<table>
<thead>
<tr>
<th>Títol</th>
<th>Life-cycle assessment (LCA) of existing bridges and other structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autor/a</td>
<td>Ewa Zimoch</td>
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<td>Construcció</td>
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<td>Data</td>
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Life-cycle assessment (LCA)
of existing bridges and other structures

By
Ewa Zimoch
SUMMARY

Title: Life-cycle assessment (LCA) of existing bridges and other structures

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Most buildings are intended to have a long service life, usually over 50 or even 100 years. It is, thus, important to analyse all phases of their life, considering both the influence on environment and expenses. In order to do this precisely the Life Cycle Assessment (LCA) and the Life Cycle Costs (LCC) methods are used. There are many commonly used LCA and LCC software tools. They make it easier to control maintenance issues, and let their users accumulate all the data for the building. This paper takes into consideration several LCA tools and presents the main assumptions concerning the LCA and LCC methods.

The most widely used theory of the LCA analysis is an approach described in International Standards ISO 14040, that assumes four phases of the LCA: Goal and scope definition, Inventory Analysis, Impact Assessment, and Interpretation. There are a few variants of life cycle assessment, namely cradle-to-grave, cradle-to-gate, cradle-to-cradle or gate-to-gate. For analysis in the building industry the most common method is cradle-to-grave approach, which best presents all the significant issues connected with buildings. The LCA of a building takes into consideration phases such as material acquisition, creation, transportation, use, and finally the disposal of the products.

Strongly connected with the Life Cycle Assessment is the issue of the Life Cycle Costs. The LCC is used to help decision-making in all the phases of a building’s life. It ought to be taken into account that construction costs are only the beginning, and in further phases there will be other costs connected with operation and management, or special costs (e.g. taxes).

Bridge Management Systems are based on the LCA and LCC methods. They have been developed so as to help manage resources effectively and to maintain bridges in satisfactory condition. Bridge Management Systems assess the present condition of the bridge and they also intend to predict the future performance of a bridge.
La mayoría de los edificios están construidos con la intención de que tengan una larga vida útil, normalmente de más de 50 años o hasta 100 años. Por eso es importante analizar todas las etapas de su vida, tomando en cuenta ambos la influencia sobre el medio ambiente y los gastos. Para hacer esto con mucha precisión se utilizan los métodos de Análisis de Ciclo de Vida (ACV) y Coste del Ciclo de Vida (CCV). Hay muchas herramientas de software populares que son utilizadas. Estas herramientas hacen que los temas de mantenimiento sean más fáciles y permiten a sus usuarios acumular toda la información sobre el edificio. Este trabajo toma en cuenta muchas herramientas de ACV y expone las principales suposiciones sobre los métodos de ACV y CCV.

La teoría más común en cuanto al análisis de ACV está descrita en Estándares Internacionales ISO 14040, que supone cuatro etapas de ACV: metas y alcances, análisis del inventario, evaluación del impacto y interpretación. Existen varias variantes de la evaluación de ciclo de vida, concretamente análisis de la cuna a la tumba, análisis de la cuna a la verja, análisis de la cuna a la cuna, o análisis de la verja a la verja. Para la análisis en el sector de la construcción el método más común es análisis de la cuna a la tumba que es el método que mejor presenta todos los temas importantes relacionados con los edificios. ACV de un edificio considera etapas como adquisición de materiales, creación, transportación, uso y finalmente y desecho de los productos.

El tema de Coste del Ciclo de Vida está muy vinculado con Análisis de Ciclo de Vida. CCV está utilizado para ayudar tomar decisiones en todas las etapas de la vida del edificio. Deberíamos tener en cuenta que los gastos de construcción son solamente un principio, ya que en las siguientes etapas habrán más gastos relacionados con funcionamiento y gestión, o gastos especiales (por ejemplo impuestos). Sistemas de Gestión de Puentes están basados en los métodos de ACV y CCV. Han sido desarrollados para ayudar la gestión eficaz de recursos y para mantener los puentes en un estado satisfactorio. Sistemas de Gestión de Puentes analiza el estado actual del puente y también tiene la intención de predecir el rendimiento del puente en el futuro.
TABLE OF CONTENTS

1. Introduction ......................................................................................................................... 7

2. Concept of Life Cycle Assessment (LCA) ......................................................................... 8
   2.1. International Standards ISO 14040 .............................................................................. 9
   2.2. Variants of Life Cycle Assessment method .............................................................. 11
   2.3. The life cycle of a building ........................................................................................ 12

3. Concept of Life Cycle Costs (LCC) .................................................................................. 15

4. Available tools and methods for LCA and LCC ............................................................... 21
   4.1. Life cycle of construction project .............................................................................. 22
   4.1.2. RIBA Plan (Royal Institute British Architects Plan) ................................................ 24
   4.2. Examples of Life Cycle Assessment software tools .................................................. 26
   4.2.1. EcoProP ......................................................................................................................... 26
   4.2.2. Building for Environmental and Economic Sustainability (BEES) ...................... 27
   4.2.3. ATHENA® Impact Estimator for Buildings ............................................................ 27
   4.2.4. ATHENA® EcoCalculator for Assemblies ............................................................... 29
   4.2.5. Building Life-Cycle Cost (BLCC) Program ........................................................... 30
   4.2.6. Environmental Impact Estimator ............................................................................. 31
   4.2.7. LEGEP ........................................................................................................................ 31
   4.2.8. Eco-Bat ........................................................................................................................ 33
   4.2.9. LTE-OGIP .................................................................................................................. 34

5. Bridge Management Systems ........................................................................................... 35
   5.1. Examples of Bridge Management System tools ....................................................... 44
   5.1.1. Ontario Bridge Management System (OBMS) – Canada ...................................... 44
   5.1.2. DANBROweb Bridge Management System – Denmark ...................................... 45
   5.1.3. Eirspan – Ireland ..................................................................................................... 47
   5.1.4. SMOK – Poland ....................................................................................................... 49
   5.1.5. Sistema de Gestión de Puentes (SGP) – Spain ......................................................... 50
   5.1.6. Pontis – United States of America ........................................................................... 51
   5.2. Comparison of Bridge Management Systems ........................................................... 52

6. Conclusions ....................................................................................................................... 56

References ................................................................................................................................ 59
TABLE OF FIGURES

Figure 1. Phases of LCA ............................................................................................................ 9
Figure 2. The Life cycle of a building...................................................................................... 12
Figure 3. Main areas of the life cycle quality................................................................. 15
Figure 4. The Life Cycle Costs of a project - categories....................................................... 17
Figure 5. Global methodology for LCA................................................................................... 21
Figure 6. Models of bridge/element deterioration - source [13] ............................................. 36
Figure 7. Essential and Preventive Maintenance Strategies.................................................. 37
Figure 8. A basic state-space deterioration model - source [13] .............................................. 38
Figure 9. The Bridge Life-Cycle Cost Analysis process......................................................... 40
Figure 10. Eirspan organization chart .................................................................................... 47
Figure 11. Comparison of Bridge Management Systems – based on [14] ......................... 55
1. Introduction

Every part of the construction process affects more or less the world around us. Natural resources are used in construction industry and it has significant influence on environment. This is the reason why we are looking for the model solutions to optimize the construction process, taking into consideration such parts as design, construction, use and demolition of structures or buildings. One of such a solution is Life Cycle Assessment (LCA).

In recent years, researchers and real estate companies focus their attention on the analysis of the whole life cycle of a building, including both its performance and cost in the whole life span. All the estimations and assumptions considering the life cycle issues will have significant meaning in the future. Specialists from all over the world are trying to get a common definition of terms like Life Cycle Assessment and Life Cycle Costs and to prove how important this topic is for the operational management of the life cycle of a building. While engineers have access to many different tools for the design, planning and calculation of construction costs, the tools used for calculation of operational costs are not so common yet. Nevertheless, more and more scientific publications focus on this topic.

