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LIFE CYCLE MANAGEMENT OF CONCRETE STRUCTURES BASED ON SUSTAINABILITY INDICATORS

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Abstract.
A concrete structure should be sufficiently planned, designed, executed and maintained to ensure its requirements during the life cycle. However, structures suffering from serious deterioration in structural members and sometimes subsequent loss in sustainability have been often found due to various reasons. One of the reasons is lack of total management for the structure. To meet these facts, it is extremely important to pursue coordination of engineering work in the design, execution and maintenance stages. The life cycle management is an organized system to support engineers decision to realize sufficient sustainability of the structure in the design, execution, maintenance, and all related work during its life cycle. The life cycle management is implemented based according to the life cycle management scenario in which balance of several sustainability indicators should be considered with ensuring overall sustainability. The sustainability indicators will be determined from the social, environmental and economic points of view. The scenario should be regularly reviewed based on the PDCA cycle and be updated if necessary. This paper deals with the concept and framework of the life cycle management of concrete structures to ensure sustainability during the structural life.

Keywords: Life-cycle management, life-cycle scenario, PDCA cycle, performance, sustainability indicator.

1. Introduction

A concrete structure is constructed having its own purposes, such as protecting a society from disasters and ensuring a comfortable, safe life for people. The structure is required to ensure its functions and performance to achieve these purposes during its life cycle. However, serious damages are likely brought as the results of the application of physical and/or environmental actions, which provokes structural performance degradation and collapse. Those damages may considerably cause a loss of sustainability not only of the structure but also of the society.

The life cycle of a structure is made up of the planning, basic and detailed designs, execution including material selection, production and construction, maintenance including assessment and remedial action, and decommissioning stages. The life cycle management (LCM) is a coordinated system to ensure that the structure meets the associated performance requirements defined at the time of structural planning and may be subsequently updated during the service life of the structure. There are lots of standards and guidelines on how to make effective service life design and maintenance work. Most of them cover durability design of concrete structures focusing on chloride-induced rebar corrosion, carbonation, chemical erosion, freeze/thaw deterioration, and fatigue. The maintenance standards deal with the basic principles of maintenance and repair for concrete structures and specify codes of practice underlying the basic principles covering inspection, prediction, evaluation, and remedial action. However, there are very few standards dealing with design and maintenance simultaneously with the consistent framework and concepts. It is of considerable importance to pursue collaboration between design and maintenance as well as execution. As the international standard on the LCM led by the authors, ISO 22040 Life cycle management of concrete structures, was published in January 2021 for specifying the concept of LCM.

Introduction of the LCM for a structure contributes to all aspects of sustainability while maintaining the functions and performances to fulfil its purposes. Sustainability is defined from environmental, economic, and social aspects. It is likely to be considered in terms of resources and energy consumption, initial construction and/or life cycle costs, and environmental burden. Sustainability is generally considered with one or a few sustainability indicators. The paper presents the principles and the framework of LCM of concrete structures by compiling the authors' previous papers [1–3].

