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Service Life Management System of Concrete Structures in Nuclear Power Plants

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1 Abstract

A service life management system is being developed in VTT in cooperation with the Finnish nuclear companies TVO and FORTUM. The project belongs to the Finnish Research Programme SAFIR 2010 and is implemented during the years 2007 - 2010. The service life management system is developed for the maintenance staff of nuclear power plants for conducting systematic maintenance policy and for planning, organising and optimising maintenance strategy of concrete structures in nuclear power plants.

2 GENERAL PROPERTIES

The service life management system (SLMS) consists of a service life management tool, ServiceMan, for maintenance of structures and supplementing analyses on structural performance and risk. The program ServiceMan is capable of:

- timing of special inspections
- timing and specification of intervention actions
- timing and planning MR&R (maintenance, repair and rehabilitation) projects and
- annual resources planning (balancing MR&R costs with budget).

The methodological ground for the management system was developed during the EC FP5 project LIFECON (2001-2003) [1]. A scheme of the planning process is presented in Figure 1. The process starts from the inspection of structures and ends in the implementation of maintenance, repair and rehabilitation (MR&R) projects. The LC management tool uses the data of system database and makes preliminary plans for the MR&R actions. The database contains datatables on structures, modules and MR&R systems.

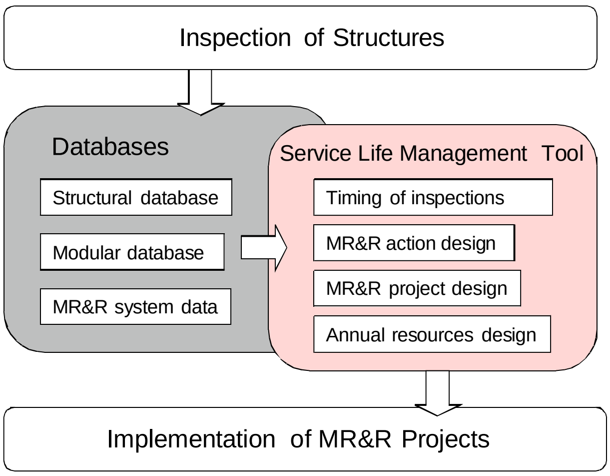

Figure 1. Service Life Management System. Database and Service Life Management Tool.

All phases of life cycle planning are performed using the management tool ServiceMan. ServiceMan is an MS Excel based tool which contains the necessary databases and calculation procedures in it. The plant units are shared into structures, which are the main building parts such as the containment, sea water channelling etc. The structures are further divided into modules. The breakdown of the structures into modules is made based on the principle of homogeneity so that the modules are approximately uniform with respect to materials, structural features and exposure. Modules are the basic units in service life evaluation, life cycle analyses and life cycle planning processes.

3 PROCEDURE OF THE SLMS

Figure 2 shows a scheme on the calculation procedure and the data flow of the service life management system. On top the databases of structures, modules and MR&R systems with their contents are presented. The structural and modular databases contain identification data, measuring data, data on exposure, observed degradation (inspection data), data on MR&R actions that have already performed and actions that will be performed in the future etc. The database of MR&R Systems consists of data on protection systems, repair systems and renovation systems. For each system group the database contains material data, cost data, environmental impact data, performance data and service life data.

The life cycle action planning is performed for each module in row. Accordingly, each module in turn is selected and the data pertaining to that module is gathered and checked before inserting them to the life cycle analysis procedure. The data is partly gathered from the modular database and partly from the MR&R system database. Sometimes data coupling and calculations have to be performed in order to get the desired data (e.g. service life).

The LC analysis process is systemised so that the calculations are performed using the same analysis procedure irrespectively on the module at hand. So, the initial data is changed according to the active module but the procedure itself is the same. In the life cycle analysis table the life of modules and protection systems is imitated with respect to condition and service life. The calculation table is able to automatically trigger maintenance and repair actions whenever the limit state of condition is exceeded by the allowable probability.

Following each life cycle analysis the data on the MR&R actions are gathered into the datatable of specified and timed actions. This is done by a macro program which controls the analysis processes. After this the design process continues with MR&R project design (combining MR&R actions into groups) and Annual Resources Design (balancing the annual MR&R costs with the budget). These design phases require sorting, filtering and supplementing of the table of specified actions.

