODI 5000.2 specifies that LCC should be considered for decision at each milestone(33).

Design-to-Cost (DTC) procedures have been included in all major U.S. Army aviation procurements since 1972. The policy for DTC is addressed in DODD 4245.3 issued in 1983. The DOD's policy on this concept is; Cost parameter shall be established which consider the cost of acquisition and ownership; discrete cost elements shall be translated into "design to" requirements. DTC goals should be established for all elements of future LCC which are design controllable. Acquisition strategies must then be structured to achieve these goals. In 1989, the DTC program was approved as a tri-service document (MIL-STD-337). Nondirective guidance implementing DTC may be found in the DOD Design to Cost Handbook, DOD-HDBK-787.

During the period of 1970s to the beginning of 1980s, the LCC analysis was mainly applied in the military field. After that period, the applications of LCC analysis have spread to other industries such as aircraft, electrical power plants, oil and chemical industries, and railway systems as shown in Fig.

3-1[28,38,39,124-126,129-131,133-136].

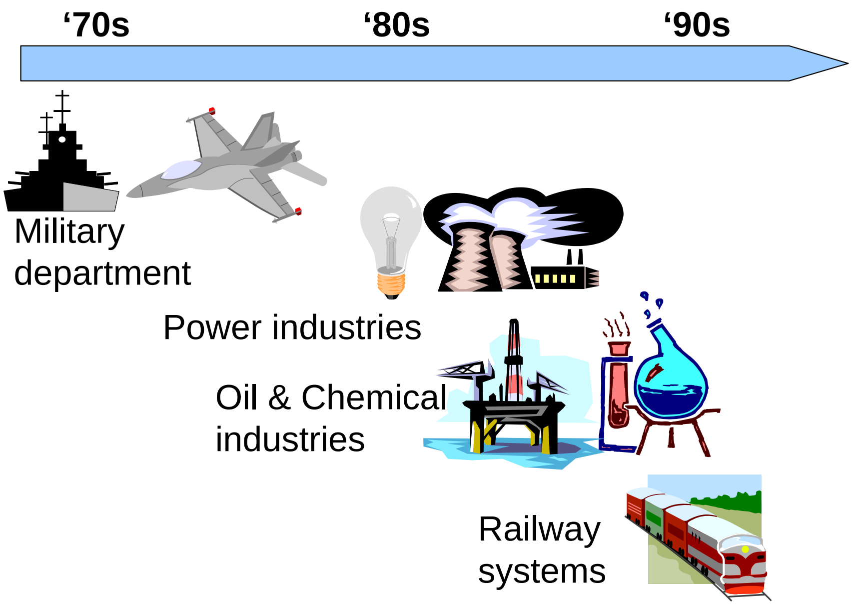

Figure 3-1: Development of LCC analysis applications

In the electrical power plants and oil & chemical process industries, LCC analysis seems to be more closely linked to system availability analysis, so-called reliability-availability-maintainability (RAM) analysis, than in other industries, because the production regularity is one of the major topics of concern for plant owners(38,39,58). The importance of RAM analysis in LCC prediction has also been pointed out in a report within the military field(33).

LCC analysis in oil and chemical industries therefore tends to focus on prediction of the unavailability of the total system due to component failures, maintenance and spurious trips of emergency shutdown systems(34-36,39,124).

4. Timing of LCC analysis

LCC analysis is preferably carried out in any and all phases of a product's life cycle to provide input to decision makers. However, early identification of acquisition and ownership costs provides the decision makers with more opportunity of balancing performance, reliability, maintenance support and other goals against life cycle costs(1).

Figure 4-1 shows the typical cost profiles of commitment and expenditure of activities performed in each program phase, and also shows the range of uncertainty in cost prediction(5). It illustrates that LCC analysis in the early program phase has significant opportunities for minimizing the LCC, because the cost profile of commitment rapidly increases in the early program phase. It is generally believed that 80 % of the LCC is allocated by decisions that are made within the first 20 % of the life of the project.

However, we also have to consider the uncertainty of the LCC estimated in each program phase. The uncertainty of the LCC analysis significantly depends on the timing when the LCC is predicted. It is obvious that in the earlier program phases, the predicted LCC has more uncertainty than in later program phases. The uncertainty that exists in the conceptual studies, are in particular quite large, and rapidly decreases after development has begun as shown in Fig.4-1.

It is therefore important to decide the best timing of the LCC analysis for each program in consideration of the trade-off between the commitment curve and the uncertainty curve.

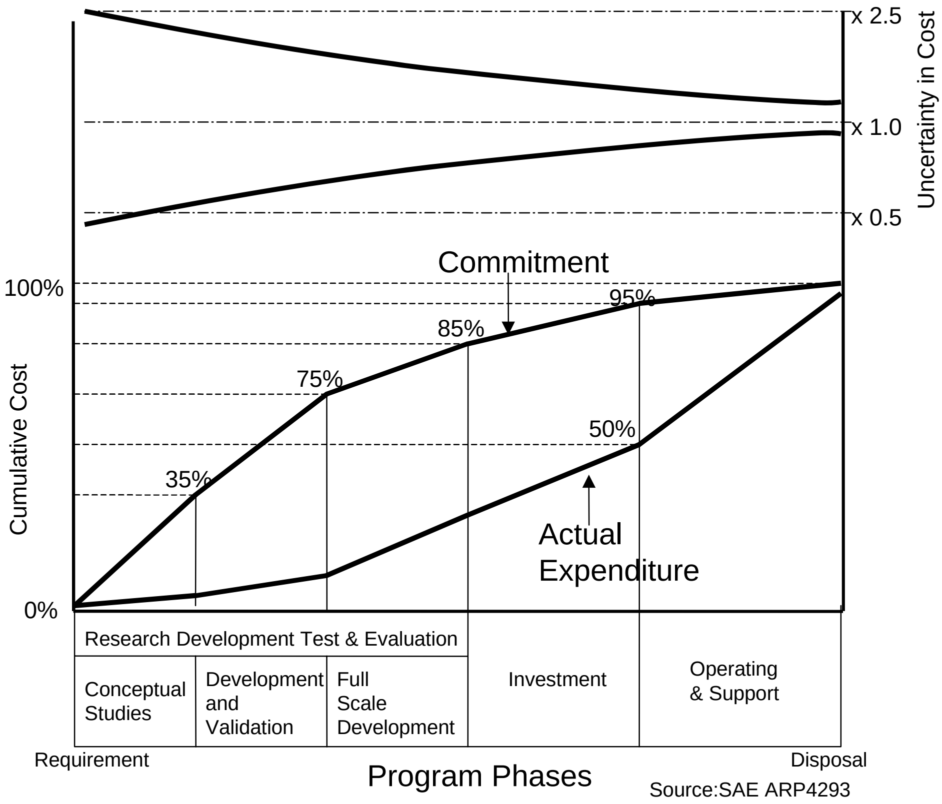

Figure 4-1: An example of influence of program decision stage on LCC

5. Basic Process of LCC Analysis

5.1 LCC Sub-processes

Many procedures of LCC analysis have been proposed[1-5,26,29,30,33]. It is obvious that the procedures are not completely the same due to differences among the systems analyzed. However, we find some common processes, which seem to be essential, in all of the proposed procedures. It may be summarized as six basic processes as follows (please refer to Fig. 5-1):

Process 1: Problems definition
Process 2: Cost elements definition
Process 3: System modeling
Process 4: Data collection
Process 5: Cost profile development
Process 6: Evaluation

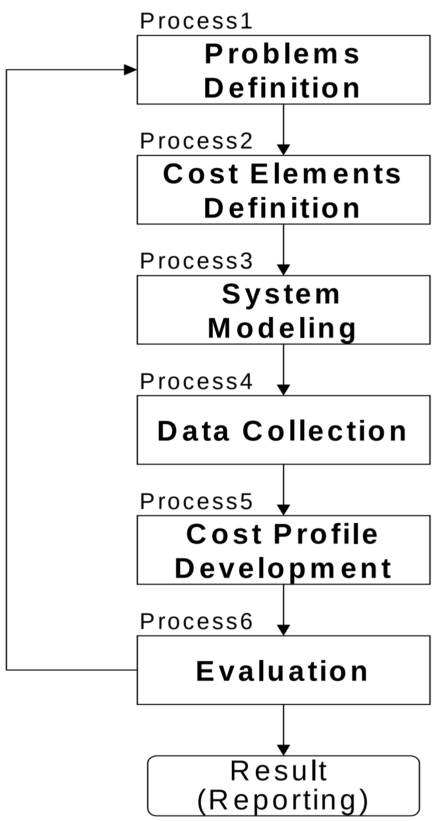

Figure 5-1: The basic LCC processes in six steps

Figure 5-2 illustrates a concept map of LCC analysis developed from the six basic processes. Figure 5-2 shows that LCC analysis is a collective activity comprising the six basic processes symbolized by a hexagon surrounding the core hexagon named "LCC". Each basic process is further broken down into sub-activities listed in each sub-area. LCC analysis starts from the process "Problems definition", and the other five processes are iteratively carried out clockwise in Fig. 5-2 as long as the system does not satisfy the criteria defined in the first process. The arrow with the word of "Iteration" on the upper left of Fig. 5-2 expresses that a baseline system, which is an initial design concept, may be improved throughout the iterative LCC analysis. More detailed information of each sub-activities incorporated in the LCC analysis is introduced in the following sections.

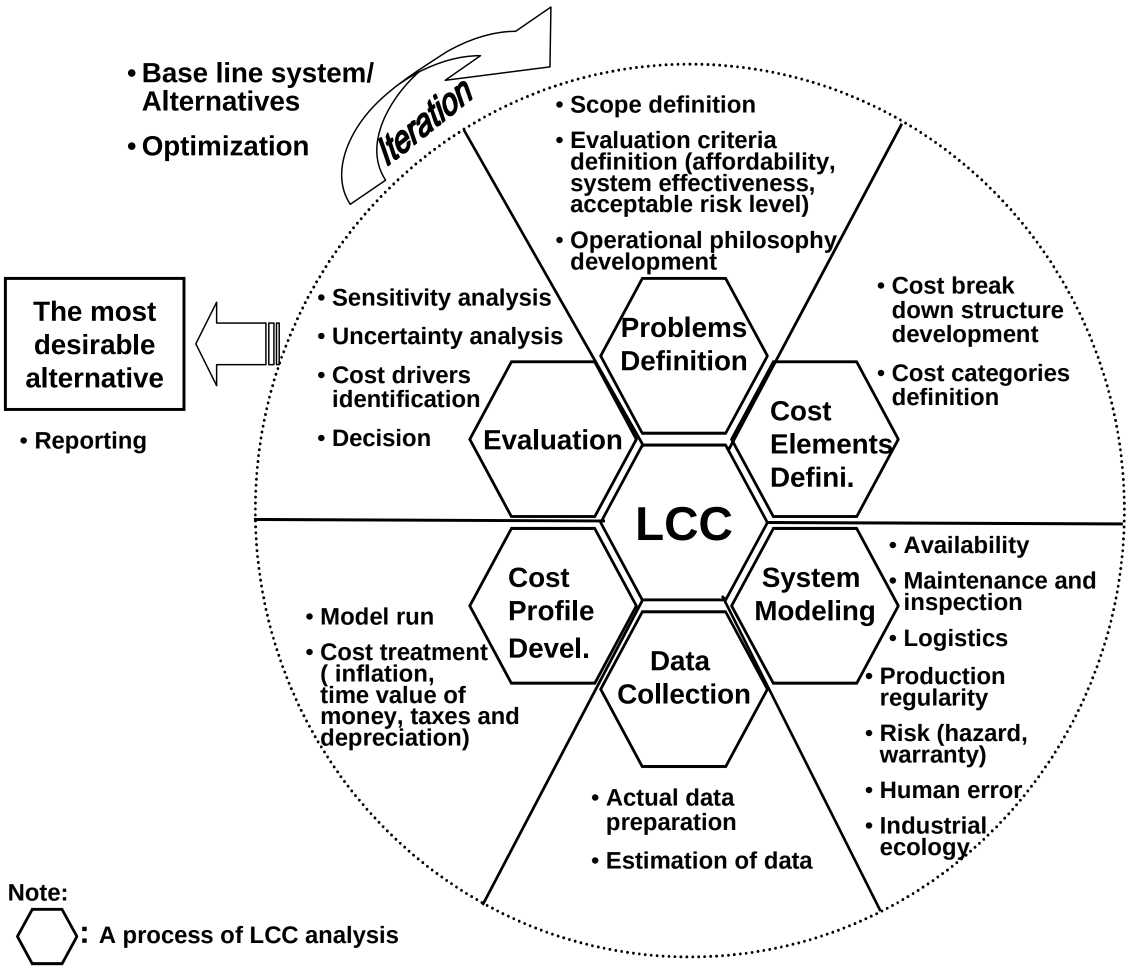

Figure 5-2: A LCC concept map (The six basic processes and sub-activities)

5.2 Process 1: Problems definition

5.2.1 Scope definition

The first step of any LCC analysis should be to clearly the problems and the scope of work. The term "scope" means aspects, such as the scope of program phases to be modeled, the scope of equipment to be modeled, the scope of activities to be modeled, etc. A clear definition of the scope is necessary to get a clear definition of the cost elements (please refer to section 5.3), which are the basis for predicting the total LCC. We have to clearly define all assumptions in the LCC analysis as well.

5.2.2 Evaluation criteria definition

The evaluation criteria in the last process named "Evaluation" in Fig.5-1 should also be defined in the Process 1. The criteria should encompass not only the total cost, but also system performance and effectiveness as show in Fig. 5-3.

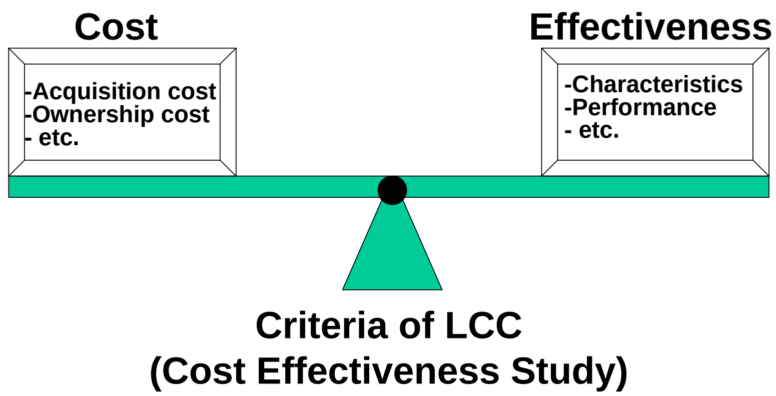

Figure 5-3: Cost effectiveness studies in LCC

Figure 5-3 illustrates that decisions concerning "Cost" of a system should not be made independently. The decisions should be made with considering "Cost", together with "Effectiveness" of the system as well[33,124]. The effectiveness may comprise system characteristics, like production capacity, product quality etc., and also system performance characteristics, like system availability, the safety integrity level of shutdown systems, etc. Regulations, codes and standards, and project specifications may specify the system effectiveness in many cases.

5.2.3 Operational philosophy development

Operational philosophy, e.g. operational requirements and maintenance strategies, etc., should be developed before the calculation of LCC. The operational philosophy means, for instance, an acceptable time interval of predictive maintenance, or the maximum available resources for maintenance, etc. It significantly depends on the plant owners' philosophy about the plant operation.

5.3 Process 2: Cost elements definition

5.3.1 Cost breakdown structure (CBS) development

It is important to identify all cost items, or the so-called "cost elements", that considerably influence the total LCC of the system. It is accordingly recommended to define the cost elements in a systematic manner to avoid ignoring significant cost elements. According to an international standard of LCC (IEC 60300-3-3), it is recommended to develop a cost breakdown structure (CBS) as a basis to the definition of the cost elements in the LCC analysis. CBS may be developed by defining items along three independent axes, which are "Life cycle phase", "Product/work breakdown structure", and "Cost categories" (please refer to Fig.5-4).