All the civil infrastructure facilities like buildings, infrastructure and industrial facilities are designed to be used over long time. Most of these constructions are subject to unfavorable operational or environmental conditions, which makes them much more open to aging, while deterioration of their performance is progressing over their whole life span. It is hard to assess correctly the performance of a building, which is dependent on time, because of such factors like evolving requirements for regulatory compliance, changing owners and occupiers, security issues, and a economic dictated decisions of many owners to preserve instead of to replace a facility. Moreover, it usually makes a difficulty to justify the huge investment of public funds, which is required for most of the public projects. Therefore, in recent years, more and more attention is given to the life-cycle performance in view. According to this tendency it took place a fast growth of decision support tools in Life Cycle Assessment.

This thesis will present the main assumptions in using Life Cycle Assessment Tools, and will show existing experiences. It will be also put forward the concept of Life Cycle Costs (LCC), which is related to the economic aspects, therefore the relation between Life Cycle Assessment and Life Cycle Costs may not be passed over. Moreover, there will be presented and compared Bridge Management Systems (BMS), that are used in different countries.
around the world, and their methodology is based on life-cycle assessment and life-cycle costs techniques.

2. Concept of Life Cycle Assessment (LCA)

In general, Life Cycle Assessment is used to determine the potential environmental risks during a whole life of the product. This method has a wide application and civil engineering is just one of many discipline which uses LCA tools. The essence of this method is that the attitude is not only focused on the final outcome, but also on a impact of the process on environment. Therefore Life Cycle Assessment is a process of evaluating the effects which the product has emitted to the environment during the entire life cycle.

The environmental impact assessment can be conducted both for the product and for its function, for example for the whole building. The main elements of Life Cycle Assessment are:

- identification and quantitative assessment of the burden on the environment, such as used materials and their impact on the environment,
- impact of finished materials on human being,
- energy consumption during production and during the period of use (the use time is as long as it is the expected for each product – given by regulation or assumed by designer).

Apart from technical and organizational work, which is usually considered as the most important parts of a production process, environmental aspects should be already taken into consideration at the design stage of structures or other buildings. Only then it is possible to carry out correctly Life Cycle Assessment. One of the main assumptions of the LCA technique is seeking to establish all the factors which may have a potential impact on the environment, associated with a product or technology. Thanks to results of the analysis with the LCA technique it is possible to determine the impact of a product or technology on the environment throughout its whole life cycle.

The first mention of this type of method is derived from the work of Harold Smith, presented at the World Energy Conference in 1969. Original scientist’s research were involved with the manufacture of various types of energy in some chemical processes. One of the first
companies that were interested in using these tests in practice, was Coca-Cola, which commissioned a further study on this subject.

The energy crisis, that took place in the 1970s, contributed to the development of LCA methods and was the inspiration for further research and analysis based on assumptions of this method. Gradually, as a result of research and development the method began to differ from the form originally presented in the work of Harold Smith. The development of method contributed to the growing interest in the issue of acid rain and greenhouse effect.

2.1. International Standards ISO 14040

Most of tools used in Life Cycle Assessment works are based on ISO standards. According to them (the International Standards ISO 14040:2009), a Life cycle assessment should be carried out in four phases (shown in Figure 1). The phases are usually connected and the results of one may affect on another.

![Figure 1. Phases of LCA](image)

**Goal and scope**

Work with the LCA should be started from characterizing the goal and scope of the study, which determine the field of the study and shows who is a recipient and how the results are going to be put forward. This is a very important part of LCA and it is required that the goal and scope are clearly defined and coherent with the application. This is the reason why the goal and scope document must include following technical details (that present a work which should be done in consecutive phases):

- the functional unit, which defines the field of study;
- the system boundaries;
assumptions or limitations;
the allocation methods, when some products or functions take part in the same process;
choice of impact categories.

**Life cycle inventory**

The main task of Life Cycle Inventory is to analyze flows from and to nature for the product. Into "flows" should be included such components as energy, water and raw materials, and releases to air, water and land. Using data on inputs and outputs it is possible to create a flow model of the technical system, which is usually presented with a flow chart that shows the operations that are going to be done. For all activities that are included into the system there are collected the input and output data, which then can be used to create the construction of the model.

The data may be presented in tables, but it still must be connected with the goal and scope definition. Life Cycle Inventory is the results of these operations and it provides information about all inputs and outputs in the flow to and from the environment.

**Life cycle impact assessment**

The next phase is an impact assessment. Thanks to the results received in Life Cycle Inventory in this part of the life cycle assessment is possible to evaluate the significance of potential environmental influence. Life cycle impact assessment usually includes the following elements:

- selection of impact categories,
- determination of the classification stage,
- impact measurement.

**Interpretation**

This phase is used to analyze, identify, quantify and evaluate information from the results which were gained in previous phases: the life cycle inventory, and the life cycle impact assessment. The outcome of the interpretation phase is very important because it includes conclusions and recommendations for the study.
According to the standards, the interpretation should include:

− identification of significant issues based on the results of the Life Cycle Inventory and Life Cycle Impact Assessment phases of an LCA;
− evaluation of the study considering completeness, sensitivity and consistency checks;
− conclusions, limitations and recommendations.

The results of a life cycle assessment is not easy to interpret. Firstly, it is necessary to know and realize how much the results are accurate, secondly it must be ensured that they meet the goal of the study.

Work with the use of LCA methods requires the use of very precise data, because on them depends the accuracy of results, which will be finally received, and therefore the accuracy of the whole LCA method. Besides, in order to properly compare the results of different processes, it must be used the same number of data. If the tests were conducted on different amounts of data, it is not possible to compare several different processes.

### 2.2. Variants of Life Cycle Assessment method

In general there are a few variants of Life Cycle Assessment method, for example cradle-to-grave, cradle-to-gate, cradle-to-crade or open loop production, gate-to-gate.

**Cradle to grave** is a variant in which the analysis is carried out from the extraction of materials (cradle) to their disposal (grave). In all phases of product’s life there are taken into account all inputs and outputs.

**Cradle to gate** is a variant, which takes into account only the part life of the product from the extraction of the products (cradle), to the processing plant (gate). The use and disposal stages are omitted. This type of LCA is sometimes used to create the environmental product declarations.

**Cradle to cradle** is a method in which the life of the product does not end at its disposal, but it is further recycled. This operation is particularly environmentally friendly, because it assumes an open loop production and leaves a minimal amount of material effects in the environment. This method assumes introducing into the consciousness thinking not only about the present needs but also about the future. Recycled products can be processed in the same products, or in a completely different, but based on the same material.
**Gate to gate** is a method that focuses only on one stage of production, selected from the entire production process. Of course this part can be later included into the complete production chain and be used in a cradle-to-gate variant.

2.3. The life cycle of a building

The diagram below (Figure 2) presents the life cycle of a building.

![Figure 2. The Life cycle of a building](image)

In the case of buildings it should be considered the following steps:

- construction (preparation, design, production),
- use (utilization, maintenance),
- end of using (demolition, dismantling, final waste processing, recycling).

Considering product's lifecycle there must be taken into account all the impacts within established earlier boundaries which may cause an influence on environment.

**Materials acquisition and Creation**

To determine the impact of a product, there must be known all the components of the product and necessary is the knowledge of this how it was created. It is not enough to determine what kind of material was used, but also what part of the whole product it makes up, and how it was produced. Some processes or materials which take part in a lifecycle of a product are not
well described and there are no existing data for them. In this case, it is necessary to estimate all impacts and to use the data, that are available, which more or less reflect a character of the product.

**Transportation**
Transportation should also be included in a life cycle assessment of a product, taking into account firstly transport of raw materials and later finished goods. Designers may not know figures that describe this part of life cycle, and then they have to compare the results in several different alternatives, then to choose the best of them.