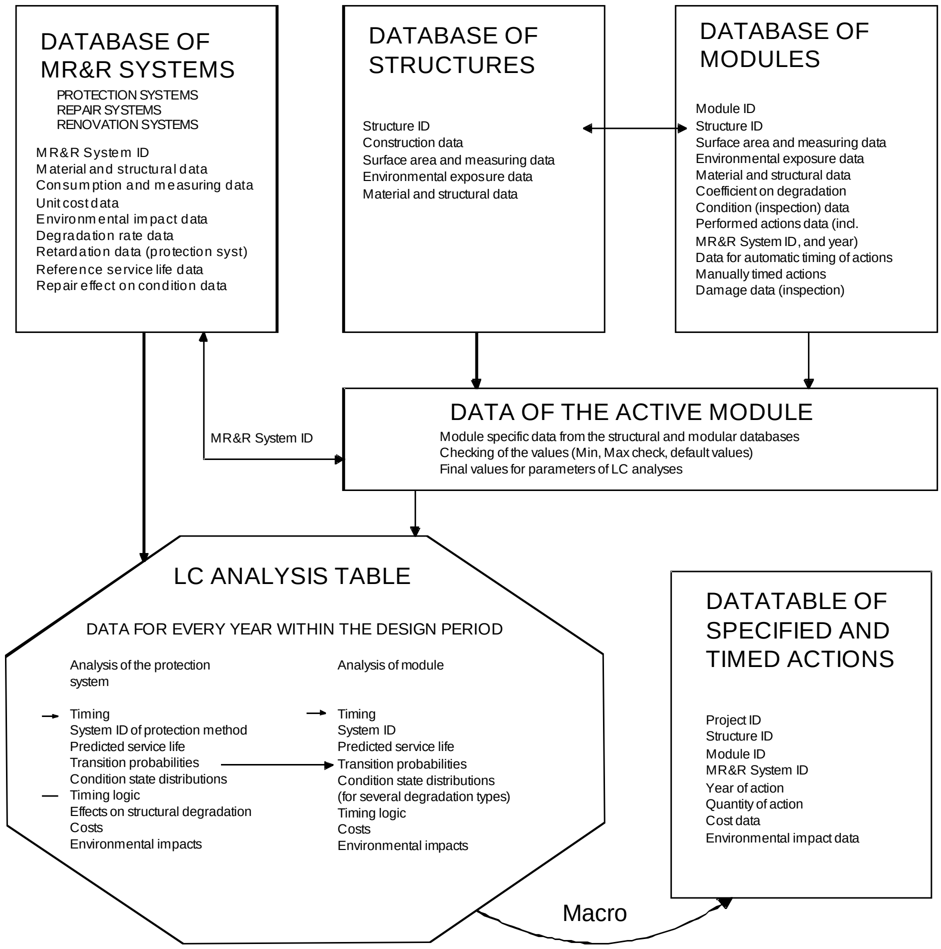

Figure 2. Service Life Management System. Database and Service Life Management Tool [3].

In the condition analysis the structure is evaluated with regard to five degradation types:

- carbonation and corrosion of reinforcement
- chloride penetration and corrosion of reinforcement
- degradation of concrete
- carbonation and corrosion of reinforcement at cracks
- chloride penetration and corrosion of reinforcement at cracks.

In addition the condition of the protection system is evaluated (one degradation type). The protection systems have an influence on the degradation types of the structure. The retarding effect of the protection system on the degradation of the structure depends on the condition of the protection system. At the beginning of the service life the retarding effect of a protection system is greatest and reduces gradually towards the end of the service life.

The LC analysis ranges from the year of manufacture to the end of the design period. As a result of the LC analyses MR&R actions are defined and timed and the data on MR&R cost and environmental impact data are determined.

4 COMBINED LIFE CYCLE ANALYSIS

The core of the management system consists of a combined condition, cost and environmental impact analysis. A scheme on the system is presented in Figure 3. The annual condition state distributions are determined by the Markov Chain method in the analysis table left in the figure. The condition state distributions show the probabilities by which the module belongs to different condition states (in this case the condition states range from 0 to 4). The annual changes in the condition state distributions are predicted by the transition probability matrices (degradation and action effect matrices in the upper left corner of the figure). The transition probabilities of the degradation matrix are automatically determined based on the model formula of degradation. The transition probabilities of the action effect matrices are specific to each MR&R action.

In this example the limit condition state is defined to be 3 and the maximum allowable probability for exceeding the limit state is 50%. In the column Prob > 3 the probability that the module exceeds the limit state (3) is determined. Whenever Prob > 3 is greater than the maximum probability (50%) a repair action is automatically triggered. In the next year the repair is implemented and the action effect matrix is applied instead of the degradation matrix (to define the condition state distribution after the repair). At the same time the repair costs are added in the cost calculator right in the figure. The cost calculator totals the costs and environmental impacts from the whole design period. Thus the data presented in the upper right corner of Figure 3 can be determined.