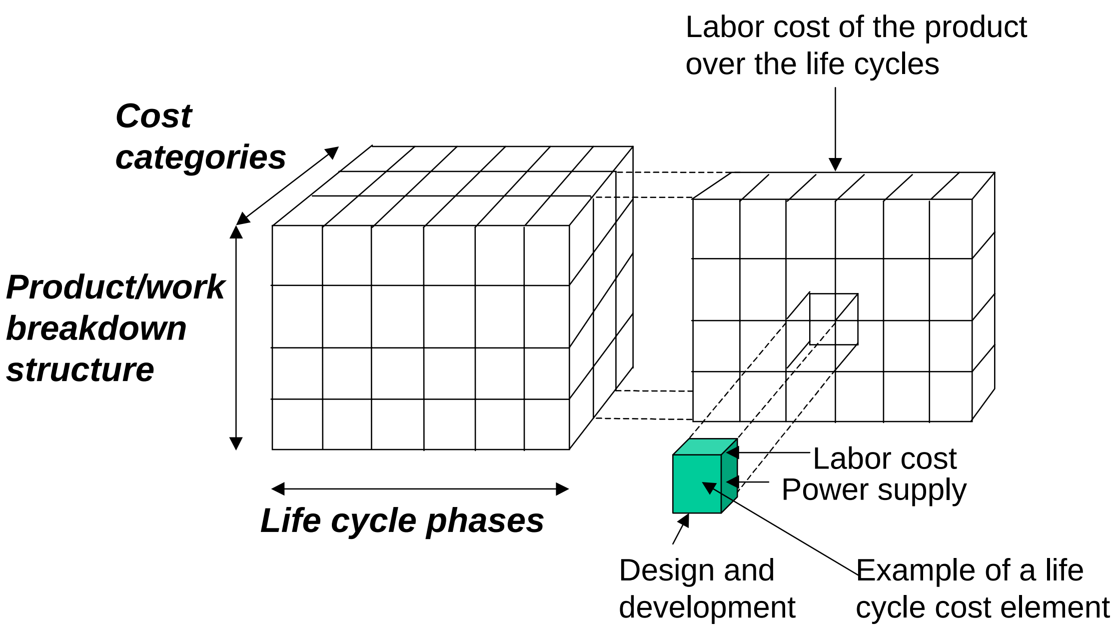

Figure 5-4: Cost element concept (source:IEC-60300-3-3)

We also find a similar concept of the three-dimensional CBS in the US-DOD ILS program[81] .

5.3.2 Cost categories definition

As mentioned above, it is very important to consider all cost element that significantly affects the total LCC. Analogous to the difficulty to find one universal method of LCC analysis, it is also difficult to define the cost elements that are applicable for every LCC analysis, because LCC analysis may be applied to various types of systems. Many configurations of the cost elements have therefore been developed for LCC analysis[1-5,26,61,64,114,124,125]. Samples of the definition of cost elements applied in some industries are listed in APPENDIX B of this report as a reference. We recommend that CBS and cost categories should be tailored for each application area for LCC analysis.

However, we find some cost categories on the highest level that are commonly used in many LCC analyses; i.e, "Acquisition costs" and "Ownership costs". This categorization of cost elements is adopted in IEC 60300-3-3. The two cost categories may be alternatively called "Capital expenditure (CAPEX)" and "Operation expenditure (OPEX)" in other cases, e.g. in ISO 15663. Of course, we can flexibly expand the cost categories on the highest level depending on the system to be analyzed.

For instance, a reference[114] defines three cost categories on the highest level of the CBS, which are "Acquisition cost", "Operating cost", and "Cost of deferred production". The cost of deferred production may be generally quantified based on the unavailability performance of the production system, and a unit cost of the product. The cost of deferred production may give a considerable impact on the LCC, if the unavailability of the system and/or the unit cost of the product are high. It seems to be common for plant owners in oil, gas and electric power industries to contract to supply a certain amount of production within a period. If the contracted production amount is not supplied, a penalty fee is charged on the plant owners. Accordingly, it is a feature of LCC analysis in oil, gas and electric power industries to take the cost of deferred production into consideration as an important cost category.

A reference [125] further introduces the cost induced by hazards that could occur in a railway system, the so-called "Hazard cost", in addition to the other three cost categories on the highest level, the three cost categories which are "Investment cost", "Maintenance and operating cost", and "Delay cost". "Delay coat" is rather similar to "deferred production" in oil and chemical process industries.

Figure.5-5 shows a sample of a cost category definition, which may be applicable to the CBS in LCC analysis of oil and chemical process facilities. The sample of the CBS is proposed with reference to some CBSs listed in APPENDIX B of this report.

1. Life Acquisition Cost (LAC)
    - 1.1 Equipment purchase cost
    - 1.2 Installation cost
    - 1.3 Commissioning cost
    - 1.4 Insurance spares cost
    - 1.5 Reinvestment cost
    - 1.6 Design and administration cost
2. Life Ownership Cost (LOC)
    - 2.1 Man-hour cost
        - 2.1.1 Corrective maintenance
        - 2.1.2 Preventive maintenance
        - 2.1.3 Servicing
    - 2.2 Spare parts consumption cost
        - 2.2.1 Corrective maintenance
        - 2.2.2 Preventive maintenance
        - 2.2.3 Servicing
    - 2.3 Logistics support cost
    - 2.4 Energy consumption cost
    - 2.5 Insurance cost
3. Life Loss Cost (LLC)
    - 3.1 Cost of deferred production
    - 3.2 Hazard cost (Liability cost)
    - 3.3 Warranty cost
    - 3.4 Loss of image and prestige cost

Figure 5-5: A sample CBS in LCC analysis for oil and chemical industries

5.4 Process 3: System modeling

We need to make a model to quantify the cost elements encompassed in a LCC analysis. To make a model means to find appropriate relations among input parameters and the cost elements. If any existing models appropriate for estimating of cost elements are available, we can utilize the models to estimate the cost elements. If not, we need to establish new models for the cost elements.

In general, a system should be modeled from many viewpoints such as availability, maintainability, logistics, risk, human error in the system, etc., as shown in Fig. 5-2. However, it is supposed that the availability and the maintainability are the most significant cost drivers in LCC analysis, because they may have a wide range of impact on the cost elements categorized as operating and support cost(33). Furthermore, availability and maintainability are parameters, which could be controlled in a design phase by system designers. It is therefore very important to properly model the system availability and maintainability.

5.4.1 Availability modeling

The availability of production facilities has significant effects on the cost category "3.1 Cost of deferred production" listed in Fig. 5-5. If the product has a high selling value, the cost of deferred production accordingly increases. So that the higher selling value the product has, the more important it is to achieve high production availability in order to reduce the total LCC.

A general definition of "Availability" is found in Chapter 2 of this report. In oil and chemical process industries, "Availability" may be calculated by subtracting shutdown time plus the loss time of major stoppage from the total calendar time of system operation, and dividing it by the total calendar time of system operation. This calculation of availability is only applicable, if we have plenty of data of actual plant operation

In prediction of availability, we may use various measures(30,31,49,55). For instance, the availability of a repairable component is approximated by dividing the mean time to failure (MTTF) by the MTTF plus mean time to repair (MTTR) as expressed in Eq. (5.1), if "as good as new" after repair and no trends in the time to failure are assumed(31,49).

$$Availability = \frac{MTTF}{MTTF + MTTR} = \frac{MTTF}{MTBF} \tag{5.1}$$

where MTBF represents the mean time between failures, which is equal to MTTF+MTTR (please refer to Fig. 5-6)

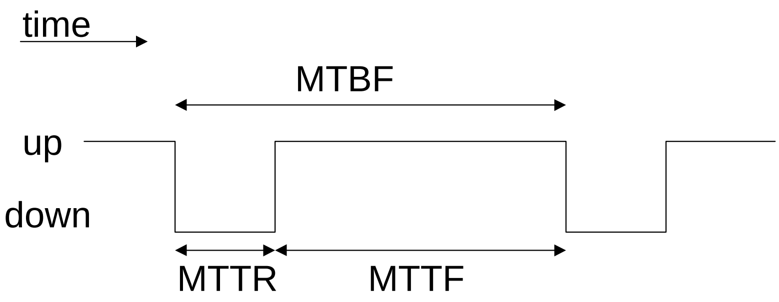

Figure 5-6: MTBF, MTTF and MTTR

We also find some alternatives to Eq. (5.1) as measures of system availability[30].

$$A_i = \frac{MTBF}{MTBF + MCT} \tag{5.2}$$

$$A_a = \frac{MTBM}{MTBM + MAV} \tag{5.3}$$

$$A_o = \frac{MTBM}{MTBM + MDT} \tag{5.4}$$

where:
MCT the mean corrective maintenance time;
MTBM the mean time between maintenance;
MAV the mean active maintenance time;
MDT the mean maintenance down time including active maintenance time, logistics delay time, and administrative delay time.

A_i, A_a, A_o are called "Inherent availability", "Achieved availability", and "Operational availability", respectively.

A_i excludes preventive or scheduled maintenance actions, logistics delay time, and administrative delay time. A_i indicates the availability in an ideal support environment, i.e., readily available tools, spare parts, personnel, etc.
A_a includes preventive or scheduled maintenance actions, but excludes logistics delay time, and administrative delay time. A_a indicates the availability in an ideal support environment with consideration of preventive maintenance.
A_o includes preventive or scheduled maintenance actions, logistics delay time, and administrative delay time. A_o indicates the availability in an actual operational environment.

To estimate availability measures of a total system, some conventional methodologies have been developed for general purposes. The conventional methodologies are reliability block diagram (RBD), fault tree analysis (FTA), Markov modeling, Petri net, etc. The details of the conventional methodologies are discussed in many publications (textbooks or standards)[7,16,17,18,49,52,53]. Many applications of the conventional methodologies have been reported[57,59,60,74].

We also find that some modeling methodologies have been developed rather recently, which are dedicated for RAM analysis in oil or electric power industries. Most of the proposed methodologies are structured with a combination of some conventional modeling techniques (e.g. RBD, FTA, Markov, etc.).

For instance, we find the following methodologies are developed for availability modeling:
(1) A combination of Markov modeling and Petri net modeling[56].
(2) A combination of FTA and Markov modeling[58].
(3) A combination of FTA and Flow network[39].

The pros and cons of each of the conventional modeling methodologies have been discussed in some references[10,72]. The international standard IEC60300-3-1[10] tabulates characteristics of analysis techniques as shown in Table 5-1.

Table 5-1: Characteristics of analysis methods (Extracts from Table 2 of IEC60300-3-1)

Analysis method	Characteristics														
	Ability of method to handle model characteristics as:								Attributes						IEC Standard
									Approach		Analysis		Analysis effort		
	Number of components	Redundant structure	Irreducible structure	Failure/event combinations and dependencies	Time varying failure/event rates	Complex maintenance strategies	Simulation of functional process	Symbolic represent-ation	deductive	inductive	qualitative	quantitative	qualitative	quantitative	
FMEA	Up to several thousands	(no)	no	(no)	yes	no	no	List	(nc)	c	c	nc	high	–	60812
FMECA	Up to several thousands	(no)	no	(no)	yes	no	no	List	nc	c	c	(c)	high	low	60812
Fault tree analysis	Up to several thousands	yes	(yes)	(yes)	yes	no	no	Fault tree	c	nc	c	c	high	medium	61025
Reliability block diagram	Up to several thousands	yes	(yes)	(yes)	(yes)	no	no	Reliability block diagram	c	nc	(c)	c	medium	medium	61078
Markov	2 to 100	yes	yes	yes	(no)	yes	(yes)	System state diagram	(nc)	c	c	c	high	medium	61165
Parts count	1 to thousands	(no)	(yes)	no	(no)	–	–	List	nc	c	(nc)	c	low	low	–
Cause/consequence	Up to several hundreds	yes	yes	(yes)	(yes)	yes	no	Cause/consequence chart	(c)	c	c	c	high	low/high	–
Event simulation	Up to several hundreds	yes	yes	yes	yes	yes	yes	Any	c	c	c	c	high	high	–
System reduction	Up to several thousands	yes	no	(yes)	(yes)	(yes)	no	Reliability block diagram	nc	c	(nc)	c	medium	medium	–
Event tree	2 to 50	yes	yes	(yes)	yes	no	yes	Event tree	c	c	(nc)	c	low	low	–
Truth table	2 to 50	yes	yes	yes	–	–	–	Table	nc	c	c	nc	high	–	–

Abbreviations in Table 5-1 are as follows:

()	With restrictions/exceptions.
nc	Not capable, or not applicable
c	Capable

Table 5-1 is an extraction of Table 2 of IEC60300-3-1. The original table contains many remarks and descriptions of each item in the table. Please refer to the original table in the IEC60300-3-1 for further information. Table 5-1 indicates that there is no single, comprehensive availability (dependability) analysis method. Analysts should choose the method which best fits the particular system or analysis objective.

The methods mentioned above are applied not only for predicting availability of a total production system, but also for modeling subsystems of the total system or a specific phenomenon of components, such as a reliability level of emergency shutdown systems (ESD)(34-36, 42,43), degradation of components(50,51), a life distribution of a component (45), the effect of periodical testing of a component (60), etc.

Methodologies to roughly predict the reliability (availability) of complex systems comprising many components have been developed to reduce the efforts of reliability analysis(34,35,46,47). The methodologies model the total system as a group of homogeneous components, so that it is possible to approximate the reliability of the total system using some simple formulas. For instance, a new method based on the theory of stochastic processes has been proposed to estimate the reliability of redundant structures composed of multiple components of the same type (with respect to failure behavior)(46).

Modern process plants are usually controlled by many software packages installed into distributed control systems (DSC). Not only for control loops for production, but also control loops for safety, like emergency shut down systems, it is a recent trend to control them using software packages, e.g. programmable logic controller (PLC)(19,89,137). Methodologies of availability (reliability) assessment for software have therefore become more important in order to quantify the availability of total production systems. Such methodologies have recently been developed(93-95).

5.4.2 Maintenance and inspection modeling

The frequency of maintenance or inspection considerably influences on both the "availability performance" and the "operating cost", i.e., man-hour cost, spare part consumption cost. Maintenance may be categorized in two main type: "Corrective maintenance" and "Preventive maintenance". The definitions of corrective maintenance and preventive maintenance are found in Chapter 2 of this report. Sometimes, a preventive maintenance based on condition monitoring by modern measurement and signal-processing techniques is called "Predictive maintenance".

Maintainability may be measured through a combination of different factors as follows [66]:

(1) Mean time between maintenance (MTBM), which includes both preventive and corrective maintenance requirements.

(2) Mean time between replacement (MTBR) of an item due to a maintenance action.

(3) Maintenance downtime (MDT), or total time during which the system (or product) is not in condition to perform its intended function. It includes mean time to repair (MTTR)

(4) Turnaround time (TAT), or that element of maintenance time needed to service, repair, and/or check out an item for recommitment.

(5) Maintenance labor hours per system/production operating hours.

(6) Maintenance cost per system/production operating hours.

Since the frequency and quality of maintenance or inspection significantly affects the total LCC, in particular the "Ownership cost" (OPEX), many strategies for improving the efficiency of maintenance or inspection have been studied and standardized[6,13-15,23,63]. For instance, methods like "Reliability-Centered Maintenance (RCM)", and "Risk-Based Inspection (RBI)" are applied for planning of efficient maintenance or inspection.

RCM is a systematic process used to determine what must be done to ensure that a physical asset continues to fulfill its intended functions in its present operating context[31].

The RCM concept and methodology has been reported in many textbooks, papers, and reports(68-71). Applications of RCM have been reported as well(65,67).

As a methodology for RCM, the following twelve major RCM steps have been proposed in a reference(69):

(1) Study preparation
(2) System selection and definition
(3) Functional failure analysis (FFA)
(4) Critical item selection
(5) Data collection and analysis
(6) Failure mode, effects, and criticality analysis (FMECA)
(7) Selection of maintenance actions
(8) Determination of maintenance intervals
(9) Preventive maintenance comparison analysis
(10) Treatment of non-critical items
(11) Implementation
(12) In-service data collection and updating

RBI is a systematic inspection process to prioritize equipment inspection based on probability and consequence of failure. It could reduce the potential for catastrophic equipment failure and provides the ability to efficiently allocate limited inspection budgets and personnel.

For instance, in the U.S.A., a standard (OSHA passed Standard 1910.119 "Process Safety Management of Highly Hazardous Chemicals") states that "Inspections and tests shall be performed on process equipment and inspection and testing procedures and the frequency of inspections shall follow generally accepted good engineering practices… " in Paragraph (j) Mechanical Integrity. This standard may encourage companies to incorporate an efficient inspection or testing strategy, such as the RBI strategy. We also find requirements of RBI in the standard API580/581(6).