**Use**
It must also be estimated energy and other resource use during the life of a product. These estimates must be very accurate and precise, because this part of life cycle is often decisive. It must be considered many different options and possibilities, that may take place during a life of some product.

**Disposal**
Product’s end of life impacts must also be estimated. There are a few possibilities of the ends, that depend on material that product was made of, for example it can be recycled, incinerated or sent to the landfill. The best results are received when there are considered many scenarios. Then it is necessary to choose one, but it also should be assumed that another may happen with some probability.

For buildings the life cycle assessment method should be considered as an analysis of the impacts of construction’s materials on the environment. According to a definition of the LCA, the analysis should take into account the production process of every used material. Structures and buildings may serve different functions, they have a long life span and strongly interfere with the surrounding environment. For new buildings there may be a problematic issue to characterize the condition of the building after its utilization. However, in old buildings it is difficult to determine the data concerning its construction phase. As it was mentioned before, to carry out the analysis it is necessary to determine the borders of the system, which strictly depend on its function.

The Life Cycle Assessment is a method that lets to characterize the interaction between a process and the environment. Moreover it specifies quantity of mass and energy’s flow
transmitted and collected from the environment. In the LCA it is considered a consumption and processing of raw materials needed to produce a product, the process of production, transportation, distribution, consumption, or the reprocessing and storage after the end of the use phase. In each of these stages there are pollutions emitted, they can have both negative and positive impact on the environment. The environmental impact is determined on the balance of negative and positive impacts.

Analysis of Life Cycle Assessment consists of several phases (materials acquisition, creation, transportation, use, disposal of the product). It is possible that the greatest detrimental impact on the environment is in one of them, then appropriate action will be to reduce the impact by focusing just on this item. Sometimes better results can be achieved through changes in the use phase (then decisive is a long duration of this phase), other times it is more advantageous to reduce the negative effects even in the production phase.

Civil engineering and building structures are one of the longest lasting products in our societies. Usually life of structures is between 50 years and a few hundred years. Therefore sustainable structural engineering is challenging comparing with others areas of technology. The main task is to reach a stable economic and social development in harmony with nature. The construction branch part in Europe is: 15% of employment, 11% of Gross National Product (GNP), 40% of raw materials and energy consumption and waste production. Taking all these facts into consideration civil engineering and building structures have a huge influence on our environment, and this fact cannot be omitted during design process in this area. Sustainability in structural engineering should base on thinking about all areas of structural engineering over generations.

Requirements for buildings are on constant increase, especially such demands as:

- reducing consumption of materials,
- minimizing water and energy during construction and manufacturing activities,
- decline of pool of labour meant for the construction industry,
- rapid change in society and lifestyles of people that increase requirements for buildings which surround us,
- increasing restrictions in land use,
- imposed impact of climate change.
Moreover, there are some trends that are becoming more and more common:

− minimizing energy use through changes in building technologies,
− changing fashion affects on more flexible buildings with replaceable fixtures and fittings,
− attitude to recycling, reuse and deconstruction of buildings,
− requirements for change of use, adaptation and conversion during life of buildings,
− increase in technology used in households.

All these facts lead to the concept of life cycle planning – designing building with taking into consideration a view to operations that will take place through the whole of its life.

The aim of a life cycle assessment is to design for the best quality in viewpoints mentioned on the diagram below (Figure 3).

![Figure 3. Main areas of the life cycle quality](image)

It is very important to remember about all these aspects together. The integrated life cycle design consist of physical, economical, mechanical, environment, energy and health viewpoints.

3. **Concept of Life Cycle Costs (LCC)**

The Life Cycle Cost is methodology that enables to compare the cost impact of alternative design solutions throughout the life of the building. Life Cycle Cost (LCC) is strictly connected with the Life Cycle Assessment method. Life cycle cost is the total cost incurred over the lifetime of a building or other assets. A time counting begins during the acquisition
of materials and design through the production, use, maintenance, repairs, renovations, replacement and removal. The life cycle costs include not only the financial costs that are the easiest to estimate, but also environmental and social costs, which is often difficult to assign them numerical values.

The Life Cycle Cost Analysis is used in the design phase and help making decisions in selecting materials, choosing production methods and construction technology. The LCC includes the cost covering the entire life of the asset. The best is such a solution that gives the best results in financial terms. It should be noted that the reduction construction costs by using inferior materials, often results in increased costs during an utilization. Conversely, the use of better quality and therefore more expensive materials, usually reduces maintenance costs and causes the increase in a durability of a building.

There are often problems with making decisions that concern finances by the authorities, because the LCC method assumes long term perspective and may occur following problems:

- Design of the minimum life cycle cost often assumes that a initial expenditure must be higher than other alternatives. Thus, such a decision means that more money must be invested from current funds, and for the public it is hard to observe savings, because they are not immediate, but they ultimately lead to the lower lifetime cost.

- The public usually do not appreciate funds which are spent on maintenance (especially preventive maintenance), because there are not visible any immediate changes and in addition it may involve some inconvenience.

- Another issue is a decision about additional strengthening of construction that would provide the lower annual probability of problems due to e.g. overload, natural hazards or environmental effects. Nevertheless these effects have a low probability of occurrence and they usually are not problem for reasonably designed structure.

It is very important to combine LCA and LCC analysis, which allows making maximum optimization of this both: costs and environmental impact. For many buildings, it is possible to estimate costs, that would be necessary to pay in case of use some solution, and what environmental impact it would have. This relationship is very strong.

In case of cost programming it is important to set up a cost schedule, in which costs for all parts of the project are specified. Thanks to the life cycle costs method, it is possible to avoid focusing only on the short-term costs of design and construction. Usually the longer-term
maintenance and operation costs have much more important proportion of the whole-life cost. A control of the costs in all the parts of a project gives a possibility to check how they are changing and to compare estimated and actual costs.

On the construction sector there is a permanent pressure to create buildings with increasing standards of performance, simultaneously reducing costs of construction and use, and decreasing environmental impacts. Economic pressure drives prices down, so there must be found the way to build more cost-effectively. There are many factors that affect on the project cost, their existence depends on various stages in the project construction. Figure 4 shows the main categories of life cycle costs of a project. It used to be common to concentrate only on the initial stage of a project during making the project cost control. As a result of such a behavior, it could have been observed a tendency in the project operation to make lower costs in the initial stage and higher in the final stage. In this case, it is hard to gain a cost efficiency for the project. Besides, in the method of life-cycle cost it is necessary to remember about the supporting cost, that may happen in the whole life of the building, it lets to get a balance point and better efficiency in the life cycle periods of a project.

![Figure 4. The Life Cycle Costs of a project - categories](image)

In modulation of the cost data there are four main factors that should be considered:

- **Quantity Factor**

Each part of a project has its price which is the price of building area per unit. It can change because of the difference in quantity of parts that are specified in a design and that are really built.
− Quality Factor

The price of each part must be modulated for every project separately, because of the difference in quality resulted from workmanship and materials.

− Time Factor

The price of each part of a newly building project should be modulated based on the change in prices that may happen till date of planning completion of the project.

− Comparable Rule of Data for Cost Analysis

All the factors mentioned above like quantity, quality and time are based on number gathered from the same kind of projects. The data for cost analysis is selected for cost index, according to the design specification and sketch of some similar project.

Long-life structures ought to be designed and maintained so as to guarantee safe operation during a demanded time, but at the same time condition of reasonable price should be considered. These structures are usually expensive, thus it is devoted great effort so as to improve their design and maintenance management with respect to costs. The main aim is to minimize the life-cycle costs, that consist of the costs connected with design, construction, maintenance and disposal at the end of life, and also the costs that are caused by failures.