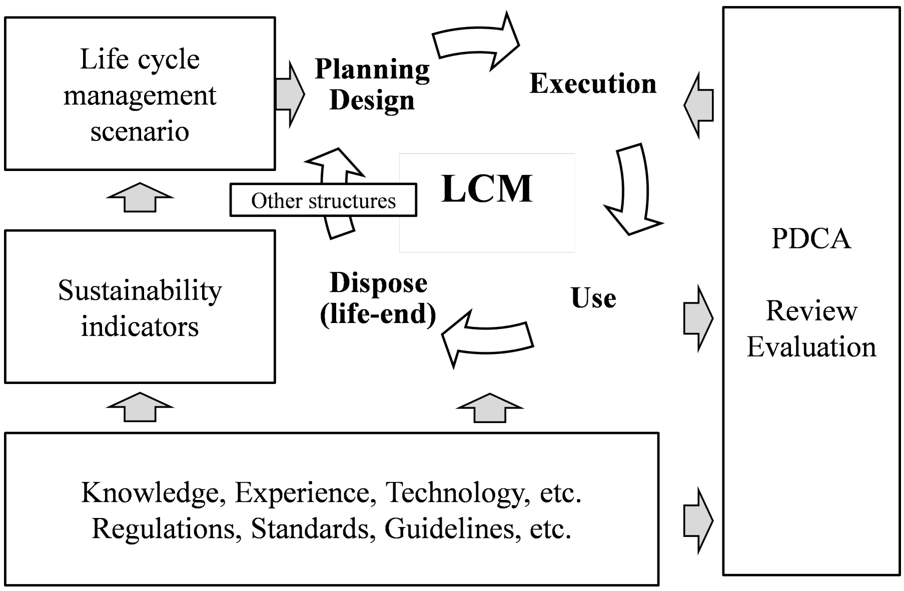

FIGURE 1. Overall framework of the life cycle management.

2. Concept of life cycle management

2.1. Overall framework of LCM

A concrete structure goes through different stages during its life cycle: from structural planning, design, execution, use, and to the life-end stages. This implies that it is essential to coordinate all the stages sufficiently and to transfer important information from one stage to another effectively. However, no system has been developed to date regarding the basic concept and specific methods to achieve this and manage the whole life of the structure in a consistent manner.

The overall framework of the LCM is presented in Figure 1. The LCM is undertaken according to the LCM scenario. The scenario is made up with basic strategies on how the whole life of the structure will be managed in consideration of the balance in sustainability indicators. The sustainability indicators will be determined from the social, environmental and economic aspects, which will be mentioned later. The scenario should be regularly reviewed and evaluated based on the PDCA cycle and be updated if necessary. As shown in Figure 1, it is easily understood that the LCM is a coordinated concept to support activities for managing the total life of structure. which consists of managements of each stage of life and overall management to cover whole life to ensure structural functions and performance and to achieve sustainability.

2.2. Procedure of LCM

Figure 2 shows the standard procedure for LCM. For a new structure, the scenario is drawn up in the planning stage. The scenario describes the fundamental strategy on how the structure will be managed its structural performance and sustainability aspects. The structure is initially designed to ensure its requirements without major remedial measures; however, planned remedial measures should be declared in the scenario if they are necessary. The scenario links and coordinates the life cycle stages the structure.

Design is created to satisfy the scenario that was already drawn up in the planning stage. When the design does not meet the scenario, either the scenario is modified to be consistent with design considerations, or the design is created once again. Construction work is engaged to follow the design outputs in the execution stage. Then, in the use stage, initial inspection, diagnosis and evaluation is carried out to check the conditions of the structure. When defects or unexpected damages are found, remedial measures should be implemented as necessary. Decision will be made whether the scenario is suitable for the subsequent maintenance work or not. When the scenario is found to be unsuitable at this point, it has to be updated.

In the use stage, the above procedures will be repeated. When the scenario is updated, the updated scenario will be applied for the subsequent maintenance work. If remedial measures are found to be difficult mainly because they are rather costly or burdens, the structure will go to the life-end stage. In conclusion, the LCM can provide the overall strategy in order to ensure the structure to ensure the associated performanc

In the life-end stage, where removal or renewal of the structure or diversion or change of use of the whole or part of the structure or members is investigated, consideration is given to reducing the amount of waste and promoting reuse/recycling of materials and members.