In practice, maintenance activities should be carefully managed, because maintenance activities might induce accidental events, e.g., in the chemical process industriy(62). According to studies by the British Health and Safety Executive of deaths in the chemical industry showed that some 30% were linked to maintenance activities, taking place either during active maintenance or as a result of faulty maintenance.

5.4.3 Logistics modeling

Logistics may be measured by indexes like "Logistics support" and "Supportability"[132] as defined in Chapter 2 of this report.

Elements covered by a logistics model and quantitative measures of logistics may vary depending on a type of logistic system to be modeled. It is therefore impossible to specify elements and measures to be considered in any logistics modeling. For instance, a DOD guide of Integrated Logistic Support (ILS) specifies the following eight elements to be considered in the analysis of logistic support[30,82],

(1) Maintenance personnel
(2) Training and training support
(3) Supply support
(4) Support equipment
(5) Computer resources
(6) Packing, handling, storage, and transportation
(7) Maintenance facilities
(8) Technical data, information systems

Sparing analysis is an important topic in supportability analysis. A number of spare parts stocked in warehouses on site may influence the time to repair and the operation cost, so that the sparing analysis may employ the primary reliability parameters and may reveal much valuable information in addition to the number of spares[75-78,80]. Some methods to predict support cost have been developed[79].

5.4.4 Production regularity modeling

Regularity may be defined as follows:
Regularity is a term used to describe how a system is capable of meeting demand for deliverys or performance[(22)].

A reference[(22)] illustrates the relation of availability, production availability, and deliverability as shown in Fig. 5-7.

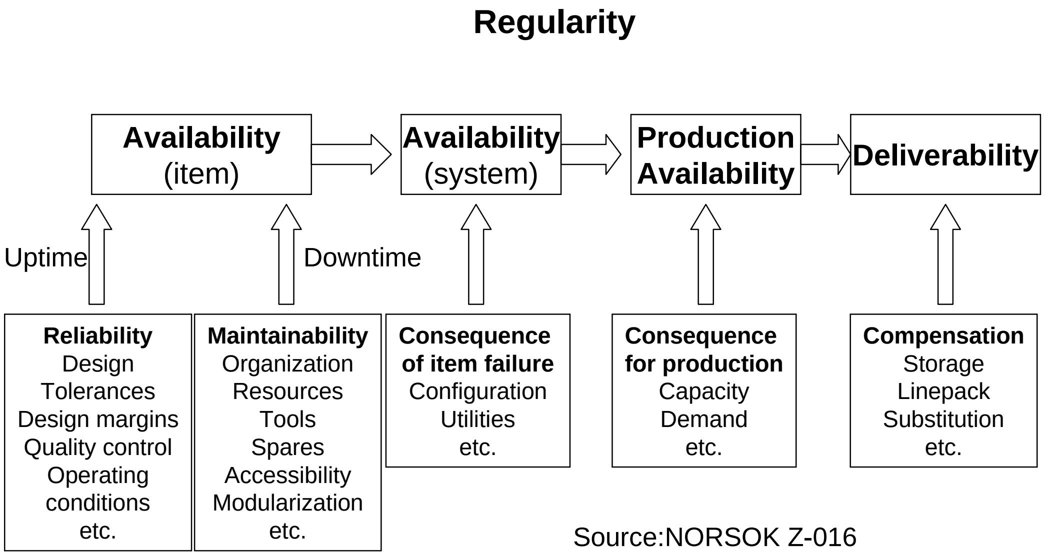

Figure 5-7: Measurements for regularity management

"System availability" is the ratio of a period of up time to a period of operating time.

"Production availability", defined as the ratio of production to planned production, could be simple measure of regularity. It is, however, possible to consider not only the production system, but also buffer tanks or any other back-up systems in case that the production system is down. Therefore, regularity may preferably be measured by a factor called "deliverability" defined as follow:

"Deliverability" is the ratio of deliveries to planned deliveries over a specified period of time, when the effect of compensating elements such as substitution from other producers and downstream buffer storage is included[22].

We can define various measures for production regularity, it is therefor important to explicitly define the measures to be applied in a regularity analysis according to the contents of the contract.

For instance, in an actual regularity analysis, the following three measures may be applicable as measures of "production availability".

(1) Production availability:
The ratio of real gas production to contracted production volumes. The production availability may be expressed per year or as a life cycle average.

(2) Demand production availability:
The percentage of time when the system is capable of producing 100% of the contracted production volume.

(3) On-stream production availability:
The percentage of time the production rate in the system is larger than zero. This measurement reflects the risk of having a total production shutdown.

Figure 5-8 illustrates the above three measures for "production availability". When an actual production profile is shown in (a) of Fig.5-8, the three measures, which are the production availability, the demand production availability, and the on-stream production availability, can be accordingly drawn as shown in (b), (c), and (d) in Fig.5-8, respectively.

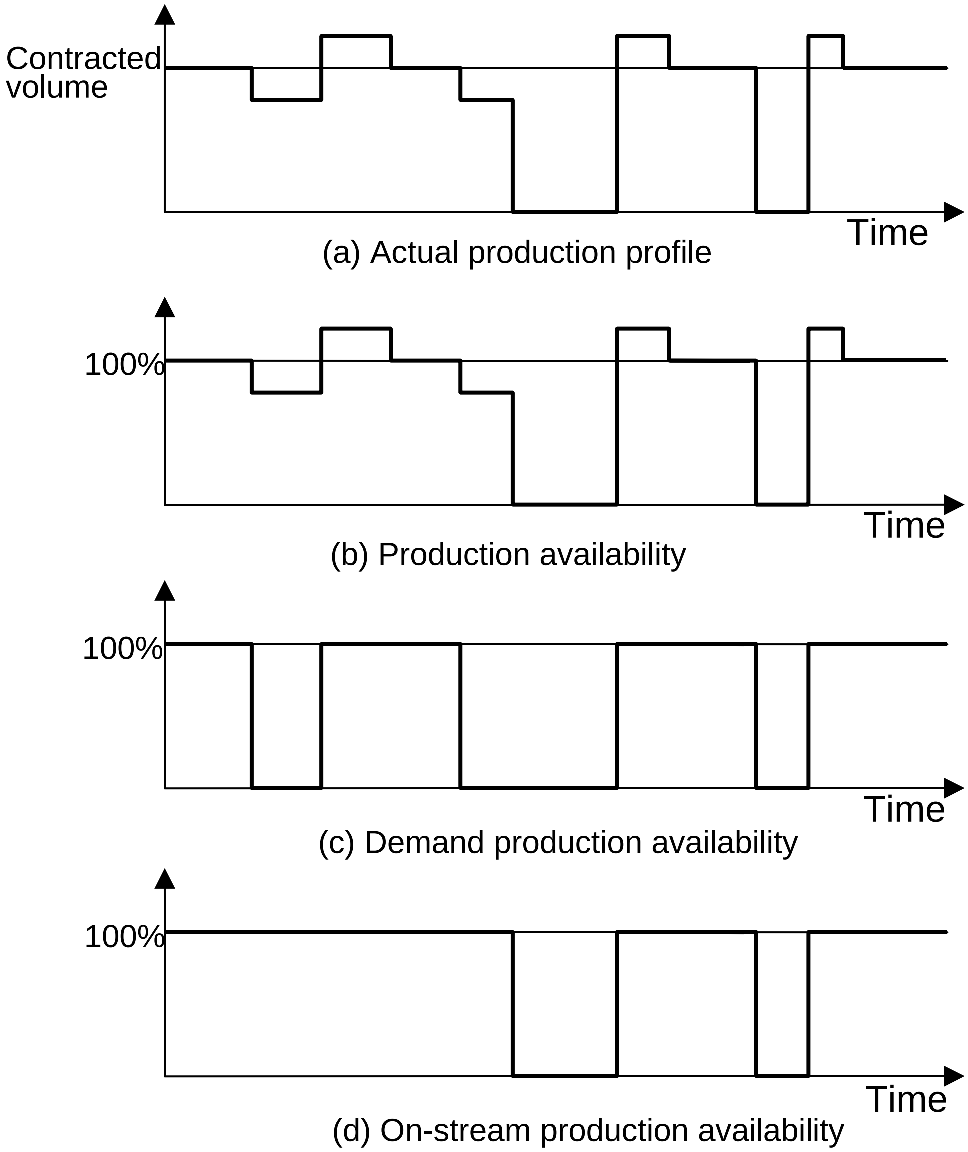

Figure 5-8: Illustration of different "production availability" measures

5.4.5 Risk (hazard, warranty) modeling

The potential risk related to a system is useful information for decision making in system development, if the risk is quantified. To control risk within a certain level during plant operation, references(87-89) point out the importance of management of risk through the plant life cycle, and the importance of safety assessment at purchasing equipment.

An international standard (IEC-60300-3-3) recommends considering liability costs derived from risk analysis executed in the LCC analysis. It is also recommended to include warranty costs in the CBS of the LCC analysis. In a case study (125), the loss cost due to the occurrence of accidental events has been actually incorporated into the LCC analysis. (please refer to the CBS of B8 in APPENDIX B of this report)

Risk is generally quantified by multiplying the magnitude of the "consequences" of accidents by the "frequency" of the accidents.

As for the quantification of the risk of hazardous events, the "consequence" is derived from predicted damage in case that potential hazard scenarios would happen, and the "frequency" is derived from probability of occurrence of the potential hazard scenarios.

Methodologies for risk assessment were originally developed within the nuclear industries, and applied in space, offshore, and chemical process industries(85,86). In oil and chemical process industries, many models for estimation of "consequence" and "frequency" of hazardous events have been reported, and various software tools have been also developed(8,90-92).

As for the quantification of the risk of warranty, the "consequence" is quantified as cost per claim, and "frequency" may be represented by expected times of claim per warranty period(83,84)

5.4.6 Human error modeling

In the actual operation of a process plant, a human error may induce a hazardous event, and the contribution of the human error is not negligible in many cases. Human error has been defined as follows[138]:

"any member of a set of human actions or activities that exceeds some limit of acceptability, i.e., an out-of-tolerance action where the limits of human performance are defined by the system"

Human error may be categorized into the following three types[138].

(1) Omission error

- failing to carry out a required act

(2) Action error

- failing to carry out a required act adequately;
- act performed without required precision, or with too much/little force;
- act performed at the wrong time;
- acts performed in the wrong sequence.

(3) Extraction error

- unrequired act performed instead of or in addition to the required act.

There is a range of techniques to quantify the human error, i.e., so-called Human Reliability Quantification (HRQ). Among these are: THERP (Technique for Human Error Rate Prediction), HEART (Human Error Assessment and Reduction Technique), SLIM (Success Likelihood Index), etc. The pros and cons of HRQ techniques are summarized in reference[138].

5.4.7 Industrial ecology modeling

Growing concern over potential global climate change, loss of bio-diversity, acid precipitation, and the effect of multiple chemicals on ecological systems has highlighted the need for flexible problem-solving approaches. According to the growing concern of ecology, requirements and procedures to reduce impact on the environment due to system operations have been discussed, e.g. the Framework Convention on Climate Change, in the Kyoto Meeting in 1997.

For instance, the clean air act amendments of 1990 issued by the US-Environmental Protection Agency (EPA) introduces a new mechanism to encourage companies to reduce pollutant emissions, the mechanism which is tradable pollution "permits" for sulfur dioxide (SO_2) emissions. According to the introduction of the tradable permits, a company that succeeds to reduce pollutants emission below a permitted amount can sell the right of emission as equal to the margin between the permitted amount and actual amount of their emission. The company accordingly has two options to observe the regulation. One option is to reduce the emission level of the company by himself. The other option is to buy the right of emission from the other companies. We consider that the Clean Air Act Amendment (CAAA) framework may enable us to quantify the impact on the environment due to SO_2 emission as a cost factor in LCC analysis.

US-EPA reported a framework for environmental health risk management in 1997. It proposes a general framework to work in a wide variety of situations. In the framework "ecological risk assessment" is defined as:

"a process used to estimate the likelihood of adverse effects on plants, animals from exposure to stressors, such as chemicals or the draining of wetlands. The process includes problem formation, characterization of exposure, characterization of ecological effects, and risk characterization."

US-EPA has also proposed a guideline for ecological risk assessment, which is prepared to help the ecological risk assessment in practice(9). Methodologies of financial analysis related to environmental issues have also been developed(96).

5.5 Process 4: Data collection

Accuracy of input data is crucial to improve the certainty of the LCC prediction. As for data collection, it is required to identify the requirements of input data and to access reliable data sources related to the LCC analysis.

If actual data are available to quantify cost elements in a CBS, each cost element may be quantified by directly applying the collected actual data to the model of LCC. If actual data are not available, the cost elements relevant to the non-available data may be estimated, e.g. based on expert judgements.

5.5.1 Actual data preparation

A wide variety of data, e.g. reliability data, maintainability data, operation data, cost data, etc., are required in LCC analysis. It is relatively easy to find data sources providing reliability data, however difficult to find data sources for operation data and cost data that are available to the public.

As for reliability data and maintainability data, there are some standards to specify collection of data(11,20). A number of data sources have been developed through a lot of effort to collect data(97,99,100-105,107,127). Procedures for data collection have been developed as well(98). The following data bases of reliability data are available to the public: e.g. OREDA Handbook(Offshore Reliability Data), IEEE Std. 500, MIL-HDBK 217F, NPRD-91, T-Book, WASH-1400, AIChE CCPS guidelines, EIReDA, etc. (49,102,105,107).

Concerning operation data and cost data, most of the data are stored in operating companies' in-house databases. A database is, however, available in the market; a software tool called "ICARUS2000". The software tool has been developed by ICARUS Corporation, (600 Jefferson Plaza Rockville, MD 20852-1150 USA). ICARUS 2000 is a computer-aided design, estimating, and scheduling system. The software is used to evaluate the capital cost of process plants and mills worldwide, and provides a data base containing cost data of plant components based on some particular area, e.g. gulf coast base, Japan base, etc.

5.5.2 Estimation of data

When actual data related to an analyzed system is not available, the value of data may be estimated. To estimate the value of data, in particular cost data, some methods have been proposed such as stochastic models, parametric techniques, and analogous techniques(5).

(1) Stochastic models take into account the random nature of events and rely on specialized statistical techniques.

(2) Parametric techniques are based on statistical analysis of historic data bases. It usually results in a cost estimating or cost factor relationship.

(3) Analogous techniques draw on relationships between current and similar previous data. Expert judgement is used to make adjustments to the previous data to reflect characteristics of the data under consideration.

As for estimation of reliability data, some methodologies have been reported(41,44,48,49,106). For instance, a method based on Bayesian reliability theory, which derives posterior (estimated) information from prior (known) information, may be applicable in prediction of reliability data(41,48,49). A reference(106) proposes a method to predict the failure rate of degraded components.

A reference(37) discusses about the difference between predicted reliability data and actual reliability data of field systems. The main six causes of the differences are identified in the reference, i.e.;

(1) Data accuracy
(2) Prediction of techniques
(3) Environmental factors
(4) Manufacturing processes
(5) Design related factors
(6) Short-term management factors

It is recommended to consider the above six causes when estimating reliability data.

5.6 Process 5: Cost profile development

One of the main objectives of LCC analysis is an affordability analysis considering a long term financial planning. In the affordability analysis, a cost profile over the life cycle is key information. Figure 5-9 illustrates a sample of cost profile. It is consequently an essential process in LCC analysis to draw a cost profile over the entire life cycle or to provide a summary identifying the cost for each cost element in the CBS. It is obviously noticed that the cost profile of each design case should be compared on a common basis or reference point when making financial judgements. It is also recommended to examine an economic analysis when modifying system design or planning investment[112,113,128].

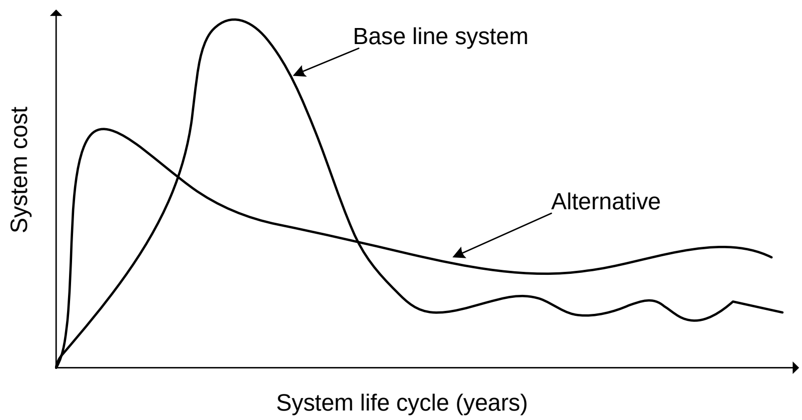

Figure 5-9: A sample of cost profile

5.6.1 Model run

A development of the cost profile is achieved through running cost models developed in a LCC analysis with input data. It may be done by manual calculation, with simple standardized spreadsheets, or with dedicated computer tools. Chapter 7 discusses some computer tools for LCC analysis in the market. Please refer to chapter 7 for further information.