Usually it is impossible to accurately predict the operations that will take place in distant future, e.g. because of changing loading and climatic influences. Nevertheless, it is reasonable to divide the whole life of a structure into two stages: design and operation. In the first stage – design, the structure should be dimensioned for the demanded service time. In the second stage – operation, it ought to be maintained so that the total costs from beginning of operation until its replacement or demolition keep at minimal level.

There are some basic formulas that may be used to estimate cost of deteriorating structures:

− the costs, on which influence may have dimensioning,

\[ C = C_o + C_f \]

\( C_o \) – the price of a new structure or component,
\( C_f \) – the costs caused by premature failures.
the costs should be related to the lifetime $T$ of the structure or component, the effectiveness of costs may be evaluated thanks to the value of costs per unit-time of operation:

$$C_t = \frac{C}{T}$$

A failure may occur after some time of using of a structure. Condition of structures is deteriorating gradually, which is caused by load effects and due to an influence of environment (e.g. corrosion, carbonation of concrete).

the lifetime $T$ which lasts until replacement is dependent on the load effect $S$, that can be an amplitude in cyclic loading or the stress magnitude, but also it can be affected by the intensity of a corrosive environment. The simplest case is following: $T$ decreases with increasing $S$, according to the formula,

$$T = BS^{-m}$$

$B, m$ – constant (determined from tests).

This equation is known as Wöhler curve for fatigue. $S$ means the stress amplitude. For example the time necessary for carbonation of a concrete beam into some depth can be expressed in this formula.

the load effect $S$ is dependent on the resistance $Z$ of the loaded cross-section and the load $L$, thus in the simplest case

$$S = \frac{L}{Z}$$

$Z$ – e.g. the cross-section area

the characteristic load $L$ can be expressed as below

$$L = L_0 + k_{AL}A$$

$L_0$ – load-independent value,

$A$ – cross-section area, that affects on the own weight of the component,

$k_{AL}$ – proportionality constant.

the approximate price of the component

$$c_o = c_{oo} + k_{AC}A$$

$c_{oo}$ – a fix value,

value proportional to the cross-section area:

$A$ – cross-section area,

$k_{AL}$ – constant.
This formula is correct, when there are small deviations from the optimum dimensions. Otherwise that relationship is more complex.

Apart from the direct costs for maintenance and repair, there are other cost components that must be considered. The costs, that are spent from beginning of using the structure until its reconstruction or replacement, are following:

\[ C_{use} = C_i + C_m + C_r + C_f + C_u + C_a - V_s \]

- \( C_i \) – inspection costs, there must be included cost of every inspection that will take place during using period,
- \( C_m \) – maintenance costs that cover current minor repairs,
- \( C_r \) – repair costs that include the costs of large repairs and reconstructions,
- \( C_f \) – failure costs, they include the whole costs that must be borne in case of a structure’s collapse or its closure (when a collapse is imminent). Nevertheless, we assume that failure will happen only with some probability \( P_f \), in this case
  \[ C_f = C_{ff} \cdot P_f \]
  The costs of a failure \( C_{ff} \) should cover the direct costs (e.g. replacement), and the indirect costs caused by the collapse (e.g. damages).
- \( C_u \) – user costs that must be borne in case of any delays or e.g. the necessity to use longer alternative routes (for bridges),
- \( C_a \) – additional costs, e.g. repair works on nearby localities, more expensive night work,
- \( V_s \) – salvage value of the object at the end of the considered period (in case of reuse of structure’s materials).

In long-term planning it must be considered that there are usually economic differences in the costs at present and the costs in the future. This phenomenon is caused by interests, because the value of money that are suitably deposited increases gradually. Thus, the today’s value \( V \) in \( n \) years will correspond to \( V(1 + r)^n \), \((r – the interest rate)\). During calculation for a long period, costs should be considered as a sum of expenses arising in various times, but individual components’ values should be based on the same time \( T_o \), that take place when the
study is made. The common formula for the conversion of some component $C_{j,T_1}$ paid at time $T_1$ is following:

$$C_{j,T_0} = C_{j,T_1} \frac{1}{(1 + r)^{T_1 - T_0}}$$

However, due to inflation the prices of work, material and components are on steady growth, and the profits from an investment are smaller. In case if the interest rate was close to the inflation rate, the profit would be negligible.

4. Available tools and methods for LCA and LCC

Nowadays, it can be observed very rapid development in every field of technology, including construction industry. Using Life Cycle Assessment Tools can be brought to some additional concerns with the ever-changing materials and production methods. Therefore, it is necessary to create such LCA tools that can be constantly improved, with no long breaks in the use of them.

Despite the fact that in every country there are different researchers and developers, the life cycle assessment methods are similar, although there exist some distinctions which make some problems to reach a global agreement in this issue. The global methodology for life cycle sustainability analysis of constructions is presented in Figure 5.

![Figure 5. Global methodology for LCA](source [20])

An Environmental Life-cycle Assessment (LCA) is usually used to measure the environmental performance. This interpretation assumes that all phases in the life of a structure have influence on the environment and for this reason must be analyzed.
A Life Cycle Cost Analysis (LCCA) is used to assess the economical performance. In a LCCA all costs related with the construction in the different phases over the life-time are considered and discounted to their present value (which is the base data of the analysis).

There may be also considered socio-cultural aspects, but comparing with environmental and economic aspects, it is much more difficult to do it. Nevertheless, social impacts are crucial and they may affect on choices related to the best environmental and economical solutions. Unfortunately, socio-cultural aspects are still in an incipient stadium and should be developed constantly.

The Life Cycle Assessment Tools may be divided into two types:
- LCA Tools which are used by people who focus on results not on the method (LCA), nevertheless all work is based on LCA but not directly;
- LCA Tools for people who are proficient in the LCA method.

In construction industry much more important is the first category. The tools may be used at different levels of the building process:
- at the product level,
- at the whole building design level and a building assembly level,
- at a building maintenance level.

4.1. Life cycle of construction project

Despite the fact that LCA methods are developed in different countries in the world, they all are based on a similar procedure and main rules of LCA are preserved. Nevertheless, there are some distinctions. In following part of the work will be presented two of Project Management theories: GDCPP and RIBA Plan (both of them are used in the United Kingdom), described in [12]. This examples show that different called procedures boil down to similar actions, and finally to similar results.


This method was created by the University of Salford (the United Kingdom) in 1998. GDCPP is a high-level process map which aim is to help companies to improve design and
construction process. This map is based on principles that were developed within manufacturing industry at every level of production.

A Process Map Creation Tool and a Process Information Management Tool are forming the Tool kit, which help users to create their project map, that is based on the Process Protocol framework. The Process Protocol is a set of documentation, definition, and procedures. It provides a seamlessly work in the organization of a construction project. The Process Protocol is composed of 10 phases.

1. Demonstrating the Need
In the first phase are established the business needs of a client, they are defined in detail so as to avoid any problems. There are also identified the key stakeholders with their requirements, that enable to develop the Business Case which make a part of overall business objectives of the client.

2. Conception of Need
The needs established in the first phase are developed into a structured brief. The whole number of project stakeholders are identified, besides their requirements are captured. Thus, the aim of this part is to answer the question: “What are the options and how will they be addressed?”.

3. Outline feasibility
Different options should be presented as a solution for the problem. The feasibility of the project is examined so as to decrease the number of solutions in a further consideration. They ought to match the best with the business needs and objectives of a client.

4. Substantive Feasibility Study and Outline Financial Authority
It is made a decision which solution should be developed, this is based on the results of exact feasibility studies. The goal of this phase is to finance the best solution for a development of a concept design and outline planning approval.

5. Outline Conceptual Design
According to the project brief, the chosen option is transformed into an outline design. Potential design solutions are presented to choose one of them. There are also identified some of the major design elements.
6. Full Conceptual Design
The chosen solution should include the conception of a design which is presented in a more
detailed form. Design studies may be carried out to prepare the design for an approval of
detailed planning.