Transition probability matrix of original structure

State	0	1	2	3	4
0	0.74	0.26	0	0	0
1	0	0.77	0.23	0	0
2	0	0	0.79	0.21	0
3	0	0	0	0.79	0.21
4	0	0	0	0	1

DEGRADATION OF ORIGINAL STRUCTURE

Coefficient c	0.3	
Exponent n	0.9	

Transition probability matrix of repair

State	0	1	2	3	4
0	1	0	0	0	0
1	0.95	0.05	0	0	0
2	0.92	0.05	0.03	0	0
3	0.9	0.05	0.03	0.02	0
4	0.88	0.05	0.03	0.02	0.02

REPAIR DATA

Cost	100	Euro/m ^{2}
Non-Ren Energ	100	MJ/m2
CO_2	10	kg/m2

Transition probability matrix of degradation after repair

State	0	1	2	3	4
0	0.85	0.15	0	0	0
1	0	0.81	0.19	0	0
2	0	0	0.80	0.20	0
3	0	0	0	0.78	0.22
4	0	0	0	0	1

DEGRADATION AFTER REPAIR

Coefficient c	0.1
Exponent n	1.2

REPAIR CRITERIA

Limit state	3
Max Prob	0.5

GENERAL DATA

Design period	40	Years
Discount rate	3	%
Surface area	50	m ^{2}

RESULTS

LC COSTS PER UNIT AREA

Cumulative real costs	**200**	Euro/m ^{2}
Cumulative PV costs	**111**	Euro/m ^{2}
Average annual costs	**5.00**	Euro/m ^{2}/yr
Equalised annual costs	**4.64**	Euro/m ^{2}/yr
Non-Ren Energy	**200**	MJ/m2
CO_2	**20**	kg/m2

TOTAL LC COSTS

Cumulative real costs	**10000**	Euro
Cumulative PV costs	**5526**	Euro
Average annual costs	**250**	Euro/year
Equalised annual costs	**232**	Euro/year
Non-Ren Energy	**10000**	MJ
CO_2	**1000**	kg

State Year	0 Prob(0)	1 Prob(1)	2 Prob(2)	3 Prob(3)	4 Prob(4)	Average De	Prob (>3)	Repair criteria	Number of repairs	LC costs real	Discount factor	LC costs discounted	Non-Ren Energy	CO_2
0	1.000	0.000	0.000	0.000	0.000	0.00	0.000	0	0	0	1.000	0	0	0
1	0.738	0.262	0.000	0.000	0.000	0.26	0.000	0	0	0	0.971	0	0	0
2	0.544	0.397	0.059	0.000	0.000	0.52	0.000	0	0	0	0.943	0	0	0
3	0.401	0.450	0.136	0.013	0.000	0.76	0.013	0	0	0	0.915	0	0	0
4	0.296	0.453	0.209	0.039	0.003	1.00	0.042	0	0	0	0.888	0	0	0
5	0.218	0.428	0.267	0.076	0.011	1.23	0.086	0	0	0	0.863	0	0	0
6	0.161	0.389	0.307	0.117	0.026	1.46	0.143	0	0	0	0.837	0	0	0
7	0.119	0.343	0.329	0.159	0.050	1.68	0.209	0	0	0	0.813	0	0	0
8	0.088	0.297	0.337	0.196	0.083	1.89	0.279	0	0	0	0.789	0	0	0
9	0.065	0.253	0.332	0.228	0.123	2.09	0.351	0	0	0	0.766	0	0	0
10	0.048	0.212	0.318	0.252	0.170	2.28	0.422	0	0	0	0.744	0	0	0
11	0.035	0.177	0.298	0.268	0.222	2.46	0.490	0	0	0	0.722	0	0	0
12	0.026	0.146	0.275	0.277	0.277	2.63	0.553	1	0	0	0.701	0	0	0
13	0.910	0.049	0.025	0.011	0.006	0.15	0.017	0	1	100	0.681	68	100	10
14	0.776	0.173	0.029	0.014	0.008	0.30	0.022	0	1	100	0.661	68	100	10
15	0.662	0.255	0.055	0.017	0.011	0.46	0.028	0	1	100	0.642	68	100	10
16	0.565	0.304	0.092	0.024	0.015	0.62	0.039	0	1	100	0.623	68	100	10
17	0.482	0.330	0.130	0.038	0.020	0.78	0.058	0	1	100	0.605	68	100	10
18	0.411	0.339	0.165	0.056	0.028	0.95	0.084	0	1	100	0.587	68	100	10
19	0.351	0.336	0.195	0.078	0.040	1.12	0.118	0	1	100	0.570	68	100	10
20	0.299	0.324	0.218	0.101	0.057	1.29	0.158	0	1	100	0.554	68	100	10
21	0.256	0.307	0.234	0.124	0.079	1.46	0.203	0	1	100	0.538	68	100	10
22	0.218	0.287	0.244	0.145	0.106	1.63	0.251	0	1	100	0.522	68	100	10
23	0.186	0.265	0.248	0.164	0.137	1.80	0.301	0	1	100	0.507	68	100	10
24	0.159	0.243	0.247	0.179	0.173	1.96	0.352	0	1	100	0.492	68	100	10
25	0.135	0.220	0.242	0.191	0.212	2.12	0.402	0	1	100	0.478	68	100	10
26	0.116	0.199	0.234	0.199	0.253	2.28	0.452	0	1	100	0.464	68	100	10
27	0.099	0.179	0.223	0.204	0.296	2.42	0.500	0	1	100	0.450	68	100	10
28	0.084	0.159	0.211	0.205	0.340	2.56	0.546	1	1	100	0.437	68	100	10
29	0.914	0.046	0.023	0.011	0.007	0.15	0.018	0	2	200	0.424	111	200	20
30	0.780	0.171	0.027	0.013	0.009	0.30	0.022	0	2	200	0.412	111	200	20
31	0.665	0.254	0.053	0.016	0.012	0.46	0.028	0	2	200	0.400	111	200	20