5.6.2 Cost treatment (inflation, tax, and depreciation)

For financial judgement, it is required to consider the effect of inflation, interest rates, and exchange rates, taxation, etc. However, due to the difficulties of accurately predicting inflation and exchange rate, the cost profile may be prepared at “constant prices” basis[1]. It is important to compare alternatives on a common baseline.

To estimate the impact of discounting and escalating, the following common equations (5.5) and (5.6) may be applied[1].

Discounting is a process for taking account of the changing value of money. Since LCC analysis considers costs that will be incurred some time in the future, it is necessary to discount all revenues and expenditures to a specific decision point.

$$NPV = \sum_{n=0}^{T} C_n \cdot (1 + X)^{-n} \tag{5.5}$$

where

NPV	is the net present value of future cash flows;
C_n	is the nominal cash flow in the n-th year;
n	is the specific year in the life cycle costing period;
X	is the discount rate;
T	is the length of the time period under consideration, in years.

Escalating takes account of the change in price levels over time.

$$EF = (1 + E_1) \times (1 + E_2) \times (1 + E_3) \times \cdots \times (1 + E_n) \tag{5.6}$$

where

EF	is the escalation factor in year n;
E_i	is the escalation rate in i-th year.

5.7 Process 6: Evaluation

We need to select the most desirable system configuration among the base line system and the alternatives evaluated in the LCC analysis shown in Fig. 5-2. During the processes of LCC analysis, we need to check if a system (a baseline or a design alternative) meets the criteria defined in the first process of the LCC analysis. If a baseline system does not satisfy the criteria, the baseline system should be modified as an alternative system, and the LCC of the alternative system should be evaluated. Sensitivity analysis is conducted to identify high-cost contributors. This information may reveal cost drivers in the CBS, so that alternative systems may be effectively found according to the result of the sensitivity analysis. During the evaluation process, the uncertainties of the input data should be considered.

5.7.1 Sensitivity analysis

Sensitivity analysis examines the impact of changes in input parameters on the result. Varying the input parameters over a range to see the impact on cost can help highlight the major factors effecting costs, and show the effects of tradeoffs on cost(33).

Many different methods have been developed for sensitivity analysis, which are often tailored to the particular application(119).

In general, there are two main approaches to sensitivity analysis(117). One is a deterministic approach, the other is a stochastic approach.

The deterministic approach computes the partial derivatives of performance indices with respect to fluctuation of parameters. The performance indices may be RAM performance measures, the LCC measure, etc. The parameters may be failure rate, repair rate, cost, etc. The deterministic approach may be applicable only to a simple system with few parameters.

The stochastic approach evaluates probabilistic properties of the performance indices against the possible statistical distributions of the parameters. The stochastic approach may be performed by Monte Carlo (stochastic) simulation. The stochastic approach can handle a complicated system with many parameters.

5.7.2 Uncertainty analysis

Uncertainty analysis is an attempt to consider possible ranges of the estimate and their effect on decisions.

Different sources of uncertainty may be categorized into the following three main groups[(115)].

(1) Parameter uncertainties

(2) Modeling uncertainties

(3) Completeness uncertainties

If the uncertainties in LCC analysis are estimated by uncertainty analysis, the figures provide confidence to decision makers in their judgements.

Methodologies and case studies for uncertainty analysis are found in references[(116,118)].

5.7.3 Cost drivers identification

One of the objectives of LCC analysis is to identify cost drivers, which have major impact on the total LCC, and to find cost effective improvements[(1)] If a cost driver is identified, it is important to establish cause-and-effect relationships, i.e. to identify "causes" of the high cost. For instance the causes may be a frequent failure in a certain equipment, or a high utility consumption in a sub-system. To modify system design according to improvements of cost drivers may effectively reduce the LCC of the system.

5.8 Optimization

Optimization is the process of seeking the best. In LCC analysis, this process is applied to each alternative in accordance with the decision evaluation(30). The optimization may be proceeded through the iterative LCC processes shown in Fig. 5-2. In a broad sense, the optimization process generally means to find a set of parameters that minimizes the LCC of the total system, however, in a narrow sense, the optimization may be applied to specific activities in the LCC processes such as design optimization(120,122,123), maintenance optimization(40,121), spare part optimization(54,110), etc.

We find some methodologies for optimization reported in textbooks and other references. A classical optimization methodology is based on the slope of a function y=f(x), which is defined as the rate of change of the dependent variable, y, divided by the rate of change of the independent variable, x. If a positive change in x results in a positive change in y, the slope is positive. Conversely, a positive change in x resulting in a negative change in y indicates a negative slope(30). The slope of a function guides system designers to change system parameters. The approximation of the slope of function may be obtained with comparing the value of the function at two arbitrary points, or with using partial differentiation.

The so-called "Genetic Algorithms (GA)" method has recently been applied to optimization problems. GA uses the Darwinian principle of natural selection to search for the optimal solution to a problem, and is analogous to biological organisms(122). Typical processes of GA are as follows:

(1) Coding of "gene"
(2) Defining fitness function of the gene
(3) Replication of genes
(4) Reproduction of genes (Crossing-over of genes)
(5) Mutation of genes
(6) Selection of genes
(7) Go to (3) until predefined criteria are fulfilled

A concept of randomness is incorporated into GA through the processes of "reproduction", "mutation", and "selection". The concept of randomness allows GA to find reasonable solutions even if the space of fitness function is non-linear.

5.9 Reporting of LCC analysis

According to the international standard IEC60300-3-3, a documentation of the results is mandatory in LCC analysis. It states that the following six elements should be included in the report:

(1) Executive summary

A brief synopsis of the objectives, results, conclusions and recommendations of analysis. This summary is intended to provide an overview of the analysis to the decision makers, users and other interested parties.

(2) Purpose and scope

A statement of the analysis objective, product description, including a definition of the intended product use environment, operating and support scenarios; assumptions, constrains, and alternative courses of action considered in the analysis.

(3) LCC model description

A summary of the LCC model, including relevant assumptions, a depiction of the LCC breakdown structure, an explanation of the cost elements and the way in which they were estimated, and a description of the way in which cost elements were integrated.

(4) LCC model analysis

A presentation of the LCC model results, including the identification of cost drivers, the results of sensitivity analyses, and the output from any other related analysis activities.

(5) Discussion

A through discussion on and interpretation of the analysis results, including any uncertainties associated with the results, and of any other issues which will assist the decision makers and/or users in understanding and using the results.

(6) Conclusions and recommendations

A presentation of conclusions related to the objectives of the analysis, and a list of recommendations regarding the decisions which are to be based on the analysis results, as well as an identification of any need for further work or revision of the analysis.

6. Codes and Standards

6.1 Four standards of which the title includes the term “LCC”

As discussed in chapter 5, LCC analysis comprises a comprehensive coverage of many analyses, so that many codes and standards are accordingly related to the LCC analysis(32,73). We find four standards of which title includes the term “LCC”; these are: IEC60300-3-3, ISO15663, NORSOK-O-CR001/2, and SAE-ARP4293/4294. This section presents a brief description of each of these standards.

6.1.1 IEC Standards

LCC standards:

IEC-60300-3-3: Life cycle costing [1996-09]

The IEC (International Electrotechnical Commission) is a worldwide organization for standardization. The IEC-60300 series are standards for “dependability management”. IEC 60300-3-3 presents a basic concept and procedure for LCC analysis, e.g. a cost element concept and a general LCC process of six steps. It does , however, not present a detailed LCC procedure. The following six-step approach is recommended in this standard:

Step 1: LCC analysis plan (including problem definition and analysis objective);
Step 2: LCC model development;
Step 3: LCC model analysis;
Step 4: LCC analysis documentation;
Step 5: review of LCC results;
Step 6: LCC analysis update.

6.1.2 ISO Standards

LCC standards:

ISO 15663 Petroleum and natural gas industries – Life cycle costing – [Draft (DIS) as of Dec., 1998]

Part 1: Methodology
Part 2: Guidance on application of the methodology and calculation methods
Part 3: Project implementation guidelines

The ISO (International Organization for Standardization) is a worldwide federation of national standards bodies. The work of preparing international standards is normally carried out through ISO technical committees. ISO collaborates closely with the IEC on all matters of electrotechnical standardization. The ISO 15663 series are standards of “LCC in petroleum and natural gas industries” in particular offshore facility, however ISO 15663 may be applicable to LCC analysis in the other industries. ISO 15663 introduces a framework of methodology of LCC analysis together with a case study, which shows more detailed methods. It is remarkable that guidelines of project implementation of LCC analysis are introduced in the part 3 of this standard. The role of participants in LCC analysis, which are operators, contractors, and vendors, is discussed in the guidelines.

6.1.3 NORSOK Standards

LCC standards:
NORSOK O-CR-001, Life cycle cost for systems and equipment [1996-04]
NORSOK O-CR-002, Life cycle cost for production facility [1996-04]

NORSOK (norsk sokkels konkuranseposisjon or in English the competitive standing of the Norwegian offshore sector) standards are developed by the Norwegian offshore oil and gas industry. O-CR-001 is a LCC standard for systems and equipment in general, and O-CR-002 is a LCC standard for oil production facilities. Both standards define all cost elements to be analyzed and provide spreadsheets to calculate the cost elements for LCC estimation. In this sense, this standard is the most practical of the four LCC standards.

[NOTE]
After the issue of the ISO 15663 (to be the end of 1999), the NORSOK O-CR-001/002 will be replaced with the ISO 15663.

6.1.4 SAE Standards

LCC standards:
SAE-ARP4293: Life cycle cost- techniques and applications [1992-02]
SAE-ARP4294: Data Formats and Practices for the LCC of Aircraft Propulsion Systems.

SAE is an American national standard. SAE-ARP is the abbreviation of The Society of Automotive Engineers Aerospace Recommended Practice.

SAE-ARP4293 describes the concept of life cycle costing with emphasis on cost analysis and applications as applied to the phases of the program cycle. Cost elements, estimating techniques and other factors that have a bearing on LCC are described; including use of cost estimating relationships (CER), simulation techniques, and top-down/bottom-up approaches. SAE-ARP4294 is directed at LCC analysis of aerospace propulsion systems.

6.2 Codes and standards related to LCC analysis

Not only the four standards mentioned above, but also many other standards are related to LCC analysis. We have surveyed 24 codes and standards related to LCC analysis, including the four LCC standards. A relationship among LCC activities illustrated in Fig. 5-2 and the related standards is summarized in Table 6-1. If a standard describes a content relevant to an LCC activity, we check with a cross (X) the corresponding box in Table 6-1. Some standards still in draft version are, also included in Table 6-1. The first five (Number 1 through 5) standards in Table 6-1 are standards dedicated to LCC analysis, the other 19 (Number 6 through 24) standards are standards for specific LCC activities.

Table 6-1: LCC sub-activities and related codes & standards (Standards in Table 6-1 are identified in the following page)

Processes	Activities	LCC Standards					Specific Standards																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1. Problems Definition	1.1 Scope definition	x	x	x		x																	x		
	1.2 Evaluation criteria definition(affordability, system effectiveness, acceptable risk level)		x												x					x		x	x		
	1.3 Operation philosophy development															x								x	
2. Cost Elements Definition	2.1 Cost break down structure development	x	x			x																			
	2.2 Cost categories definition	x	x	x	x	x																			
3. System Modeling	3.1 Availability modeling		x	x	x			x			x						x	x	x	x			x		
	3.2 Maintenance and inspection modeling		x	x	x		x							x	x	x							x	x	
	3.3 Logistics modeling																								x
	3.4 Production regularity modeling		x		x																		x		
	3.5 Risk(hazard, warranty) modeling								x				x							x		x	x		
	3.6 Industrial ecology modeling									x													x		
4. Data Collection	4.1 Actual data preparation		x		x							x									x		x		
	4.2 Estimation of data	x	x		x	x																			
5. Cost Profile Development	5.1 Model run(Any tools provided?)			x	x																				
	5.2 Cost treatment(inflation, tax, and depreciation)	x	x	x	x	x																			
6. Evaluation	6.1 Sensitivity analysis		x																				x		
	6.2 Uncertainty analysis	x	x	x	x	x																	x		
	6.3 Cost drivers identification	x	x			x																	x		

Note(*) of Table 6-1

- <u>LCC standards:</u>

1 IEC60300-3-3: Life cycle costing[1]

2 ISO15663(Draft):Petroleum and natural gas industries -Life cycle costing-[2]

3 NORSOK O-CR-001: Life cycle cost for systems and equipment[3]

4 NORSOK O-CR-002: Life cycle cost for production facility[4]

Note: NORSOK O-CR-001 and 002 will be replaced with ISO 15663 after the ISO being effective.

5 SAE ARP-4293: Life cycle cost - Techniques and applications[5]

- <u>Specific standards:</u>

6 API RP 580/581: Risk based inspection[6]

7 BS5760: Part2: Guide to the assessment of reliability[7]

8 EPA 40CFR68: Chemical accident prevention provisions[8]

9 EPA/630/R-95/002B (Draft): Proposed Guidelines for Ecological Risk Assessment[9]

10 IEC60300-3-1: Analysis techniques for dependability: Guide on methodology[10]

11 IEC60300-3-2: Collection of dependability data from the field[11]

12 IEC60300-3-9: Risk analysis of technological systems[12]

13 IEC60300-3-11 (Draft): Reliability centered management[13]

14 IEC60706-1: Guide on Maintainability of Equipment: Introduction, requirements and maintainability programme[14]

15 IEC60706-4: Guide on Maintainability of Equipment: Maintenance and Maintenance Support Planning[15]

16 IEC61025: Fault tree analysis (FTA) [16]

17 IEC61078: Analysis techniques for dependability - Reliability block diagram method[17]

18 IEC61165: Application on Markov techniques[18]

19 IEC61508: Functional safety of electrical/electronic/programmable electronic safety-related systems[19]

20 ISO14224 (Draft): Collection and exchange of reliability and maintenance data for equipment[20]

21 NORSOK Z-013: Risk and emergency preparedness analysis[21]

22 NORSOK Z-016: Regularity management & reliability technology[22]

23 NORSOK Z-CR-008: Criticality classification method[23]

24 MIL-STD-1388-1A: Logistic support analysis[24]

7. Software Tools of LCC analysis

The purpose of this chapter is to present introductory information of software packages for LCC analysis on the market; including a brief description, contact points, and basic functionality. It is NOT the purpose to select the best LCC tool on the market. The most appropriate tool will depend on the specific system and the objectives of the LCC analysis. No commercial information (license fee, etc.) is reported. All information in this chapter is based on publications of software packages (leaflets, user manuals), correspondences with the developers, and interviews to them in February or March of 1999.

7.1 Classification of software package for LCC analysis

There are two main categories for software packages for LCC analysis; "Effectiveness analysis tools (RAM analysis tools)", and "Cost analysis tools".

Effective analysis tools (RAM analysis tools) are utilized to model a plant system and to predict the system performance, e.g., availability, maintainability, etc. The predicted values are crucial input data to estimation of cost elements in the LCC analysis. For instance, the frequency of maintenance significantly affects the maintenance cost, and the period that the production rate does not meet the contracted value determines the cost of deferred production. Software packages for RAM analysis may be further categorized into two types; "Simulation tools" and "Analysis tools".

The simulation approach may be categorized as "numerical-stochastic modeling", which is also called Monte Carlo simulation[108,109]. The analytical approach may be categorized as "numerical-deterministic modeling"[108].

Cost analysis tools are mainly utilized to calculate LCC based on a predefined cost breakdown structure, e.g., the equipment cost, the maintenance cost, the cost of deferred production, etc. Cost analysis tools sum up the cost elements, estimate the impact of inflation, develop the cost profile, and calculate NPV, etc.