7. Coordinated Design, Procurement and Full Financial Authority
The detailed information provide an opportunity to predict costs of such issues as design,
production, maintenance, and others. The full financial expertise ensures an approval of
production and construction works.

8. Production Information
The details of the design are determined so as to start an advanced planning of a construction
and enable to start works. After this phase should not be introduced any changes. Then the
design ought to be optimized considering the whole life cycle.

9. Construction
The construction should be free of troubles, which should be ensured by the design fixity and
consideration of every constraints. If any problems are identified, they must be analyzed so as
to preclude a possibility of their re-occur in the future.

10. Operation and Maintenance
The product is handed over to the client. If some areas need more consideration in future
projects, it should be specified in the post-project review. The creation of learning
environment should be emphasized for everybody. When the build designs are finalized, they
are deposited for future use.

4.1.2. RIBA Plan (Royal Institute British Architects Plan)
RIBA Plan is one of the method for operation of the construction of buildings. The idea of
this method is related to a logical sequence of events that provide making correct decisions.
RIBA Plan assumes appearance of the following work stages:

- Preparation
  Appraisal
In this part there are identified client’s needs and objectives, besides there are checked
possible constraints on development. It also takes place an assessment of many options so as
to make it possible that the client decides whether the process will proceed.
Design Brief
Client should confirm his requirements and constraints, so as to create initial statement of requirements. Besides there are carried out identification of methods, procedures, organizational structures and selection of consultants and others specialists who will be employed in the project.

- Design
  Concept
The Design Brief is put into practice, furthermore there are prepared additional data and Concept Design that include outline proposals for structural and building services systems, specifications and preliminary cost plan. Is made a procurement route review.

Design Development
It is developed the concept design, for example with including structural and building services systems, updating cost plans and outline specifications. Project Brief is being completed. Application for a permission of detailed planning.

Technical Design
The technical designs and specifications are being prepared, so as to choose components and elements of the project and get information for construction safety and statutory standards.

- Pre-Construction
  Production Information
Production information in sufficient detail are prepared to make it possible for tenders to obtain them. Application for statutory approvals. There are prepared further information for construction which are required under the building contract.

Tender Documentation
A tender documentation is prepared and collated in sufficient detail so as to make possible for tenders to be obtained for the project.

Tender Action
Potential contractors and specialists for the project are identified and evaluated. Tenders are obtained and appraised, besides recommendations are submitted to the client.

- Construction
  Mobilization
The building contract is permitted, and the contractor is appointed. The contractor gets crucial information. Site is handed over to the contractor.
Construction to Practical Completion

Practical Completion is contracted to do by the administration of the building. Further Information are provided to the contractor when it is required. Information are reviewed by contractors and specialists.

- Use

Post Practical Completion

The building contract is administrated after practical completion and final inspections are made. Building user are assisted in initial using period. Project performance in use is under steady review.

4.2. Examples of Life Cycle Assessment software tools

In following part of the work will be presented examples of software tools that are used in construction projects in different countries. All of these tools are based on LCA and LCC methods.

4.2.1. EcoProP

EcoProP is Finnish tool that is being used for life-cycle design. It was created taking into consideration international and Finnish standards, norms and classifications. This tool is based on a generic classification of building properties. EcoProP is used as a guide for designers and lets producing the design brief. It was made as an Excel add-on that provides a performance of requirements for building construction projects.

At beginning of work with EcoProP it is necessary to choose a type of the building. That lets to omit unnecessary requirements in the tool, focused on different types of the buildings. Then it is created a performance profile from selected requirements.

The main abilities of EcoProP:

- documenting selected requirements and targets,
- creating a brief as an end result of the requirements setting session sequence,
- finding out about the target performance level of the building,
- comparing with other buildings.

The best results may be gained when EcoProP is used with web browser that provides a possibility to cooperate despite the distance between the project team members.
4.2.2. **Building for Environmental and Economic Sustainability (BEES)**

Building for Environmental and Economic Sustainability (BEES) is a software tool that can be used to select the most cost-effective green building products. The BEES is developed by the NIST (National Institute of Standards and Technology) Engineering Laboratory’s Applied Economics Office. The technique which is used in the BEES is based on consensus standards. Nevertheless, this tool is designed in practical and transparent way, and can be used by designers, builders as well as by product manufacturers. The BEES includes environmental and economic performance data for 230 building products.

The BEES uses an approach specified in the International Standards Organization (ISO) 14040 series of standards so as to measure the environmental performance of building products. The approach is based on the environmental life-cycle assessment, thus all environmental impacts should be analyzed. The whole life is divided into stages as following: raw material acquisition, manufacture, transportation, installation, use, waste management. In order to measure an economic performance, it is used a life-cycle cost method by the American Society for Testing and Materials (ASTM). This technique includes the costs from all the stages of the building. In BEES following environmental impacts can be considered: global warming, acid rain, resource depletion, indoor air quality, solid waste, eutrophication, ecological toxicity, human toxicity, ozone depletion, smog.

At beginning of using the BEES it is necessary to decide about importance of environmental and economic performance. In order to do this must be set importance weights. Otherwise, when we do not want to combine environmental and economic performance, it is possible to select option “No Weighting” and then results obtained in the BEES analysis will be separated. It is also necessary to set importance weights for the environmental impact categories. It should be kept in mind that impacts cannot be considered as a single, because the relation between them is usually very strong and some change may affect on other impacts.

4.2.3. **ATHENA ® Impact Estimator for Buildings**

The Impact Estimator makes it possible to evaluate and compare the environmental implications of designs (industrial, institutional, commercial, residential) for new buildings as well as for renovations. This software may also differentiate between rental and owner-occupied facilities. The influence on the environment is considered at the conceptual stage of
a project as much important as other more traditional design criteria. Thanks to the best available data the Impact Estimator is able to model most of the building stock.

The environmental impacts that are taken into consideration by the Impact Estimator are following:

− Material manufacturing (including resource extraction or recycled content);
− Transportation;
− On-site construction;
− Variation in energy use, transportation and other factors depending on a region;
− Type and lifespan of a building;
− Effects of maintenance and replacement actions;
− Demolition and disposal.

The Impact Estimator allows to enter the intermediate results of any simulation so as to calculate the overall results. Despite the fact that LCA is a complicated process, the way of using of the Impact Estimator has been designed so as not to make any problems for its users.

At beginning of using the Impact Estimator it is necessary to put required information, e.g. geographic location, building lifespan, type. Dialogue boxes suggest users different assemblies that describe building, e.g. the width, span, live load of a floor assembly. The user of the Impact Estimator, as a result, gains cradle-to-grave implications in terms of:

− Primary Energy Consumption,
− Acidification Potential,
− Global Warming Potential,
− Human Health Respiratory Effects Potential,
− Ozone Depletion Potential,
− Photochemical Smog Potential,
− Eutrophication Potential,
− Weighted Raw Resource Use.

When all the data are put into the software, the Impact Estimator builds a “tree” of information. Thanks to this it is easy to identify each individual assembly. Another possibility of the “tree” is to display the impact of each assembly in terms of a selected measure (e.g. global warming potential), and the result is given as a value or percentage. All these abilities
let the user to monitor the effects of each assembly, or to check what is the reason of some environmental effect.

Final results can be presented in tables or graphs for each of assembly group and in every life cycle stage, and show details divided into groups depending on type or form of energy. Possibility of comparisons in the Impact Estimator gives users a chance to change the design, so that to find the best environmental solution.

### 4.2.4. ATHENA® EcoCalculator for Assemblies

Detailed assessments which were completed with the ATHENA® Impact Estimator for Buildings is used by the EcoCalculator for Assemblies. The ATHENA® EcoCalculator for Assemblies allows its users to get an access to LCA results for hundreds of building assemblies. An application of the EcoCalculator can be for new construction projects, as well as for retrofits or major renovations. It can be used for most of the structures, to compare assemblies, and also to assess all of the assemblies in one structure.