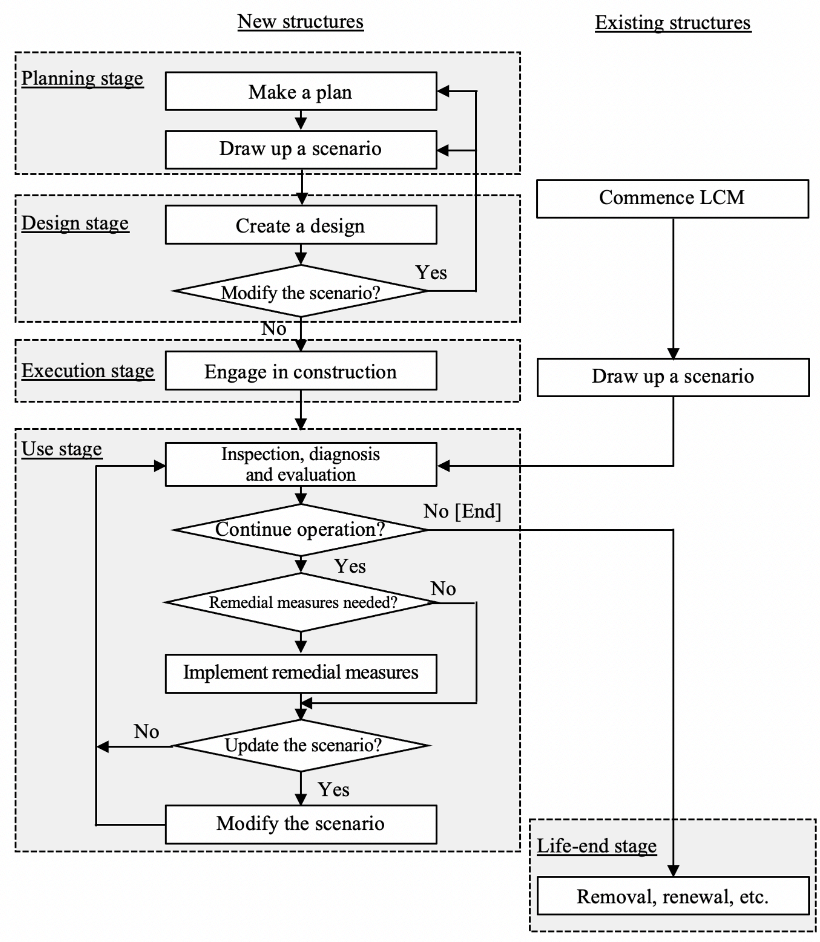

Figure 2. Standard procedure of the life-cycle management.

For an existing structure, the LCM starts with drawing up a scenario. Then, assessment including inspection, diagnosis and evaluation is carried out for understanding the structural conditions. The scenario is drawn up based on the results of the assessment. When assessment results conclude that remedial measures are difficult to be taken to restore structural performance, the structure will go to the life-end stage directly; otherwise, the LCM follows the same procedure as that for a new structure. Being different from a new structure, an existing structure may have insufficient design, execution and previous maintenance records; accordingly, missing information should be assumed.

Every structure has specific functions that will be able to meet their purposes as mentioned earlier. To ensure those functions, performance requirements are ensured, such as safety, serviceability, restorability, and environmental preservation requirements. From the structural performance point of view, in the planning and design stages, the performance requirements of the structure are set, and the structural forms, materials, and geometric data will be specified so that the structure can satisfy the requirements during its service life. Structural performance is verified during the design work. Care in structural forms, materials and dimensions should be exercised so that maintenance can be appropriately carried out to ensure structural performance requirements in the use stage. In the execution stage, the structure should be constructed to fully ensure the expected performance set in the design stage. In the use stage, periodic maintenance is required to find deterioration of materials and even performance degradation. In addition, by predicting the future progress of performance degradation, the most suitable remedial measures can be chosen, which would optimize the decision-making indicators. Maintenance work should follow the initially drawn up scenario, but the scenario is often necessary to be updated so that the scenario reflects the actual conditions of the structure relating to the structural performance. Since the initial scenario is drawn up based on the results of future prediction on materials deterioration and performance degradation based on various assumptions, the LCM-related data acquired in the use stage can be effectively utilized to review the assumptions.