Figure 7-1 illustrates the classification of software tools for LCC analysis. In this chapter five software tools for RAM analysis, MIRIAM, MAROS, AvSim+, UNIRAM, and WinRAMA, and two software tools for cost analysis, LCCWare, and Relex LCC, are introduced (please refer to Fig. 7-1).

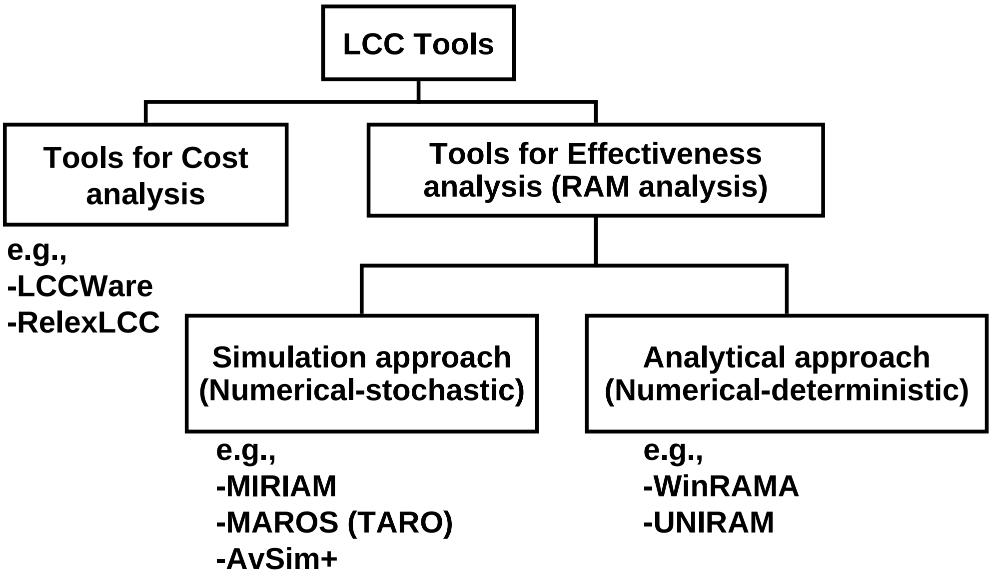

Figure 7-1: A classification of tools for LCC analysis

Tools based on the simulation approach predict system reliability at each operating time elapsing /events based on failure rates of each component in the system, and simulate system state at each time/events. Figure 7-2 illustrates a typical flowchart of the simulation method. The "event list" in Fig. 7-2 records all events that occur in the system in chronological order. The events may be a component failure, maintenance on the component, logistics required for the maintenance. The time at which an event occurs or the duration of the event is determined by generating a random number, which is substituted for a cumulative distribution function of the time of the event. Figure 7-3 illustrates a method to determine the time of occurrence of the event (t_e). We assume a single component of which time to failure (T) is distributed with a probability density function f(t) . The cumulative distribution function F(t) is derived from Eq. (7.1)

$$F(t) = \int_0^t f(u)du \tag{7.1}$$

A random number ($0 \leqq v \leqq 1$) is generated, the time to failure of the component is derived from $F^{-1}(v)$ as shown in Fig. 7-3.

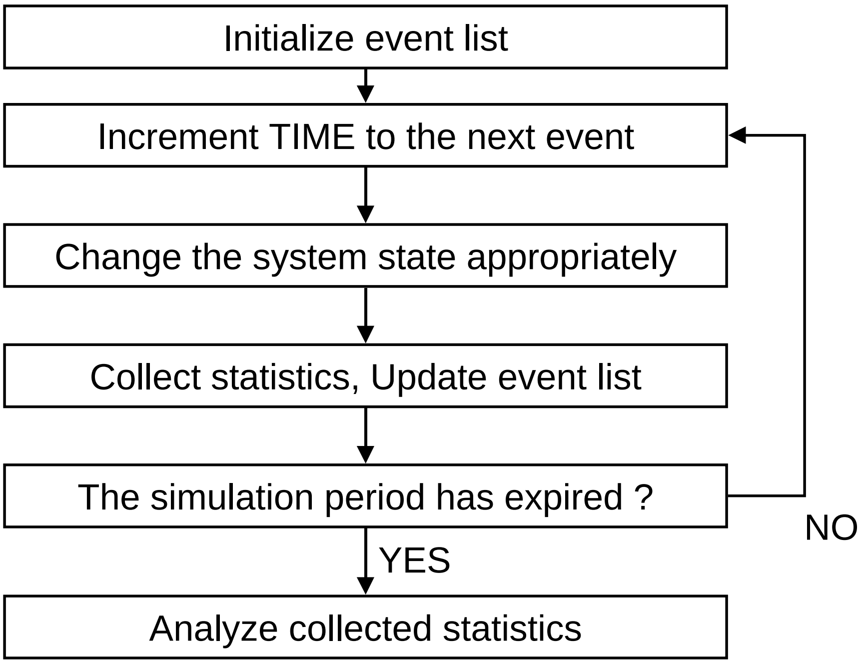

Figure 7-2: A typical flowchart of RAM analysis with simulation approach

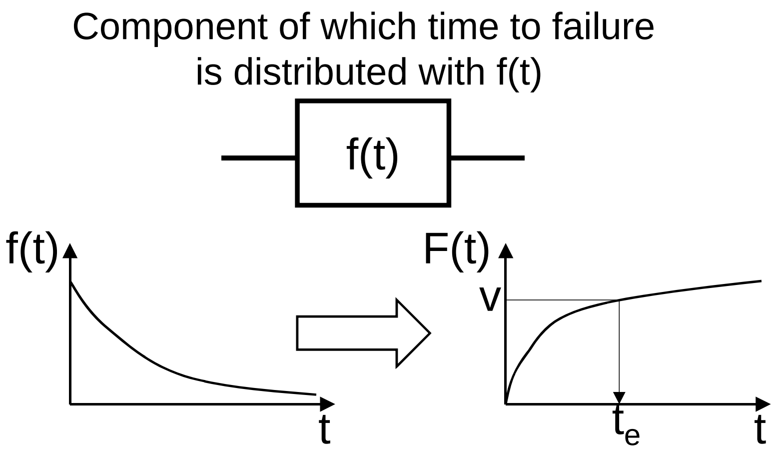

Figure 7-3: The determination of the time to occurrence of an event

Simulation tools are very flexible and capable of modeling a variety of parameters. Some simulation tools can model the maintenance time according to skill level of crews, or the logistics delay according to weather conditions. Simulation tools therefore can provide highly accurate prediction in system performance. Much effort (time and cost) is, however, required for making models and executions of LCC model.

Tools based on the analytical approach calculate system reliability by using some pre-defined formulas. For instance, if we assume that MTTF and MTTR of a component are quantified, the limiting availability of the component may be approximated with Eq. (7.2).

$$Limiting\ availability = \frac{MTTF}{MTTF + MTTR} \tag{7.2}$$

In general, analytical tools output more rough prediction of system performance than simulation tools, because modeling capability of analytical tools is not so flexible. However, less effort is required for the analysis. It means more parametric studies can be carried out within a short period.

According to the above discussion, Table 7-1 summarizes the pros and cons of simulation tools and analysis tools.

Table 7-1: Comparison between simulation and analysis

	Advantages	Disadvantages
Simulation	•High precision in predictions •High flexibility in modeling, e.g. easy to model a complicated maintenance strategy, etc.	•Long calculation time •Much effort for making a model and data preparation is required •Difficult to verify the model
Analysis	•Short calculation time •Less effort for making a model and data preparation , which allows more parametric studies within a period	•Low precision in predictions •Low flexibility in modeling, e.g. difficult to model a complicated maintenance strategy, etc.

7.2 Description of software packages for RAM analysis

This section introduces basic information of five software packages for RAM analysis, i.e. MIRIAM, MAROS (TARO), AvSim+, UNIRAM, and WinRAMA. All software packages run under the operating system "Microsoft Windows".

(1) MIRIAM

MIRIAM is a simulation tool developed by EDS in close cooperation with the Norwegian oil company Statoil for evaluating the operational performance of continuous process plants in terms of equipment availability, production capability and maintenance resource requirements. The program is licensed by EDS, and marketed by EDS and DNV. The program models the stochastic behavior of a system over its lifetime. It has been developed aiming at modeling operations of offshore facilities. It can, however, be applied to model systems in the other industries due to its flexibility in modeling.

Contact points:

a) <u>Electronic Data Systems Corporation (EDS)</u>
   Wavendon Tower, Wavendon, Milton Keynes, MK17 8LX, UK
   Tel: +44 (0)1908 284247
   Fax: +44 (0)1908 282219
   URL: http://www.eds.co.uk/

b) <u>Det Norske Veritas AS (DNV)</u>,
   Veritasveien 1, N-1322 Hoevik, Norway
   Tel: +47 67 57 72 50
   Fax: +47 67 57 74 74
   URL: http://www.dnv.com/

(2) MAROS (TARO)

MAROS is a simulation tool developed by Jardine & Associates Ltd. to model real-world systems – helping to maximize economic return by providing a greater level of accuracy and confidence throughout the decision making process. It predicts system effectiveness in terms of reliability, availability and productivity. MAROS is capable to handle cost data as well as system effectiveness data. It can be used to quantify the life cycle cost (LCC) of a system and allows optimization to improve overall profitability.

TARO, the acronym of Total Asset Review and Optimization, is a more advanced simulation tool than MAROS. It contains all the functionality of MAROS but enables substantially greater complexity in two key areas
a) Multi-product or multi-stream flow
b) Detailed maintenance analysis down to the skill make-up of repair crews. Also enables more detailed OPEX (Operating expenditure) profiles to be developed.

Contact point:
Jardine & Associates
Suite G, The Copperfields, 25 Copperfield street, London SE1 0EN, UK
Tel: +44 (0)171 928 6788
Fax: +44 (0)171 928 6799
URL: http://www.jardine.co.uk/

(3) AvSim+
AvSim+ is a simulation tool developed by Isograph Ltd, and sold by Item Software Inc. to calculate availability, reliability and maintainability. It uses Monte Carlo simulation techniques to predict component and system performance. The logic showing system failures can be represented either by Reliability Block Diagram (RBD) or by Fault Trees.

Contact points:
a) Item Software (UK) Limited (the dealer)
1 Manor Court, Barnes Wallis Road, Segensworth East, Fareham, Hampshire, England PO15 5TH, UK
Tel: +44 (0)1489 885085
Fax: +44 (0)1489 885065
URL: http://www.itemuk.mcmail.com/
b) Isograph Ltd (the developer)
Television House 10, Mount Street, Manchester M2 5WT, UK
Tel: +44 (0)161 835 2902
Fax: +44(0)161 839 2462
URL: http://www.isograph.co.uk/ (Under construction as of 21 of June, 1999)

(4) UNIRAM

UNIRAM is an analytical tool developed by the Electric Power Research Institute (EPRI) to model a power generation plant's configuration and operational characteristics. UNIRAM is maintained and licensed by Availability Systems, Inc. (ASI), whose personnel were the original developers of UNIRAM for EPRI. The model is deterministic and computes the expected RAM parameters of a plant and its subsystems as well as the probability and expected duration of operation in each possible plant state capacity level. UNIRAM also includes many execution options for further analyses; e.g., component criticality rankings, subsystems sensitivity analyses, R&M data uncertainty effects. Three types of plant operation are evaluated: Continuous (Baseload); Periodic (Cycling); and Random (Peaking). The software has been used throughout the world in a wide variety of applications including: all types of power generation plants; chemical and petrochemical plants; transportation systems; and weapon systems(110,111).

Contact point:

Availability Systems, Inc. (ASI)
409 Berkshire Drive Riva, Maryland 21140, USA
Tel and Fax: +1 410 956 0189
e-mail: DrJHW@aol.com

(5) WinRAMA

WinRAMA is an analytical tool developed by DNV Industry AS. It is developed to analyze reliability and availability problems using the Reliability Block Diagram (RBD) method. It includes the ability to handle flow calculations, and the program calculates the results analytically. It calculates the system availability, together with the fraction of time the system and blocks have at different capacity levels.

Contact point:

Det Norske Veritas AS (DNV),
Veritasveien 1, N-1322 Hoevik, Norway
Tel: +47 67 57 99 00
Fax: +47 67 57 99 11
URL: http://www.dnv.com/

7.3 Functionality of the software packages for RAM analysis

This section shows the functionality of the five software packages for RAM analysis. The survey of functionality of the tools is carried out by interviews of the originators of the software and by reviewing user manuals of the software. Most information in this section is qualitative, not quantitative.

We develop a set of items to be checked from a viewpoint of requirements of RAM analysis found in actual RAM analysis based on our experience. It should be noted that the selected items for functionality check represent neither necessary nor sufficient functions of software tools for RAM analysis.

Four main categories are defined for the functionality check, which are “Input data”, “Capability of modeling”, “Options”, and “Output data”. The four categories are further broken down into the items as follows:

1. Input data

- *1.1 Failure data*: Acceptable types of failure data of a component level.
- *1.2 Maintenance data*: What kinds of maintenance can be considered.
- *1.3 Component throughput capacity*: Acceptable types of throughput capacity data of a unit level.
- *1.4 Demand of production*: Acceptable types of demand of production of a total plant level.

2. Capability of modeling

- *2.1 System redundancy*: Acceptable configurations for system redundancy?
- *2.2 Temporary bypass*: Temporary bypass piping can be modeled?
- *2.3 Aging, degradation of components*: Aging effects can be modeled?
- *2.4 Surge tanks, Storage efficiency*: The effect of surge tanks can be modeled?
- *2.5 Periodical inspection for hidden failures*: Effect of periodical inspection can be considered in the availability calculation for hidden failures?
- *2.6 CCF, e.g. Utility failure or Spurious shutdown*: Down time due to common cause failure for a plant system, e.g. electric power failure, cooling water failure, or spurious trips of emergency shutdown system, etc., can be modeled?
- *2.7 Delay time*: Delay time due to logistics or administration can be affected in down time of system depending on the states of the system, e.g. spare stocks, weather conditions, etc.

3. Options

- *3.1 Criticality analysis*: Measures showing components importance are calculated?
- *3.2 Uncertainty analysis*: Uncertainty in data, e.g. time to failure, time for maintenance, can be analyzed?
- *3.3 Cost analysis*: Cost information is provided as a result of RAM analysis?

4. Output data

- *4.1 System availability or production regularity*: System availability is calculated?
- *4.2 Mean downtime*: Mean down time, which is not fractional dead time, is calculated?
- *4.3 Utility consumption*: Utility consumption is quantified?
- *4.4 Maintenance resource expenditure*: Expected resource required for maintenance is quantified?
- *4.5 Spares and stock-outs*: The number of spares spent or spares stocked in a warehouse are counted?
- *4.6 Lifetime system cost*: Cost information, e.g. LCC, is generated as an output data?

Table 7-2 shows a summary of functionality of the surveyed five software packages. A cross "x" is marked if a software package satisfies the functionality specified by each item. A mark of "( )" denotes that the item is satisfied with restrictions.

APPENDIX C shows five individual tables as a supplement of Table 7-2. One table is dedicated to one software package. Each table shows comments on the functionality of the tool, which is made by the software originators or the authors.

Table 7-2: Summary of functionality of the software packages for RAM analysis

			RAM Tools				
			MIRIAM	MAROS	AvSim+	UNIRAM	WinRAMA
Type	Analytical or Simulation?		Simulation	Simulation	Simulation	Analytical	Analytical
Method			Monte Carlo (Events based)	Monte Carlo (Events based)	Monte Carlo (Events based)	Availability Block Diagram and FTA	Flow network and RBD
Input data	Failure data	Constant	x	x	x	x	x
		Variable in time, or in operation modes	x	x	x	(x)	
	Maintenance data	Corrective	x	x	x	x	x
		Preventive	x	x	x	x	
	Component throughput capacity	Constant	x	x		x	x
		Variable in operation modes	x	x			
	Demand of production	Constant	x	x		x	(x)
		Seasonal variation	x	x		x	
Capability of modeling	System redundancy	Active pararell	x	x	x	x	x
		Standby operation	x	x	x	x	
	Temporary bypass		x	x	x	x	
	Aging, degradation of components		x	x	x	x	
	Surge tanks, Storage efficiency		x	x	x	x	(x)
	Periodical inspection for hidden failures		(x)	(x)	x		x
	CCF,e.g.Utility failure or Spurious shutdown		x	x	x	(x)	(x)
	Delay time	due to logistics, administration, etc.	x	x	x	(x)	(x)
Options	Criticality analysis		x	x		x	x
	Uncertainty analysis		x	x	x	x	
	Cost analysis	Flexibility in cost elements definition		x	(x)		
		Cost treatment (NPV etc.)		x			
Output data	System availability or production regularity		x	x	x	x	x
	Mean downtime		x	x	x	x	
	Utility consumption		x	x			
	Maintenance resource expenditure		x	x	x		
	Spares and stockouts		x	x	x		
	Life time system cost			x	x	(x)	

Note: ( ) represents with restrictions

7.4 Introduction of cost analysis tools

Two software packages for cost analysis; LCCWare and Relex LCC are briefly described.