First, it is necessary to select one of an assembly sheet from the categories as following:

- Foundations and footings,
- Windows,
- Columns and beams,
- Interior walls,
- Intermediate floors,
- Roofs,
- Exterior walls.

Each category contains some assemblies and their number depends on the possible combinations of materials and layers. All the assemblies are assessed depending on following performance measures: global warming potential, embodied primary energy, pollution to air and water. In order to develop results, the user may point to the area represented by assemblies. Assembly types can be evaluated by users within a category so as to get a total environmental impact for a category. All results are showed in tabular form and may present how they are changing depending on adjusting the inputs by user. Thanks to this it is possible to consider different assembly options changed by environmental impacts. This information provides making correct, scientifically-based choices.
The LCA results generated in The ATHENA® EcoCalculator for Assemblies take into consideration:

- Resource extraction, processing;
- Products manufacturing;
- On-site construction of assemblies;
- Transportation;
- Maintenance or replacement cycles during an assumed building service life;
- Demolition, transportation to landfill.

There were made some assumptions to provide good comparisons between assemblies, for example all results are showed on a per unit area basis, and it is assumed that assemblies will be used with a 60-year lifespan (maintenance, repair, and replacement schedules of building cover materials).

4.2.5. Building Life-Cycle Cost (BLCC) Program

The BLCC is an American program that was programmed in Java. The BLCC provides economic analyses by assessing the relative cost efficacy of different buildings, systems related with them, and components. The BLCC software is usually used to assess different designs that during their project life have higher initial costs and lower costs related with operating, than this designs which have the lowest initial costs. Such a conduct is very useful for renewable energy projects to evaluate the costs of energy and water conservation.

The life cycle cost of a few alternative designs are calculated and compared by the BLCC so as to specify the project with the lowest LCC which means more economical in the whole lifespan. For alternative designs can be also calculated by the BLCC comparative economic measures.

The BLCC software is able to assess projects of new as well as existing buildings. Moreover, despite the fact that the BLCC is designed for decisions related with buildings, it can be used to assess every alternative designs provided that higher capital investment costs will result in lower future costs related with operating.
4.2.6. Environmental Impact Estimator

Environmental Impact Estimator created by the Athena Institute is a North American LCA tool accessible in English language. Environmental Impact Estimator can be used to evaluate the whole building or only at its assembly level. The software of Environmental Impact Estimator can be used by architects, engineers and researchers to model most kinds of the building stock in North America.

The results obtained in the Environmental Impact Estimator software are shown in the best way the user needs it, in various levels of detail. There can be specified energy forms, waste substances, life cycle stage, assembly type, etc. The Environmental Impact Estimator can compare five different designs at the most at the same time.

The Environmental Impact Estimator includes the operating energy conversion calculator which is very useful. It has very wide options and can carry out energy simulations much better than other tools, because it computes emissions from operating energy, and in addition the Environmental Impact Estimator takes consideration of the pre-combustion effects of making and also moving energy. Furthermore, there are features that contain an "end of life" module, that can be used to simulate demolition energy and final disposition of all the materials included in a building.

4.2.7. LEGEP

LEGEP is a tool available in German and Italian language and it was created to carry out integrated life-cycle analysis. All the documents obtained during work with LEGEP follow the rules of ISO 14040-43. The LEGEP is used by designers and engineers to help in such actions like design, construction, quantity surveying and evaluation either new or existing buildings or products related with building industry. The LEGEP includes database, based on German standards DIN 276, which contains the specification of elements of a building and their life cycle costs, based on German standards DIN 18960. As LCA method assumes, information is divided along life cycle stages: construction, maintenance, operation, refurbishment and demolition. The LEGEP specifies the energy needs for heating, warm water, electricity and costs of them. The environmental assessment is based on standards ISO 14040 – 43 and also includes the material flows – input and waste.
The LEGEP is using four software tools, each of these tools has its own database. The method assumes planning by “elements”. Organization of the database is hierarchic, and starts with the LCI data at the lowest level, next are building material data, description of work process, simple elements for material layers, composed elements, macro elements (building objects) at the end.

At each level elements are equipped with data considering cost, energy, and mass-flow and impact evaluation. To characterize a building can be used preassembled elements, it is also possible to define elements from scratch, and to define a composition by making exchanges of layers. The top down approach is very good because of its completeness, in case if an some element is not significant changed or eliminated it will still be considered in the computation.

The SIRADOS database is used to specify the costs of all the elements, the database is updated each year. About 8,000 elements are “ready for use” for the landscape work, building fabric, and technical equipment. The life cycle inventories are based on the data collected in Ecoinvent and the Baustoff Ökoinventare. The work is supported by ready-made data of buildings, construction elements and work specification, that includes 2500 buildings, 8000 elements and 20000 specifications, which are evaluated by means of the transformation of work in energy and material flows. Besides, this database can be modified by the user to get his own set of elements.

Every building can be characterized in three alternative ways: with 15 macro elements, 40 complex elements, or about 150 simple elements. Thanks to this it is possible to keep up with changing data during the design and planning process, moreover this solution allows to describe the project more in detail without losing the framework. The LEGEP is able to evaluate and document entered data at each level.

At each phase are obtained results which contain related costs, set of energy, mass-flow and environmental indexes. The LEGEP can present separately indexes or all of them together, for each life-cycle stage of the building (construction, operation, maintenance, refurbishment, demolition). The LEGEP lets its user to obtain the official document of energy demand, besides it supports computation based on specific climate data and realistic energy consumption. All the LCA outcomes are presented in the database of the construction elements, which further are put together to model a building. The user gets a whole LCA analysis of the building, including construction, operation, refurbishment and demolition.
Every estimation obtained in the program can be exported and implemented to other documents. The outcomes can be compared with other elements or building. In the LEGEP are included tools which are responsible for comparison of projects (several variations of one project, or between a few reference project).

4.2.8. Eco-Bat

Eco-Bat is a software tool that assesses environmental impacts generated during the whole life cycle of a building. This program is available in English, French, and Italian language, and can be used by architects and engineers during the conception phase of a project or to evaluate environmental impacts of existing building. The assessment is based on impacts coming from energy demand and construction materials. Each of the building may be characterized by different elements (e.g. walls, windows, roofs), which can be made of various materials, selected from a database of more than 60 construction materials. The consumption of energy may be specified by energy vectors (e.g. fuel, electricity) selected for the various kind of consumption (e.g. heating, lighting).

Results obtained in the Eco-Bat are presented in detailed numerical and graphical forms, and can by divided: global, by elements, by materials, by phase. The tool allows the user to quickly assess the environmental impacts of a building. In easy way can be visualized effects depending on a construction material or an energy vector.

The Eco-Bat software do not support the life cycle inventory. The life cycle assessment methodology used in the Eco-Bat is based on ISO 14040 standards, according to them there should be taken into consideration the main stages of the building life. Obtained results are easy to interpret thanks to instant information presented in chart or numerical form, and considering building at each of its stages. The Eco-Bat uses its own database of materials and energy production installations, which is based on values taken from the Ecoinvent database and from the KBOB LCA recommendation list.

The following features are provided by the Eco-Bat:

- Different construction elements (e.g. walls, roofs, floors) can be added and their materials composition can be selected, so as to define buildings in simple way.

- In order to define the construction there are accessible over 100 generic materials (e.g. concrete, wooden products, metals). Besides there may be used additional data which were compiled basing on information coming from professionals.
The Eco-Bat takes into consideration all the transports from the place where it was manufactured to the construction site. There are two options to take into account transportation: the first uses the pre-defined standard transports valid for Switzerland, in the other is used the transportation editor and all the parameters have to be put manually by the user who determines such parameters like distances, or vehicles used for each material.