2.3. Information transfer based on PDCA cycle

Figure 3 shows the concept of information transfer particularly from the use stage. Information obtained

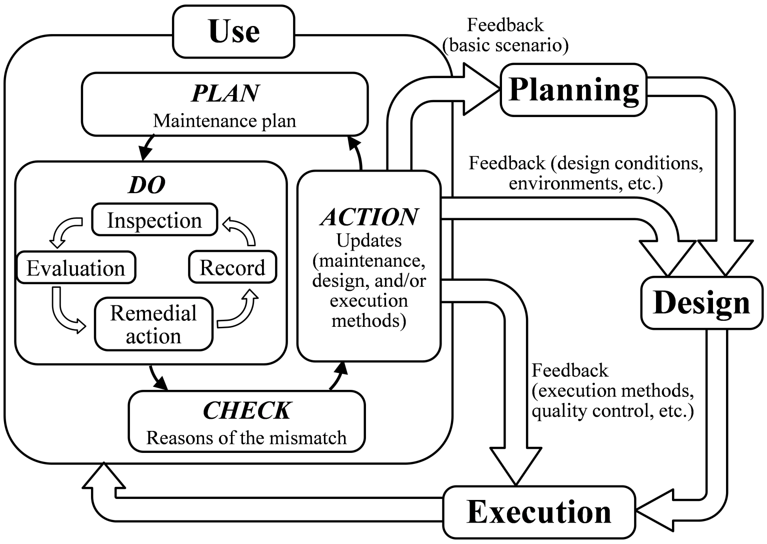

Figure 3. Information transfer from the use stage.

in the use stage is required to share not only among engineers in the use stage but also engineers in the planning, design and execution stages. The information would be utilized to improve future work in each stage based on the concept of PDCA (plan-do-check-act) cycle. The PDCA cycle for the target structure can also be extended to be utilized for other similar structures.

It is considered that well planned and organized investigation or inspection and evaluation in the use stage are important to ensure performance of the structure. During the maintenance work, it is important to identify the mismatch between design assumption and real situation, which will be applicable for improvements on future maintenance, design and/or execution work. Consequently, it is important to feedback and utilize the information collected in the use stage to the design and execution stages. When inspection data, technical knowledge and experience are accumulated, it is possible to draw up the more realistic LCM scenario.

It is necessary to review the design outputs through the comparison with the inspection, diagnosis and evaluation results in the use stage because deterioration progress does not always follow the design outputs. The deterioration progress differs widely by its location and time because of inhomogeneous characteristics of concrete and diversity of local environmental conditions. It is absolutely necessary to update the scenario by using the real inspection data.

3. Sustainability indicators

3.1. Sustainability design

Sustainability is defined as a concept based on the environmental, economic, and social aspects, and is one of the key issues in a construction sector to be well considered now. Sustainability is likely to be considered in construction work from the viewpoints of resources and energy consumption, initial construction and/or life cycle cost, durability, and environmental impact [4, 5]. In other words, sustainability is generally considered with one or a few of the above viewpoints, but it is not easy to find the best solution because no comprehensive sustainability indicator exists to represent all the aspects. It will be a typical example that the more the margin of safety is given, the more resources and energy may be needed for execution, which will require higher costs. This is the collision between the social aspect of sustainability that corresponds to the safety margin, and the economic and environmental aspects of sustainability that correspond to small costs and environmental loads. Therefore, the decision on the safety margin should be essentially made after examining the influence of the margin on the costs and environmental burdens.

It is not difficult to understand that structural collapse impairs the sustainability. Huge energy should be devoted to treat the debris produced by the collapse, and a huge amount of resources is required to reconstruct structures. Many people may be killed or injured, and employment and production bases will be at least temporally unavailable. These loss and restoration also require the huge amount of costs. Engineers have to keep it in mind what might be caused by insufficient design, execution, and maintenance of the structures.