(1) LCCWare

LCCWare is developed by Item Software Inc. to establish a life cycle costing model. The cost elements are represented in the form of a tree structure that is created interactively. The objects at the bottom level of the tree represent cost functions that can comprise both local and global variables and constants. Libraries of frequently used cost functions allow rapid development of the model.

Contact point:

Refer to Item Software Inc. and Isograph in section 7.2 (3) on page 47

(2) Relex LCC

Relex LCC is developed by Relex Software Corporation, to calculate the cost of a product over its lifetime. It is capable of handling user-defined Cost Breakdown Structure (CBS), Net Present Value (NPV) calculation, inflation factor, calculations of over multiple time interval, sensitivity analysis, etc.

Contact point:

Relex Software Corporation
540 Pellis Road
Greensburg, PA 15601 USA
Tel: +1-724 836 8800
Fax: +1-724 836 8844
URL: http://www.relexsoftware.com/

8. Concluding remarks

This report presents brief history and a state-of-the-art survey of LCC analysis based on a detailed literature survey, internet-web browsing, and interviews with experts.

We find a root of LCC analysis in the military area in the end of the 1960s, e.g., some programs of the US-DOD. The application areas of LCC analysis have been spread to other industries since the middle of the 1980s, e.g., electrical power industries, oil and chemical industries, railway industries, etc.

It is difficult to find a specific procedure applicable to any LCC analysis. LCC analysis is a collective study comprising many kinds of analysis, and the coverage of LCC analysis significantly depends on the system to be modeled. We have, however, defined six steps, which may be common for most LCC analyses. They are, "Problems definition", "Cost elements definition", "System modeling", "Data collection", "Cost profile development", and "Evaluation". These six basic processes are initially carried out to a baseline system configuration, and may be iteratively carried out until a most desirable alternative is found.

We break down the six basic processes into sub-activities to be encompassed in LCC analysis, in particular LCC analysis in oil and chemical industries. The sub-activities are illustrated in Fig. 5-2. We present a brief explanation for each sub-activity in this report.

The numbers of codes and standards related to LCC analysis is considerable reflecting the wide coverage of LCC analysis. We present four main standards closely relevant to LCC analysis, which are "IEC60300-3-3", "ISO15633", "NORSOK O-CR-001/002", and "SAE-ARP 4293". We briefly review the other standards relevant to LCC analysis as well, and summarize the relations among standards and the sub-activities in LCC analysis as shown in Table 6-1.

Some software tools for LCC analysis are introduced. The objective of the introduction of the LCC tools is to provide brief information just for reference, not to find the best software tool, because we consider that the most appropriate tool depends on the specific system and the objectives of the LCC analysis. Software tools for LCC analysis are categorized as "Effectiveness analysis tools (RAM analysis tools)" and "Cost analysis tools" as shown in Fig. 7-1. RAM analysis tools are further categorized into two types, simulation tools and analysis tools, and their pros and cons are discussed. Five RAM tools are introduced, and the functionality of the five software tools are summarized.

One of the main objectives of LCC analysis is to provide useful information for decision making, e.g., in purchasing a product, in optimizing design, in scheduling maintenance, or in planning revamping. According to the increasing complexity of systems, we have to consider about various consequences incurred from a system from wide aspects and in long perspective. We believe that the importance of LCC analysis as a tool for the decision making will increase in the future.

Acknowledgements

I wish to express my special thanks to everyone who provided me useful information through interviews and who responded to my questionnaire. The financial support received from SINTEF Department of Safety and Reliability and Japan Cooperation Center Petroleum (JCCP) are gratefully acknowledged.

APPENDIX A: References on LCC analysis

This appendix contains references reviewed during the literature survey to prepare this report. The references include papers, reports, codes and standards, and books which deal with one or more issues of relevance to an activities in LCC illustrated in Fig. 5-2.

The references are classified in the following categories, and references are listed without any particular order in each category. References are serially numbered throughout the categories, and the serial numbers are referred in the main body of this report.

Categories for classification of references

1. Codes & Standards
2. General
3. System Modeling
   3.1 Reliability
   3.2 Availability
   3.3 Maintainability
   3.4 Dependability
   3.5 Sparing
   3.6 Supportability
   3.7 Risk
   3.8 Software
   3.9 Environment
4. Data
5. Model Run
   5.1 RAM analysis
   5.2 Cost analysis
6. Evaluation
7. Optimization
8. Applications

1. Codes & Standards

[1] IEC60300-3-3: *Life cycle costing*

[2] ISO15663 (Draft): *Petroleum and natural gas industries -Life cycle costing-*

[3] NORSOK O-CR-001: *Life cycle cost for systems and equipment*

[4] NORSOK O-CR-002: *Life cycle cost for production facility*

[5] SAE ARP-4293: *Life cycle cost - Techniques and applications*

[6] API RP 580/581: *Risk based inspection*

[7] BS5760:Part2: *Guide to the assessment of reliability*

[8] EPA 40CFR68: *Chemical accident prevention provisions*

[9] EPA/630/R-95/002B(Draft): *Proposed Guidelines for Ecological Risk Assessment*

[10] IEC60300-3-1: *Analysis techniques for dependability: Guide on methodology*

[11] IEC60300-3-2: *Collection of dependability data from the field*

[12] IEC60300-3-9: *Risk analysis of technological systems*

[13] IEC60300-3-11(Draft): *Reliability centered management*

[14] IEC60706-1: *Guide on Maintainability of Equipment: Introduction, requirements and maintainability programme*

[15] IEC60706-4: *Guide on Maintainability of Equipment: Maintenance and Maintenance Support Planning*

[16] IEC61025: *Fault tree analysis(FTA)*

[17] IEC61078: *Analysis techniques for dependability - Reliability block diagram method*

[18] IEC61165: *Application on Markov techniques*

[19] IEC61508: *Functional safety of electrical/electronic/programmable electronic safety-related systems*

[20] ISO14224 (Draft): *Collection and exchange of reliability and maintenance data for equipment*

[21] NORSOK Z-013: *Risk and emergency preparedness analysis*

[22] NORSOK Z-016: *Regularity management & reliability technology*

[23] NORSOK Z-CR-008: *Criticality classification method*

[24] MIL-STD-1388-1A: *Logistic Support Analysis*

[25] IEC60050(191): *International Electrotechnical Vocabulary*

2. General

[26] Fabrycky,W.J and Blanchard,B.S: *Life-cycle cost and economic analysis*, Prentice Hall International Series in Industrial and Systems Engineering, (1991)

[27] Garin,T.A.: *A Preferred Spare Decision Support System Incorporating a Life Cycle Cost Model*, Thesis of M.S, Faculty of the School of Engineering of the Air Force Institute of Technology, Air University, (1991)

[28] Carrubba,E.R.,et al: *Integrating Life-Cycle Cost and Cost-of-Ownership in the Commercial Sector*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1992, pp. 101-108, (1992)

[29] Greene,L.E. and Shaw,B.L.: *The Steps for Successful Life Cycle Cost Analysis*, CH2881-1/90/0000-1209,IEEE, pp. 1209-1216, (1990)

[30] Blanchard,B.S. and Fabrycky,W.J.: *Systems Engineering and Analysis 3rd Edition*, Prentice Hall International Series in Industrial and Systems Engineering, (1998)

[31] Kenna,T. M. and Oliverson,R.: *Glossary of Reliability and Maintenance Terms*, Gulf Publishing Company, (1997)

[32] Miller,J.A., Moss,J., et al.: *Dependability Standards: An International Cooperation*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1998, pp. 26-29, (1998)

[33] Clarke,J.D.: *Life Cycle Cost: An examination of its application in the united states, and potential for use in the Australian defense forces*, Thesis of M.S, Naval Postgraduate School, (1990)

3. System Modeling

3.1 Reliability

[34] Aaroe,R., et al: *Reliability prediction handbook, computer-based process safety systems*, SINTEF Safety and Reliability, (1989)

[35] Bodsberg. L., et al: *Reliability quanitification of control and safety systems. The PDS-II method*, SINTEF Safety and Reliability, (1994)

[36] Hokstad,P., et al: *Guidelines for design of control and safety systems*, SINTEF Safety and Reliability, (1994)

[37] Miller,P.E. and Moore,R.I.: *Field Reliability Versus Predicted Reliability: An Analysis of Root Causes for the Difference*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1991, pp. 405-410, (1991)

[38] Vega,F.F. de la, et al: *Plant Reliability Analysis in LNG Plants*, Proceedings of 11th International Conference on LNG, paper#2.11, (1995)

[39] Dougan,K.W. and Reilly,M.C.: *Quantitative reliability methods improve plant uptime*, Hydrocarbon processing, Aug. '93, pp. 131-141, (1993)

[40] Susova,G.M. and Petrov,A.N.: *Markov Model-Based Reliability and Safety Evaluation for Aircraft Maintenance-System Optimization*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1997, pp. 29-36, (1997)

[41] Denson,W.K. and Keene,S.: *A New Reliability Prediction Tool*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1998, pp. 15-22, (1998)

[42] Karydas,D.M. and Houtermans,M.J.M.: *A Practical Approach For The Selection Of Programmable Electronic Systems Used For Safety Functions In The Process Industry*, Proceedings of 9th Int'l Symposium on Loss Prevention and Safety Promotion in the Process Industries, pp. 925-934, (1998)

[43] Beckman,L.V.: *Match Redundant System Architectures with Safety Requirements*, Chemical Engineering Progress, Dec.'95, pp. 54-61, (1995)

[44] Chan,C.K., Saraidaridis,C.I., et al.: *Sequential Sampling Plans for Early-Life Reliability Assessment*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1997, pp. 131-135, (1997)

[45] Gera,A.E.: *The Modified Exponentiated-Weibull Distribution for Life-Time Modeling*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1997, pp. 149-152, (1997)

[46] Doerre,P.: *Stochastic Reliability Analysis- Its Application to Complex Redundancy Systems*, Proceedings of the 6th EuReDatA Conference 1989, pp. 155-166, (1989)

[47] Kolowrocki,K. and Kurowicka,D.: *Domains of attraction of limit reliability functions*, Proceedings of ESREL'98(ISBN 90 5410 966 1), pp. 673-679, (1998)

[48] Grabski,F.: *Some methods of Bayesian nonparametric estimation in reliability*, Proceedings of ESREL'98(ISBN 90 5410 966 1), pp. 641-646, (1998)

[49] Hoeyland,A. and Rausand,M.: *System Reliability Theory - Models and Statistical Methods*, John Wiley & Sons, Inc., (1994)

[50] Hokstad,P. and Froevig, A.T.: *The modeling of degraded and critical failures for components with dormant failures*, Reliability Engineering and System Safety, No. 51, pp. 189-199, (1996)

[51] Haugen, K., Hokstad,P. and Sandtorv,H.: *The analysis of failure data in the presence of critical and degraded failures*, Reliability Engineering and System Safety, No. 58, pp. 97-107, (1997)

[52] O'connor, P.D.T.: *Practical Reliability Engineering 2nd edition*, John Wiley & Sons,

Inc., (1985)

[53] Lewis,E.E.: *Introduction to reliability engineering 2nd edition*, John Wiley & Sons, Inc., (1994)

3.2 Availability

[54] Fabbro,R.M.: *Availability: A Low-Density Deployment Case Study*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1979, pp. 247-253, (1979)

[55] Hurst,D.J.: *Operational Availability Modeling for Risk and Impact Analysis*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1995, pp. 391-396, (1995)

[56] Signoret,J.P.: *Availability of petroleum installation by using Markov processes and Petri net modeling*, Risk and Reliability in Marine Technology edited by C. Guedes Soares, published by A.A.Balkema, pp. 455-472, (1998)

[57] Mitchell,B.F. and Murry,R.J.: *Predicting Operational Availability for Systems with Redundant, Repairable Components and Multiple Sparing Levels*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1996, pp. 301-305, (1996)

[58] Bouissou,M. and Bourgade,E.: *Unavailability Evaluation and Allocation at the Design Stage for Electric Power Plants: Methods and Tools*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1997, pp. 91-99, (1997)

[59] Platis,A.N., Limnios,N.E., et al.: *Asymptotic Availability of Systems Modeled by Cyclic Non-Homogeneous Markov Chains*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1997, pp. 293-297, (1997)

[60] Lindqvist,B.H. and Amundrustad,H.: *Markov models for periodically tested components*, Proceedings of ESREL'98(ISBN 90 5410 966 1), pp. 191-197, (1998)

3.3 Maintainability

[61] Vatn,J.: *Strategic maintenance planning in railway systems(RESMAP)*, SINTEF Safety and Reliability, (1998)

[62] Hale,A.R.: *Evaluating safety in the management of maintenance activities in the chemical process industry*, Safety Science (Elsevier Science), vol. 28, No. 1, pp.21-44, (1998)

[63] Daugherty,G.L.: *Two-level Maintenance: How do you get there*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1991, pp. 397-399, (1991)

[64] Henderson,J.T.: *A Computerized LCC/ORLA Methodology*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1979, pp. 51-55, (1979)

[65] Hollick,L.J. and Nelson,G.N.: *Realizing Scheduled-Maintenance Requirements Using Reliability Centered Maintenance - A Canadian Air Force Perspective*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1995, pp. 11-15, (1995)

[66] Blanchard,B.S. , et al.: *Maintainability*, John Wiley & Sons, Inc., (1995)

[67] Jambulingam,N. and Jardine,A.K.S.: *Life Cycle Costing Considerations in Reliability Centered Maintenance: An Application to Maritime Equipment*, Reliability Engineering, published by Elsevier Applied Science Publishers Ltd., pp. 307-317, (1986)

[68] Jones, R.B.: *Risk-Based Management- A Reliability -Centered Approach*, Gulf Publishing Company, (1995)

[69] Rausand, M.: *Reliability centered maintenance*, Reliability Engineering and System Safety, 60, pp. 121-132, (1998)

[70] Moubray, J.: *Reliability-centered Maintenance, 2nd edition*, Industrial Press Inc., (1997)

[71] Anderson,R.T. and Neri,L.: *Reliability-Centered Maintenance: Management and engineering methods*, Elsevier Applied Science, (1990)

3.4 Dependability

[72] Hansen,G.K.: *Dependability of distributed computer control systems*, Cand. scientist. Thesis, The Norwegian University of Technology and Science, (1997)

[73] Benski,C.: *Dependability Standards: An International Perspective*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1996, pp. 258-262, (1996)

[74] Csenki,A.: *Reliability and dependability measures for systems modelled by Markov and semi-Markov processes-A review*, Proceedings of ESREL'98(ISBN 90 5410 966 1), pp. 581-586, (1998)

3.5 Sparing

[75] Myrick,Al : *Sparing Analysis - A Multi-Use Plan*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1989, pp. 296-300, (1989)

[76] Nordin,A. and Maier,F.F.: *SPAREL: A model for reliability and sparing in the world of redundancies*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1989, pp. 313-320, (1989)

[77] Dreyer,S.L. and Smith II,G.: *Innovations in Military Spares Analysis*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1995, pp. 397-401, (1995)

[78] Paisie,J.E.: *When to buy spare parts*, Hydrocarbon Processing, Jan.'98,pp. 61-63, (1998)

3.6 Supportability

[79] Alarcon,Jr.,M.E., and Donaldson,L.M.: *Support Cost Comparison Methodology*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1979, pp. 254-261, (1979)

[80] McArthur,C.J. and Snyder,H.M. : *Life Cycle Cost The Logistics Support Analysis Connection*, CH2759-9/89/0000-1206,1989 IEEE, pp. 1206-1209, (1989)

[81] Dangel,R.: *Integrated Logistic Support (ILS) Implementation in the Naval Ship System Command*, ASE 6th annual technical symposium, pp. 1-25, (1969)