In computation of the environmental impacts are taken into consideration six categories of energy consumption: heating, domestic hot water, cooling, lighting, ventilation, electrical equipment. The user should set the energy needs for all of them and choose the technical installation used.

The pre-sizing module of Eco-Bat can be used to calculate the energy needs of the building. In this module the energy needs are assessed by taking into consideration the type of use, the type of premises and the energetic norm that the building must be applied to.

Beyond commonly used indicators, user can add others. Nevertheless following conditions should be met:

- Results should be presented in numerical and graphical form on three following levels: the whole building, elements and materials of elements.
- There should be possibility to compare different projects created in Eco-Bat with a special tool. In Eco-Bat exists a tool which allows the user to monitor the assessment of the environmental impacts during the whole building lifespan. All the data can be identified (e.g. materials replacement).
- Results ought to be presented in numerical and graphical form in reports.

4.2.9. LTE-OGIP

LTE-OGIP is a tool available with interface in German language. This software tool allows architects and engineers to make an optimization of such resources like costs, energy, and environmental impact. The LTE-OGIP is based on the life cycle assessment method, there are computed energy and the costs used in the whole lifespan of the building. The environmental impacts is determined by standardized procedures and takes into consideration the construction and the operation of a building. The methodology of LTE-OGIP is based on BEK – the construction element method developed by Swiss Research Centre for
Rationalization in Building and Civil Engineering (CRB). Costs of the construction in this method are estimated at structural elements level (e.g. walls, floor slabs, windows), this way of action is more exact than a calculation based on costs per cubic meter. Further, structural elements are connected to the element costs division (EKG) of the CRB and to the life cycle results based on Ecoinvent database.

The LTE-OGIP’s most important features:
- the data structure is transparent,
- the data types are open – the user can control them in his convenient time,
- it is possible to add user’s own data.

In the LTE-OGIP each building can be characterized by elements, reference components and basis data. Each element has attributed its lifespan. Maintenance during the lifespan is taken into consideration in a replacement model. To each element is attached its disposal process. Construction and operation costs are taken into account (demolition and disposal costs are not). The energy consumed in the use phase does not include operations like cleaning and security.

The LTE-OGIP’s analysis can take into account: buildings, whole constructions, construction elements, building works and supplies, and components. Obtained results may be presented in following categories: construction, operation, demolition. Moreover, the LTE-OGIP makes comparisons between different variants of the project, it can be also generated various diagrams, that make it possible to good communicate. All the LCI data and LCIA results can be exported to other programs and be printed to PDF files.

5. Bridge Management Systems

Life cycle analysis is widely considered as the most appropriate technique for the assessment of design, operation and maintenance of every infrastructure system. Thus, most of Bridge Management Systems (BMS) are based on Life Cycle Assessment and Life Cycle Cost techniques. Bridge Management Systems are used to manage bridges in all stages of its existence, from design through construction, maintenance and operation.

Bridge constructions are very diverse and must exist in changeable environmental, economical and operational conditions. There are required advanced tools making the Bridge Management Systems intelligent, they are equipped with the ability of recognizing, learning,
concluding, choosing and achieving goals. Bridge management systems allows for sensible planning of activities and costs associated with maintaining infrastructure facilities. Working this way lets save money and provides security of the bridge, due to the long-term strategic thinking, which is the basis for the BMS. The BMS consists of four components: data storage, models of deterioration and cost, models of optimization and analysis, updating functions.

The management systems are used to manage bridges and their technical condition. The main functions of the system are:

− bridges recording,
− technical condition assessment and graphical data presentation,
− reports creation,
− scheduling inspections,
− providing database of evaluations from inspections.

The bridge management systems should have the ability to collect images and pictures of bridges and a graphic record of damage of buildings. It also need to include tools for verification and making copies of databases and create a simplified the location map of objects.

The service life of a bridge or its components is usually uncertain. There is usually designated a plan horizon, in this time all costs of bridge maintenance should be estimated. The planning horizon is not necessarily equal the service life. For example, some existing bridge may have the planning horizon shorter than a service life, because this bridge had provided years of service before the analysis was made, and the service is provided at least to the end of the planning horizon.

Figure 6 shows how the condition of elements or a whole bridge may deteriorate, there is also defined the service life (SL). A presented situation may happen in case of the absence of any particular repairs or other actions that can change conditions of a structure.

![Figure 6. Models of bridge/element deterioration - source [13]](image-url)
An example A might present e.g. a concrete deck, where the steady damage of cracking accumulates and in the future it will accelerate a penetration of water and chemicals deeply beneath its surface. An example B may present a whole bridge, in this case the overall condition is changing through a series of many phases. Thus, the various condition phases affect on a shape of the deterioration curve. The service life (SL) is characterized as the time from handing over a building into using to an appearance of unacceptable conditions, nevertheless it is independent of the deterioration curve’s shape.

The maintenance interventions on bridges can be divided on two main types: essential and preventive. Figure 7 shows how performance level of a bridge may change depending on maintenance strategy. The optimal strategy is combination of essential and preventive strategies.

![Figure 7. Essential and Preventive Maintenance Strategies](image)

Bridges are buildings that are supposed to be the long lasting products, their age should be even 100 years. Unfortunately, time works on their disadvantage and it is necessary to repair or strengthen bridges, depending on the severity of the deterioration. It is common that there are budget limitations, which do not let for such maintenance works. Thus, it is the necessity to develop the Bridge Management Systems that in advance give information about expected danger and costs that will have to be borne in the future.

The optimum variant of the maintenance system for the network of bridges would be when the objects were repaired according to the time schedule prepared earlier individual for every bridge. This ideal case assume no limitations and priorities. Unfortunately, in real life, there are many constraints that make it impossible to deal like this.
In order to represent the relationships between condition of the bridge and its service life are used deterioration models, they can predict the level of a specific condition as a function of a use of bridge element. In case of lack of some data, and the lack of knowledge about the mechanisms of physical and chemical deterioration, and if the complexity of bridge-element behavior makes problems in development of behavioral deterioration models.

One of such an approach assumes, that the condition of an element of a bridge or of the whole construction may be characterized by a “state” in which this element currently is (e.g., good, acceptable, or unacceptable) and by possible transitions from one state to another. If some element is aging or wearing then it is represented as the gradual transitions from one state to another. The fact, if the transition will happen in a defined period of time, depends on expected loadings, management actions, environmental conditions, and other important factors. In some instances the probability may be estimated with models similar to conventional decay, or fatigue functions. It also may take place a transition to a better condition state, that may be caused by repair actions undertaken by a bridge-management agency, at least it might reduce the several inter-state transitions.

![Figure 8. A basic state-space deterioration model - source [13]](image)

Figure 8 shows a simple state-space deterioration model. Every of the three states may correspond, this changes may be result from the conclusion drawn coming from a visual inspection of a bridge. Transitions that could happen during a period of time (e.g. one year) on which the whole analysis is based are represented by the narrows. With each arrow is associated a probability of the transition. Arrows which are led from a higher to a lower condition represent aging, wear, and other deterioration. Arrows which are led from lower to higher states are the outcome of rehabilitation or repair actions. If a normal maintenance is being carried out, then it is estimated probability of remaining in the same state (acceptable or better). In case if in some state, the sum of probabilities of changing into a lower state are
higher than the sum of probabilities of moving to a higher state or remaining in the same state, the “process” will get the state of “not acceptable”. The average “service life” is the expected value of the number of periods required for the system.

One of the greatest advantages of the state-space model is that it can be used for bridge elements and the whole bridge as well. For decision makers, who decide on a design, construction, and maintenance budgets, it is usually better to apply the less-detailed perspective. As long as an overall performance of the whole construction is adequate and there are no significant problems for maintenance crew, it does not matter that some elements of the bridge may be more deteriorated than others.