As mentioned earlier, we realize that the safety margin principally links the sustainability. The safety margin will be determined at the general design process, which will be subsequently verified with some sustainability indicators. Figure 4 shows the sustainability design flow for initial construction and repair. As indicated in Figure 4, the sustainability indicators should be calculated and verified from the social, economic and environmental aspects. For the purpose of verification, requirements for these aspects should be

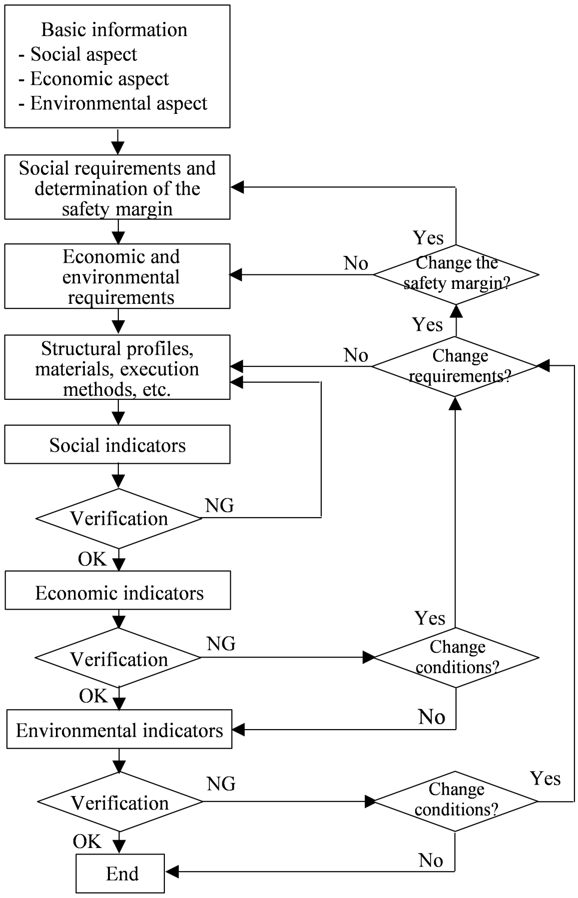

Figure 4. Flow of sustainability evaluation and verification.

made clear. Resiliency and robustness that have recently been of great interest, are related to the safety margin - social sustainability. As shown in Figure 4, the sustainability design enables us to systematically consider the sustainability of the structure in the design stage. It may be also possible for designers to find a good balance between the social, economic and environmental indicators with the sustainability design system [6, 7].

The sensitivity analyses among the sustainability indicators for a simplified reinforced concrete beam [8] found that, when a 10 % increase in the cost because of an increase in the overall safety margin is assumed to be allowable, the overall safety margin can be set at approximately 1.2; and when a 10 % increase in CO_2 emissions is assumed to be allowable, the overall safety margin can be increased to approximately 1.3. In other words, the cost increase will be small with the increase in the overall safety margin of 10 % or with enhancing durability. The same trend can be found in estimating the environmental aspect. Therefore, those sensitivity should be well considered for seeking the balance of sustainability indicators.

3.2. Scenario evaluation

In the design stage, durability is verified by the prediction of the performance degradation. Based on the durability design and prediction, the fundamental concept on how to ensure the structural performance during its service life have to be thoroughly considered. Structural conditions, design service life, structural characteristics, material properties, difficulties in assessment and remedial measures, and social and economic importance may have great influences on the concept.

Indicators that would be used for the scenario evaluation and selection should be determined among the sustainability indicators consisting of social, environmental, and economic aspects. These indicators will be quantified with respect to the period of the LCM. For the present scenario evaluation, costs, such as total cost or life cycle cost are widely used as the indicator. A scenario that provides the lowest cost will be chosen. From the viewpoint of sustainability, however, social and environmental indicators have to be considered as well for the scenario evaluation.

As the environmental aspect, appropriate indicators are determined in consideration of environmental impacts in the execution and use stages of the structure, such as resource consumption, greenhouse gas emissions, and impacts on the ambient environment. As the economic aspect, all the direct and indirect costs during execution and the use and at the life-end of the structure, as well as the benefits and values provided by the structure, can be set as indicators.