[82] Blanchard,B.S.: *Logistics Engineering and Management 4th edition*, Prentice-Hall International Series in Industrial and Systems Engineering, (1992)

3.7 Risk

[83] Tripp,H. and Propst,J.: *Using R&M Analysis to Calculate Economic Risk in the Process Industries*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1995, pp. 356-361, (1995)

[84] Majeske,K.D. and Herrin,G.D.: *Determining Warranty Benefits for Automobile Design Changes*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1998, pp. 94-99, (1998)

[85] Maggio,G.: *Space Shuttle Probabilistic Risk Assessment: Methodology & Application*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1996, pp. 121-132, (1996)

[86] Oeien,K., Sklet,S., et al.: *Development of Risk Level Indicators For A Petroleum Production Platform*, Proceedings of 9th Int'l Symposium. on Loss Prevention and Safety Promotion in the Process Industries, pp. 382-393, (1998)

[87] Bodsberg,L.: *Implementing Risk-Based Methods For Safety Management In Small And Medium-Sized Enterprises*, Proceedings of 9th Int'l Symposium. on Loss Prevention and Safety Promotion in the Process Industries, pp. 1296-1305, (1998)

[88] Frohlich,B. and Rosen,D.Z.: *Risk Reduction In Exxon Chemical*, Proceedings of 9th Int'l Symposium. on Loss Prevention and Safety Promotion in the Process Industries, pp. 289-298, (1998)

[89] Catmur,J. and Harrison,M.: *The Role of Independent Safety Assessment when Purchasing Programmable Electronic Systems for Process Plants*, Proceedings of 9th Int'l Symposium on Loss Prevention and Safety Promotion in the Process Industries, pp. 915-924, (1998)

[90] Lees,F.P., *Loss Prevention in the Process Industries 2nd edition*, Butterworths, (1996)

[91] Center for Chemical Process Safety (CCPS): *Guidelines for Chemical Process Quantitative Risk Analysis*, American Institute of Chemical Engineers (AIChE), (1989)

[92] Center for Chemical Process Safety (CCPS): *Guidelines for Chemical Transportation Risk Analysis*, American Institute of Chemical Engineers (AIChE), (1995)

3.8 Software

[93] Edson,B., Hansen,B., et al.: *Software Reliability, Availability, and Maintainability Engineering System (SOFT-RAMES)*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1996, pp. 306-311, (1996)

[94] Kaufman,L.M., Smith,D.T., et al.: *Software Reliability Analysis Using Statistics of the Extremes*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1997, pp. 175-180, (1997)

[95] Rook,P. edit: *Software Reliability Handbook*, Elsevier Applied Science, (1990)

3.9 Environment

[96] Kennedy, M.L.: *Total cost assessment for environmental engineers and managers*, John Wiley & Sons, Inc., (1998)

4. Data

[97] Eisaman,Jr.,J.E.: *The numbers game with the logistics support analysis record(LSAR)*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1989, pp. 328-331, (1989)

[98] Comer,P: *Software Data Collection and the Software Data Library*, Proceedings of the 6th EuReDatA Conference 1989, pp. 824-839, (1989)

[99] Allan,R.N., SO,T.Y.P, et al.: *An Integrated Data Base and Reliability Assessment of Electrical Distribution Systems*, Proceedings of the 6th EuReDatA Conference

1989, pp. 840-847, (1989)

[100] Moss,T.R. and Sheppard G.T.: *Common-Cause Failure-Evidence from Sellafield*, Proceedings of the 6th EuReDatA Conference 1989, pp. 141-154, (1989)

[101] Hughes,R.P.: *The Distributed Failure Probability Approach to Dependent Failure Analysis, and Its Application*, Proceedings of the 6th EuReDatA Conference 1989 , pp. 167-177, (1989)

[102] Sciver, G.R.V.: *Guidelines for Process Equipment Reliability Data by CCPS*, Proceedings of the 6th EuReDatA Conference 1989, pp. 104-114, (1989)

[103] Bertrand,A. and Escoffier,L.: *IFP databanks on Offshore Accidents*, Proceedings of the 6th EuReDatA Conference 1989, pp. 115-128, (1989)

[104] Tomic,B. and Lederman,L.: *Data Selection for Probabilistics Safety Assessment*, Proceedings of the 6th EuReDatA Conference 1989, pp. 80-89, (1989)

[105] Scarrone,M., Piccinini,N, et al.: *A Reliability Data Bank for the Natural Gas Distribution Industry*, Proceedings of the 6th EuReDatA Conference 1989, pp. 90-103, (1989)

[106] Hokstad,P. and Jensen R.: *Predicting the failure rate for components that go through a degradation state*, Proceedings of ESREL'98(ISBN 90 5410 966 1), pp. 389-396, (1998)

[107] SINTEF Industrial Management: *OREDA (Offshore Reliability Data), 3rd Edition*, (1997)

5. Model Run

5.1 RAM analysis

[108] Mitrani, I., *Simulation techniques for discrete event systems*, Cambridge University Press, (1982)

[109] Banks,J, Carson,II,J.S. and Nelson,B.L.: *Discrete-Event System Simulation 2nd edition*, Prentice Hall International Series in Industrial and Systems Engineering, (1996)

[110] Witt, J.H.: *UNISAM- An Extension of UNIRAM for Spares Optimization*, A technical paper presented in 17th Inter-ram Conference for the Electric Power Industry, (1990)

[111] *Availability Cost Optimization Methodology*, Electric Power Research Institute EPRI TR-100225, Palo Alto CA, December , (1991)

5.2 Cost analysis

[112] Jelen,F.C. editor: *Cost and optimization engineering*, McGraw-Hill Book Company, (1970)

[113] Uppal,K.B.: *Cost estimating made simple*, Hydrocarbon Processing Sep'97, pp. 168C-168E, (1997)

6. Evaluation

[114] Aaroe,R. et al: Subsea *HIPPS Development Study, Part 8: Overall Economic Evaluation*, SINTEF Safety and Reliability, (1996)

[115] Kortner,H.: *An Analytic Method to Estimate Uncertainty in a Risk Function*, Proceedings of the 6th EuReDatA Conference 1989, pp. 195-205, (1989)

[116] Goossens,L.H.J., Kraan, B.C., et al.: *COSYMA accident consequence uncertainty analysis: Procedure and first results*, Proceedings of ESREL'98(ISBN 90 5410 966 1), pp. 191-197, (1998)

[117] Bertini,S., Fracchia,M., et al.: *Electric ship propulsion RAM performances: Sensitivity analysis*, Proceedings of ESREL'98(ISBN 90 5410 966 1), pp. 1389-1394, (1998)

[118] Porn,K.: *A new measure of uncertainty importance- Theory and applications*, Proceedings of ESREL'98(ISBN 90 5410 966 1), pp. 1403-1408, (1998)

[119] Marseguerra,M., Padovani,E, et al.: *Sensitivity analysis of nonlinear reliability model* , Proceedings of ESREL'98(ISBN 90 5410 966 1), pp. 1395-1401, (1998)

7. Optimization

[120] Coit,D.W. and Smith,A.E.: *Considering Risk Profiles in Design Optimization for Series-Parallel Systems*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1997, pp. 271-277, (1997)

[121] Vassiliadis,C.G. and Pistikopoulos,E.N.: *On the Interactions of Chemical-Process Design under Uncertainty and Maintenance-Optimisation*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1998, pp. 302-307, (1998)

[122] Joyce,P.A., Withers,T.A, et al.: *Application of genetic algorithms to optimum offshore plant design*, Proceedings of ESREL'98(ISBN 90 5410 966 1), pp. 665-671,

(1998)

[123] Vassiliadis,C.G. and Pistikopoulos,E.N.: *Design and maintenance optimization of chemical process under uncertainty*, Proceedings of ESREL'98(ISBN 90 5410 966 1), pp. 255-262, (1998)

8. Applications

[124] Lydersen,S., and Aaroe,R.: *Life cycle cost prediction handbook, computer-based process safety systems*, SINTEF Safety and Reliability, (1989)

[125] Hokstad,P., et al.: Life Cycle Cost Analysis in Railway Systems, SINTEF Safety and Reliability, (1998)

[126] Burstrom,B.,et al.: *Verification of Life-Cycle Cost and Reliability for Swedish High Speed Train X2000*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1994, pp. 166-171, (1994)

[127] Coutinho,J. de S. : *M113A1 Estimated Provisioning Versus Field Experience*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1979, pp. 231-242, (1979)

[128] Genet,R.M., et al.: *Identifying and Evaluating R&M Investments For Fielded Military Equipment*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1979, pp. 243-246, (1979)

[129] Rose,J and Phelps,E.: *Cost of Ownership Application to Airplane Design*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1979, pp. 47-50, (1979)

[130] Oesteboe,R.: *System-effectiveness Assessment in Offshore Field Development using Life-cycle Performance Simulation*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1993, pp. 375-381, (1993)

[131] Akselsson,H. and Burstrom,B.: *Life cycle cost procurement of Swedish State Railways' high-speed train X2000*, Proceedings of International Mechanical Engineers(IMechE), vol. 208, pp. 51-59, (1994)

[132] Followell,D.A.: *Enhancing Supportability Through Life-Cycle Definitions*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1995, pp. 402-409, (1995)

[133] Prescott,N.J.: *Equipment Life: Can We Afford To Extend It?*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1995, pp. 529-535, (1995)

[134] Karyagina,M.: *Designing For Fault-tolerance In the Commercial Environment*,

Proceedings of IEEE Annual Reliability and Maintainability Symposium 1996, pp. 258-262, (1996)

[135] Barnett,G. and Fry,C.: *The RASSP Integrated Systems Tool Set Provides a Concurrent Engineering Environment for Design Trade-Offs*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1997, pp. 220-225, (1997)

[136] Bluvband,Z., Barel,A., et al.: *IQLM: Application for Rail Systems*, Proceedings of IEEE Annual Reliability and Maintainability Symposium 1997, pp. 333-338, (1997)

[137] Houtermans,M.J.M. and Karydas,D.M.: *Overview Of Programmable Electronic Systems And Their Diagnostic Systems*, Proceedings of 9th Int'l Symposium on Loss Prevention and Safety Promotion in the Process Industries, pp. 905-914, (1998)

[138] Kirwan,B: Human Factor & Human Reliability in Offshore Systems, Material of a intensive course at SINTEF, (1998)

APPENDIX B: Samples of cost elements definition

Ten samples of cost element definition are introduced in this appendix. They may be a reference for an actual LCC analysis.

B1: IEC 60300-3-3 (1996)

1. Concept and definition
    - 1.1 market research
    - 1.2 project management
    - 1.3 system concept and design analysis
    - 1.4 preparation of a requirement specification of the product
2. Design and development
    - 2.1 project management
    - 2.2 system and design engineering, including reliability, maintainability and environmental protection activities
    - 2.3 design document
    - 2.4 prototype fabrication
    - 2.5 software development
    - 2.6 testing and evaluation
    - 2.7 productivity engineering and planning
    - 2.8 vendor selection
    - 2.9 demonstration and validation
    - 2.10 quality management
3. Manufacturing and installation
    - (a) non-recurring
    - 3.1 industrial engineering and operations analysis
    - 3.2 construction of facilities
    - 3.3 production tooling and test equipment
    - 3.4 special support and test equipment
    - 3.5 initial spares and repair parts
    - 3.6 initial training
    - 3.7 documentation
    - 3.8 software
    - 3.9 testing(qualification testing)
    - (b) recurring
    - 3.10 production management and engineering
    - 3.11 facility maintenance
    - 3.12 fabrication (labor, materials, etc.)
    - 3.13 quality control and inspection
    - 3.14 assembly, installation and checkout
    - 3.15 packing, storage, shipping and transportation
    - 3.16 ongoing training
4. Operation and maintenance
    - (a) operation
    - 4.1 labor/training
    - 4.2 materials and consumables
    - 4.3 power
    - 4.4 equipment and facilities
    - 4.5 engineering modification
    - 4.6 new software release
    - (b) maintenance
    - 4.7 labor/training
    - 4.8 facilities
    - 4.9 contractor services
    - 4.10 software maintenance
    - (c) supply
    - 4.11 labor/training
    - 4.12 spare parts and repair material
    - 4.13 warehousing facilities
    - 4.14 package, shipping and transportation
5. Disposal
    - 5.1 system shutdown
    - 5.2 disassembly and removal
    - 5.3 recycling or safe disposal

B2: ISO 15663-2 (Draft)

1. CAPEX (Capital cost)
    - 1.1 design and administration man-hours
    - 1.2 equipment and material purchase
    - 1.3 fabrication cost
    - 1.4 installation cost
    - 1.5 commissioning cost
    - 1.6 insurance spares cost
    - 1.7 reinvestment cost
2. OPEX (operating cost)
    - 2.1 man-hours per system
    - 2.2 spare parts consumption per system
    - 2.3 logistic support cost
    - 2.4 energy consumption cost
    - 2.5 insurance cost
    - 2.6 offshore support cost
3. Revenue impact

    Revenue impact is based on the production profile given in the plan for development and operation. For fields already in operation actual and predicted future production form the basis.

    Revenue impact can be estimated from failure data, etc.

    For instance, OREDA (offshore reliability data) provides the following data,

    - inventory data
    - operating data
    - failure event data
    - maintenance data

B3: NORSOK:O-CR-001 (1996)

1. Capital cost
    - 1.1 Equipment purchase cost
    - 1.2 Installation cost
    - 1.3 Commissioning cost
    - 1.4 Insurance spares cost
    - 1.5 Reinvestment cost
2. Operating cost
    - 2.1 Man-hour cost
        - 2.1.1 Corrective maintenance
        - 2.1.2 Preventive maintenance
        - 2.1.3 Servicing
    - 2.2 Spare parts consumption cost
        - 2.2.1 Corrective maintenance
        - 2.2.2 Preventive maintenance
        - 2.2.3 Servicing
    - 2.3 Logistics support cost
    - 2.4 Energy consumption cost
3. Cost of deferred production

B4: NORSOK:O-CR-002 (1996)

1. Capital cost
    1.1 Design and administration cost
    1.2 Equipment purchase cost
    1.3 Fabrication cost
    1.4 Installation cost
    1.5 Commissioning cost
    1.6 Insurance spares cost
    1.7 Reinvestment cost
2. Operating cost
    2.1 Man-hour cost
        2.1.1 Corrective maintenance
        2.1.2 Preventive maintenance
        2.1.3 Servicing
    2.2 Spare parts consumption cost
        2.2.1 Corrective maintenance
        2.2.2 Preventive maintenance
        2.2.3 Servicing
    2.3 Logistics support cost
    2.4 Energy consumption cost
    2.5 Insurance cost
    2.6 Onshore support cost
3. Cost of deferred production

B5: SAE ARP4293 (1992)

1. Acquisition cost
    1.1 Research, development, test & evaluation cost
        1.1.1 Conceptual studies
            1.1.1.1 Feasibility studies
            1.1.1.2 Program definition
        1.1.2 Development & validation
            1.1.2.1 Airframe
            1.1.2.2 Engines
            1.1.2.3 Avionics
        1.1.3 Full scale development
            1.1.3.1 Airframe
            1.1.3.2 Engines
            1.1.3.3 Avionics
    1.2 Investment cost
        1.2.1 Facilities investment
        1.2.2 Production investment
            1.2.2.1 Initial tooling
            1.2.2.2 Production tooling
        1.2.3 Production
            1.2.3.1 Tooling maintenance
            1.2.3.2 Aircraft
                1.2.3.2.1 Airframe
                1.2.3.2.2 Engines
                1.2.3.2.3 Avionics
            1.2.3.3 Delivery charges
        1.2.4 Initial support
            1.2.4.1 Initial training
            1.2.4.2 Initial spares
                1.2.4.2.1 Airframe spares
                1.2.4.2.2 Reserve engines
                1.2.4.2.3 Engine spares
                1.2.4.2.4 Avionics spares
                1.2.4.2.5 Technical publications
        1.2.5 Support equipment & simulators
            1.2.5.1 Support equipment
            1.2.5.2 Simulators

B5: SAE ARP4293 (1992) (continued)