Figure 3. Combined Life Cycle Analysis with automatic triggering of actions.

4.1 Special Inspections

Special Inspections form an essential part of the SLMS. Special inspections include taking samples from modules and the condition assessment based on the samples. A special data form is reserved for inputting the condition assessment data to the modular database. The input data includes

- special inspection year
- carbonation depth
- depth of critical chloride content
- thickness on concrete cover
- crack width
- amount of cracks.

Based on these results the degradation models are calibrated specifically for each module. These models are used instead of the original ones in the consequent timing of MR&R actions. When more and more special inspection data is obtained also the general degradation models can be re-evaluated.

In practice the timing process of inspections and MR&R actions proceeds as presented in Figure 4. The ServiceMan tool first gives tentative timings of inspections and MR&R actions based on the general degradation models. The special inspections for a module are supposed to be carried out approximately at the proposed time. After special inspection the degradation models are calibrated based on the module specific condition assessment. Thus a more accurate timing for the MR&R action can be given by the ServiceMan tool. Then the MR&R actions are supposed to be implemented approximately at the revised timing. However, small changes in the timing of actions can be done manually by the maintenance engineer during the project design and the annual resources design to gain the synergy profit.

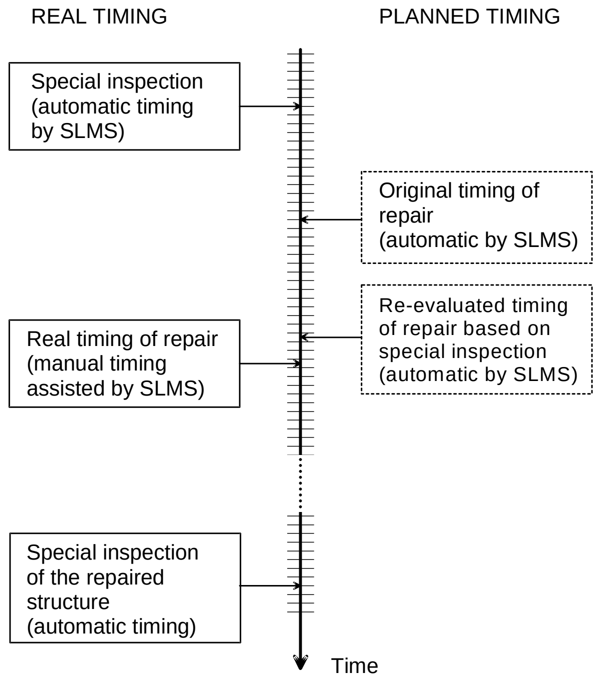

Figure 4. Timing of inspections and repair actions.

4.2 Supplementing analyses

The supplementing structural performance and risk analyses are conducted mainly for the containment building. The risk analyses are focused on the prestressing tendons the steel liner. The structural analyses are used to evaluate the structural implications of possible degradation in materials and components. By the supplementing analyses the safety and uninterrupted service of concrete structures are ensured during the planned service life of power plants. Another objective of the analyses is to find acceptance limits for various types of degradation. Cracking of concrete is studied by a special application developed for serviceability limit state design.

5 CONCLUSIONS

The project SERVICEMAN (Service life Management System in Nuclear Power Plants) under the auspices of the research programme SAFIR 2010, that started in 2007, aims at developing a service life management system for concrete structures in nuclear power plants in Finland. The service life management system is capable of predicting degradation in structures with respect to different degradation types of degradation and of timing special inspections and MR&R actions for the remaining operating life of the plant.

The service life management tool can be used for systematic and proactive maintenance of concrete structures in nuclear power plans. The core process of the system is the combined condition, cost and environmental impact analysis. The condition analysis is based on degradation models and the Markov Chain method.

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