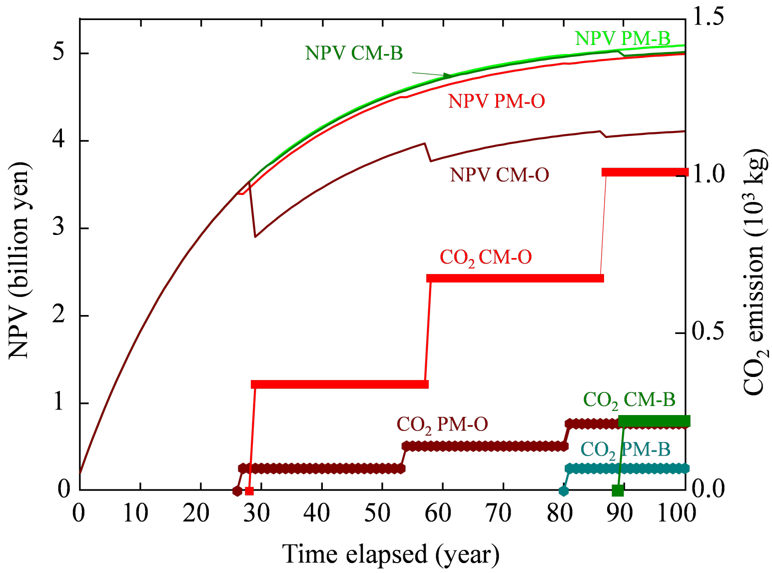

Figure 5. Calculation example of sustainability indicators.

Indicators objectively expressing performance of the structure during the use period, such as safety of the structure itself and safety of users of the structure, can be determined for the social aspect. Some indicators related to the social aspect are difficult to be quantified because of the non-representational features, such as adaptability, comport, cultural values, and social contribution. However, they may be considered by a social-scientific manner. The appropriate scenario should be selected among its alternatives in consideration of the balance among sustainability indicators.

Figure 5 shows an example of the scenario evaluation in terms of NPV (net present value) and CO_2 emissions of a group of concrete structures during its life cycle [9]. The NPV and the CO_2 emissions indicate the economic and environmental aspects, respectively. In Figure 5, two scenarios were drawn up based on a preventive repair strategy (PM) and a corrective repair strategy (CM). Also, two types of cements, such as OPC (O) and BB (B) were considered. The deterioration progress was predicted with the Markov process considering the diffusion coefficient of concrete. The scenario having higher NPV would be preferable. In this calculation, the scenarios with PM-B, CM-B and PM-O produce almost the same NPV, which is superior to that with CM-O. CO_2 will be emitted by repairing the deteriorated parts of a structure and the less emissions, the better scenario from the environmental aspect. The CO_2 emissions are the least for scenario PM-B and followed by CM-B and PM-O showing almost the same values. Scenario CM-O would emit a great amount of CO_2. In conclusion, scenario PM-B is judged to satisfy economic and environmental requirements, and scenario CM-O has the least possibility to be selected when the structures' life cycle is 100 years. This example shows a simplified calculation, and more factors should be considered for drawing up a practical scenario. It is important to predict changes in sustainability indicators during a structure's life cycle and draw up a suitable scenario according to the prediction.

4. Conclusions

It is extremely important to manage a concrete structure to ensure functions and performance that people and users expect during its life cycle. A concrete structure can be expected to have a long service life when it is well planned, designed, constructed, and maintained. Coordinated management during the structural life cycle would provide the structure with longer life and would realize sufficient sustainability. For this purpose, all activities from the planning stage to the life-end stage of a concrete structure are well linked and coordinated as the LCM.

1. For doing infrastructure management, planning, design, execution, and use stages should be well coordinated with smooth information transfer and exchange.
2. The PDCA cycle is a key point for realizing excellent LCM. For this purpose, necessary information should be shared in each stage of the structural life cycle and be transferred between the life cycle stages.
3. Sustainability is one of the most important considerations during the LCM. Sustainability should be well considered from the environmental, economic and social aspects when the management scenario is drawn up.
4. It is necessary to consider the balance in the sustainability indicators. The sustainability design and verification procedure are proposed for this purpose.

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