2. Ownership cost
    - 2.1 Operating & support cost
        - 2.1.1 Operating consumables
            - 2.1.1.1 Fuel, oil & lubricants
            - 2.1.1.2 Drop tanks
            - 2.1.1.3 Oxygen
            - 2.1.1.4 Ammunition
        - 2.1.2 Aircrew
            - 2.1.2.1 Training
            - 2.1.2.2 Back-up personnel
            - 2.1.2.3 Overheads
        - 2.1.3 Base support
            - 2.1.3.1 Spares
            - 2.1.3.2 Consumables
            - 2.1.3.3 Support equip. depreciation
            - 2.1.3.4 Support equip. maintenance
            - 2.1.3.5 Engineering personnel
            - 2.1.3.6 Back-up personnel
            - 2.1.3.7 Training
            - 2.1.3.8 Other duties (Military)
            - 2.1.3 9 Overheads
        - 2.1.4 Depot support
            - 2.1.4.1 Personnel & overheads
            - 2.1.4.2 Replacement spares
        - 2.1.5 Contractor support
            - 2.1.5.1 Personnel & overheads
            - 2.1.5.2 Spares
        - 2.1.6 Sustained design services
            - 2.1.6.1 Investigation and design
            - 2.1.6.2 Production (Mod Kits)
            - 2.1.6.3 Amendments to documentation
        - 2.1.7 Component improvement program
            - 2.1.7.1 Research, design and development
    - 2.2 Disposal cost

B6: SINTEF LCC prediction handbook (1989)

1. LAC (Acquisition)
    - 1.1 CIE (Equipment)
        - 1.1.1 CIEH (Component)
        - 1.1.2 CIEA (Additional equipment)
    - 1.2 CIIC (Installation, commissioning)
    - 1.3 CIM (Management, engineering)
        - 1.3.1 CIMV (Vendor management, engineering)
        - 1.3.2 CIMC (Contractor management and engineering)
2. LSC (Support)
    - 2.1 CIR (Investments)
        - 2.1.1 CIRS (Spare parts)
        - 2.1.2 CIRT (Training)
    - 2.2 CYC (yearly)
3. LUC (Unavailability)

B7: SINTEF HIIPS project (1996)

1. Capital cost
    1.1 Design and administration cost
    1.2 Equipment purchase cost
    1.3 Fabrication cost
    1.4 Installation cost
    1.5 Commissioning cost
    1.6 Insurance spares cost
    1.7 Reinvestment cost
2. Operating cost
    2.1 Additional Maintenance Cost due to the introduction of HIPPS
        2.1.1 Corrective maintenance
        2.1.2 Preventive maintenance
    2.2 Spare parts consumption cost
    2.3 Energy consumption cost
    2.4 Onshore support cost
    2.5 Cost of risk (cost of possible rebuilding and clean-up)
3. Cost of deferred production
    3.1 Cost of short-duration shutdowns, e.g. due to minor problems or servicing
    3.2 Cost of long-lasting shutdowns, e.g. subsea intervention
        3.2.1 Preventive intervention
        3.2.2 Corrective intervention

B8: REMAIN (Railway maintenance) project by SINTEF (1998)

1. INV (Investment costs of the system or equipment/product: primary investment)
    1.1 Equipment and material purchase cost
    1.2 Engineering cost
    1.3 Installation cost
    1.4 Initial spares cost
    1.5 Initial training cost
    1.6 Disposal and reinvestment cost
2. AMC (Annual maintenance and operating costs)
    2.1 Corrective Maintenance cost
    2.2 Calendar based PM cost
    2.3 Condition based PM cost
    2.4 Operating cost
    2.5 Energy consumption cost
3. ADC (Annual delay-time costs)
    3.1 Short term delay cost
    3.2 Long term delay cost
4. AHC (Annual hazard costs)
    4.1 Human safety cost
    4.2 Environmental threat cost
    4.3 Cleaning cost
    4.4 Rebuilding cost

B9: US Air Force INPUT data to Decision Support System in Air Force (1990)

1. Acquisition costs
    - 1.1 System Acquisition
    - 1.2 Pre-production Engineering
    - 1.3 Installation
    - 1.4 Initial Technical Data
    - 1.5 Initial Item Management
    - 1.6 Start Up
    - 1.7 Shipping Containers
    - 1.8 Pre-production Refurbishment
    - 1.9 Initial Training
    - 1.10 Tool and Test Equipment
    - 1.11 Training Devices
    - 1.12 Support Equipment
    - 1.13 Hardware Spares
    - 1.14 Spares Reusable Containers
    - 1.15 New Facility Upgrades
    - 1.16 Warranty
    - 1.17 Miscellaneous
2. Operating cost
    - 2.1 Labor and Manpower
    - 2.2 Support Equipment
    - 2.3 Repair Parts and Materials
    - 2.4 Condemnation Spares
    - 2.5 Engineering Changes
    - 2.6 Repair Labor
    - 2.7 Consumables
    - 2.8 Technical Data Revisions
    - 2.9 Recurring Item Management
    - 2.10 Recurring Training
    - 2.11 Recurring Facilities
    - 2.12 Transportation
    - 2.13 Contractor Services
    - 2.14 Miscellaneous

B10: Henderson, J. T., A Computerized LCC/ORLA Methodology, Proceedings of IEEE Annual Reliability and Maintainability Symposium, (1979)

1. Cost of technical data exclusive of Technical Orders (TO's)
2. Cost of that portion of the TO's concerned with organizational level maintenance
3. Site preparation and installation costs
4. Peculiar Support Equipment required for installation and alignment
5. Common support acquisition costs
6. Training costs associated with CI-level trouble shooting
7. Initial and continuing costs for Air Force special operator training
8. Acquisition costs of peculiar training equipment
9. Maintenance personnel transit time to a site
10. ORLA (: Optimum Repair Level Analysis)-related costs associated with non-repairable items
11. Design and development costs of a system
12. Acquisition costs of the system hardware

APPENDIX C: Descriptions of functionality of software tools for RAM analysis

C1: Functionality of MIRIAM and comments on the items

			MIRIAM	Comments
Type	Analytical or simulational?		Simulational	
Method			Monte Carlo (Events based)	MIRIAM maintains a list of events, ordered according to the following points: (1) Time: Events are scheduled to occur sequentially, (2) Priority: Coincident events are ordered by priority, (3) Order of generation: Coincident events with equal priority are handled in the order they were generated.
Input data	Failure data	Constant	x	
		Variable in time, or in operation modes	x	MIRIAM accepts the following distributions: Constant, Uniform (interval (a,b)), Triangular, Exponential, Gamma, Weibull (3 parameters), Normal, and Lognormal
	Maintenance data	Corrective	x	
		Preventive	x	
	Component throughput capacity	Constant	x	
		Variable in operation modes	x	Ramping of flowrate is represented by some flow levels varying in stepwise. If any events leading the ramping flow occure, the stepwised flowrates are automatically applied in the simulation. Throughput capacity may be modelled with calendar variation (i.e. time dependent capacity). Also there exist a functionality called yield, which means that new throughputs may come into being anywhere inside a flow network (indeed very much alike a separator where well stream is split into gas, oil and water). This yield
	Demand of production	Constant	x	
		Seasonal variation	x	
Capability of modeling	System redundancy	Active pararell	x	Operating rules for active standby can be specified.
		Standby operation	x	Operating rules for passive stadby can be specified, as well.
	Temporary bypass		x	
	Aging, degradation of components		x	
	Surge tanks, Storage efficiency		x	
	Periodical inspection for hidden failures		(x)	There is not a data input field for periodical testing for hidden failure. However the effect of periodical inspection for hidden failure can be modeled with a modeling technique.
	CCF,e.g.Utility failure or Spurious shutdown		x	Spurious shut down is modeled with data of the failure frequency, the affected subsystems and the repair time distribution.
	Delay time	due to logistics, administration, etc.	x	MIRIAM considers weather condition, which affects the delay time.
Options	Criticality analysis		x	Detailed histories of failure and repaire are listed for each components level, subsystems level, and the tolat system level.
	Uncertainty analysis		x	Uncertainity is considered in the failure distribution and the repair time distribution of each components. It is a merit of simulational tool to be capable of considering the uncertainty in the system.
	Cost analysis	Flexibility in cost elements definition		
		Cost treatment (NPV etc.)		
Output data	System availability or production regularity		x	
	Mean downtime		x	
	Utility consumption		x	
	Maintenance resource expenditure		x	
	Spares and stockouts		x	
	Life time system cost			

Note: ( ) represents with restrictions

C2: Functionality of MAROS and comments on the items

			MAROS	Comments
Type	Analytical or simulational?		Simulational	
Method			Monte Carlo (Events based)	MAROS utilises a graphical user Interface (GUI) which employs relaibility block diagrams to construct the input file
Input data	Failure data	Constant	x	
		Variable in time, or in operation modes	x	
	Maintenance data	Corrective	x	
		Preventive	x	
	Component throughput capacity	Constant	x	
		Variable in operation modes	x	
	Demand of production	Constant	x	
		Seasonal variation	x	
Capability of modeling	System redundancy	Active pararell	x	
		Standby operation	x	
	Temporary bypass		x	
	Aging, degradation of components		x	MAROS offers the use of the Weibull distribution with the characteristic life and beta factor to be defined by the user. Selection of the beta factor greater than 1.0 e.g. 2 will give wear-out characteristics
	Surge tanks, Storage efficiency		x	
	Periodical inspection for hidden failures		(x)	MAROS does not have an explicit input field for the periodical inspection. However, it can be modeled with a modeling technique.
	CCF,e.g.Utility failure or Spurious shutdown		x	
	Delay time	due to logistics, administration, etc.	x	
Options	Criticality analysis		x	
	Uncertainty analysis		x	To establich an LCC range based on uncertainty of input parameters, a number of sensitivity or "what if" scenarios are run. The results from these runs can then be plotted to show uncertainty or band widths of
	Cost analysis	Flexibility in cost elements definition	x	The cost profile presented in the ouput file can be manipulated by changing the input data arrangment
		Cost treatment (NPV etc.)	x	MAROS now has a integrated Life-cycle cost (LCC) module which enables plats and calculations of opex, capex, revenue and NPV
Output data	System availability or production regularity		x	
	Mean downtime		x	
	Utility consumption		x	
	Maintenance resource expenditure		x	
	Spares and stockouts		x	
	Life time system cost		x	

Note: ( ) represents with restrictions

C3: Functionality of AvSim+ and comments on the items

			AvSim+	Comments
Type	Analytical or simulational?		Simulational	
Method			Monte Carlo (Events based)	AvSim emulates failures and repaires on each components through over a system life cycle. Each time a components fails, AvSim checks whether the system has failed, or not using the logic diagram represented by FTA or RBD. All events are recorded, so detailed information of system performance is accordingly
Input data	Failure data	Constant	x	
		Variable in time, or in operation modes	x	AvSim accepts the following failure distributions: Constant, Exponential, Weibull
	Maintenance data	Corrective	x	AvSim accepts the following repair time distributions: Exponential, Normal and Lognormal
		Preventive	x	
	Component throughput capacity	Constant		AvSim does not accept any throghput capacity data. However, the capability to handle capacity will be realized in the next version.
		Variable in operation modes		
	Demand of production	Constant		
		Seasonal variation		
Capability of modeling	System redundancy	Active pararell	x	Apportionments of failure/ aging in hot stanby mode can be specified.
		Standby operation	x	
	Temporary bypass		x	
	Aging, degradation of components		x	
	Surge tanks, Storage efficiency		x	
	Periodical inspection for hidden failures		x	AvSim has the data input field for the interval of periodical test for hidden failures.
	CCF,e.g.Utility failure or Spurious shutdown		x	
	Delay time	due to logistics, administration, etc.	x	Three defferents delay times can be specified for each component according to the location of the component, i.e. on-site, in a depot, and in a factory.
Options	Criticality analysis			
	Uncertainty analysis		x	
	Cost analysis	Flexibility in cost elements definition	(x)	User can not create a new cost category in the model. However, any cost elements, e.g. risk cost, can be considered using the cost category named miscellanious cost.
		Cost treatment (NPV etc.)		Cost analysis can be examined with a software package dedicated for cost analysis named LCCWare which is a family of AvSim+
Output data	System availability or production regularity		x	
	Mean downtime		x	
	Utility consumption			
	Maintenance resource expenditure		x	
	Spares and stockouts		x	
	Life time system cost		x	

Note: ( ) represents with restrictions

C4: Functionality of UNIRAM and comments on the items

			UNIRAM	Comments
Type	Analytical or simulational?		Analytical	
Method			Availability Block Diagram and FTA	Availability Block Diagram (ABD) shows functional connections among basic subsystems in the plant with data of throughput capacity. ABD do not need to correspond to the physical arrangement of equipment. Failure model for each basic subsystem is represented by a logic diagram in the fault tree style.
Input data	Failure data	Constant	x	
		Variable in time, or in operation modes	(x)	The Uncertainty Option allows for variation in the estimate of the mean; The Weibull Option allows for variation in component failure rate with time.
	Maintenance data	Corrective	x	
		Preventive	x	
	Component throughput capacity	Constant	x	
		Variable in operation modes		
	Demand of production	Constant	x	
		Seasonal variation	x	
Capability of modeling	System redundancy	Active pararell	x	
		Standby operation	x	
	Temporary bypass		x	This can be accomodated in the development of the UNIRAM model by use of a perfect (A=1) dummy bypass basic subsystem with reduced throughput capacity in parallel with the original basic subsystem(s).
	Aging, degradation of components		x	The Weibull Option provides this function by permitting the user to enter alpha, beta, gamma Weibull parameters for selected components along with designated overhaul times.
	Surge tanks, Storage efficiency		x	These effects are represented within the basic UNIRAM model as surge times at the component, gate, and subsystem levels as appropriate.
	Periodical inspection for hidden failures			
	CCF,e.g.Utility failure or Spurious shutdown		(x)	It can be modeled with defining a unit representing CCF in the structure diagram in series.
	Delay time	due to logistics, administration, etc.	(x)	Delays due to logistics or administrative are assumed to be contained within the MDT values used for each component.
Options	Criticality analysis		x	
	Uncertainty analysis		x	It has the statistical uncertainty option uses Monte Carlo sampling to select MTBF and/or MDT values to be used for each component having multiple values for each iteration. The measures are then evaluated analytically and averaged over the iterations with the corresponding 90% confidence values computed
	Cost analysis	Flexibility in cost elements definition		
		Cost treatment (NPV etc.)		
Output data	System availability or production regularity		x	
	Mean downtime		x	
	Utility consumption			
	Maintenance resource expenditure			
	Spares and stockouts			Though not calculated directly by UNIRAM, the effects can be evaluated by determining the impacts on MDT values with changes in sparing levels and then using the Data Change Option. The companion program, UNISAM, is intended to do this function.
	Life time system cost		(x)	The user inputs a cost per megawatt hour or a cost per ton as part of the input file. The outputs then provide a cost value per period associated with various determined parameters

Note: ( ) represents with restrictions

C5: Functionality of WinRAMA and comments on the items

			WinRAMA	Comments
Type	Analytical or simulational?		Analytical	
Method			Flow netwok and RBD	Flow network shows physical connections among basic subsystems in the plant with data of throughput capacity. Failure model for each basic subsystem is represented by the logic diagram in RBD style.
Input data	Failure data	Constant	x	Failure data is represented either by MTTF or by probability of fail on demand (PFD)
		Variable in time, or in operation modes		
	Maintenance data	Corrective	x	Repair time is represented by MTTR
		Preventive		
	Component throughput capacity	Constant	x	
		Variable in operation modes		
	Demand of production	Constant	(x)	Production regularity can be calculated based on the result of system availability.
		Seasonal variation		
Capability of modeling	System redundancy	Active pararell	x	
		Standby operation		
	Temporary bypass			
	Aging, degradation of components			
	Surge tanks, Storage efficiency		(x)	It can be modeled if a component with a proper MTTF and MTTR is added in the system in parallel.
	Periodical inspection for hidden failures		x	WinRAMA has the data input field for the interval of periodical test for hidden failure.
	CCF,e.g.Utility failure or Spurious shutdown		(x)	It can be modeled if a component with a proper MTTF and MTTR is added in the system in series.
	Delay time	due to logistics, administration, etc.	(x)	All delay time can be modeled if they are included in the value of MTTR
Options	Criticality analysis		x	
	Uncertainty analysis			
	Cost analysis	Flexibility in cost elements definition		
		Cost treatment (NPV etc.)		
Output data	System availability or production regularity		x	
	Mean downtime			
	Utility consumption			
	Maintenance resource expenditure			
	Spares and stockouts			
	Life time system cost			

Note: ( ) represents with restrictions