Nevertheless, if data to support a more detailed analysis are available or it is necessary because of a non-sufficient condition of some element, probabilities of transition may be estimated at the element level. For example, a specific study may be required, if inspection shows that deck cracking and road salt may cause serious problems with corrosion of reinforcing steel. This study would help to estimate the probability that the bridge needs repairs within the nearest period of time.

The most important factor is the amount of money available for maintenance and repairs for every bridge. In case if each of them is repaired or reconstructed in its individual optimum time, it would be possible that at the same time more, than the possible budget would permit, bridges should be reconstructed. Meanwhile, in other years may happen stoppage and the working capacities would not be used completely. The best solution for the maintenance of bridges is to spend similar value of the money every year. Thus, the expenses should be planned for a group of bridges, assuming that every of them will be repaired in its optimal time ensuring security of using. Such a plan of the bridges maintenance ought to prepared for time interval, in which renewal should be optimistic (e.g. 20 years). Dealing this way, some bridges must be repaired in changed times, so as to the whole value of spent money for the year was close to the assumed sources. Nevertheless, in case of making changes in “optimal for each bridge schedule” there will appear a consequence, which provide to spend more money than it was supposed while summing costs for each bridge separately. Thus, these changes should be as low as possible, so as to the increase of total costs for each bridge was not high. Every of such a change ought to consider the sensitivity of the total costs (in individual variants). To find optimal solution the best way is always to compare several variants, and to choose the best one of them.
A technique called Life-Cycle Cost Analysis (LCCA) considers the economic efficiency of expenditures. In Bridge Management System this technique has a common use, it is called Bridge Life Cycle Cost Analysis (BLCCA) and refers to the various activities of design, planning, operation and maintenance. All these actions determine how a bridge ought to be configured throughout its service life. One of the reason why LCCA is used in bridge management is an effort that is made to understand that some tradeoffs are profitable, e.g. to spend more money to install more durable coatings of steel elements in order to avoid in the future frequent repainting, or acceptance of a some more costly design detail to make less costly and easier maintenance in the future. The basic steps in the Bridge Life-Cycle Cost Analysis are presented in Figure 9, it shows step by step how to proceed using this technique.

![Figure 9. The Bridge Life-Cycle Cost Analysis process](image-url)
An extended LCC analysis may be called Life-cycle cost-benefit (LCCB) analysis, in this case all indirect costs such as user costs are included. There are a few different approaches which may perform LCCB analysis, they can be divided into three levels, which come from three levels of deterioration models presented in [23]:

- Level 3 – scientific level;
- Level 2 – engineering level;
- Level 1 – technical level.

The most advanced level is level 3. Modeling in scientific level is very exact, and is based on consistent and reliable scientific basis. This model is usually used in the design of a new large bridge, for example a long suspension bridge. There are taken into account detailed information on the deterioration of the bridge, and on the environmental loading. The model on level 3 is very expensive, and it is not difficult to formulate a level 3 method. Nevertheless, it is very important to prepare level 3 models, because they supply information that are used in a level 2 model.

Level 2 is less sophisticated than level 3. Models in engineering level can be based on the average results of maintenance and the semi-physical or material deterioration parameters. There are also used many of engineering simplifications. At level 2 model are often used only a few types of deterioration to describe the deterioration of the bridge. Models made at level 2 can be used to estimate deterioration of existing structures or they may be helpful in designing of new structures. Moreover, the level 2 models provide information that can be used in a level 1 model.

The most simplified of the LCCB analysis is level 1. Level 1 draws from observations and specialist experience considering repair types, intervals and costs. Parameters that are used in level 1 have usually a limited number, they are limited by the data obtained from level 2 models. Models from technical level can be used on groups of bridges and may help in optimization of maintenance strategy. This model can be used, for example to estimate the optimal intervals between preventive maintenance activities.

Apart from mentioned issues, there must be considered several other factors that may cause a problem in a bridge management:

- the condition of each bridge is individual and every of them behave in the other way, depending on conditions on and around it (e.g. loading, traffic),
there must be ensured steady inspection on the rate of deterioration, because some bridges that are in a better condition may deteriorate faster, in this case a repair should be carried out sooner,

− some of the bridges are more important (and the others are less) in the network or in region (the importance of the route has often influence on it),

− it must be taken into account unpredictable events (flood, traffic accidents) which may have a strong influence on condition of bridges.

The bridge maintenance optimization process may be divided into three following steps.

1. Condition rating

Firstly, each bridge should be ranked according to its condition, which is determined by inspections, after this it is possible to characterize the condition of each part of the bridge (e.g. pillars, girders, carriageway). It should also be considered failure consequences and the possibility of a collapse. This selection reduces the number of bridges for further steps, because only these of them which are in a condition worse that some limit value, are taken into account in the next step.

Another criterion of rating may be the remaining life till the reconstruction of the bridge. In this case, it is combined the current condition with the rate of deterioration. The more reliable is this estimate the more available are the data from inspections.

2. Bridge importance

In the second step it is considered how important are individual bridges in the whole network of roads and railways. Even though some bridges may be in a worse condition than the others, usually it is taken into consideration on how important road they are situated. The consequences of failure or closure of the bridge for long time would be worse in a main road with big traffic than in a rural area. The priority is to repair in the first order bridges that serve as more important.

In the pre-selection it can also be considered more aspects, e.g. the importance of the particular bridge due to its width, importance of the route and the traffic volume. This action will reduce the number of candidates and make the next step easier. At first it should be chosen those bridges, which are ranked in the highest places according to both the condition and other importance criteria.
3. Money allocation

In the third step, taking into account the total amount of money the individual maintenance strategies are compared, besides there are considered the work capacities necessary in individual years. After these analysis within the longer period the best strategy is chosen. It ought to be economically most favourable. So as to get the best solution there are used various techniques, including linear programming. It may happen that the choice is caused by other criteria, like the repair of bridges on one route. To sum up, the maintenance strategy for the bridges should assume that the condition of the bridge stock as a whole should gradually improve, not get worse.

It can be specified the following basic system functions for all types of bridge structures occurring in the BMS:

1. Inventory
Describing administrative data (e.g. structure identification, its location), basic technical data (e.g. construction type, dimensions, materials), collecting structure photos and drawings.

2. Technical Condition and Safety
Collecting the data from all types of inspections (e.g. characterizing damages, needs for maintenance works, estimated costs), evaluating a technical condition and safety of a structure, and deterioration models.

3. Deterioration Models
Creating models that may predict the level of a condition of specific element of a bridge, and determine if it is acceptable or not for further using. Deterioration models are based on scientific examinations, experience gained earlier, or observations of similar elements in another bridges.

4. Serviceability and Operation
Describing service parameters of the structures (e.g. load capacity, speed limit), evaluating serviceability and service life, determining important events in the life of the structure (e.g. maintenance works, collisions), carrying out an administration of overstandard transports.

5. Planning and Budget
Preparing maintenance strategies, making economic evaluation, optimizing maintenance works, preparing short- and long-term budgeting.
5.1. Examples of Bridge Management System tools

In following part of work will be presented a few existing Bridge Management Systems, that are used currently in different countries. There are many more BMS which are used in other countries, but principles of their operation are very similar to those presented systems.

5.1.1. Ontario Bridge Management System (OBMS) – Canada

The Ontario Bridge Management System (OBMS) started being developed in 1998 and for the first time was it implemented in 2000 as a help in the bridge inspections and data management features, which are used by inspectors in ministry regional offices. However, analytical features of the software were completed in 2002 (Version 1.0), the current version of OBMS is Version 2.0.1 (2008).

The navigation among the data in OBMS is provided by three ways:

− Table View

In the database in a table form are collected all structures with the data about each of them. To select a subset of structures are used filters. So as to create building reports or charts, it is possible to export the whole data in Table View to MS Excel. It may also be printed directly blank inspection reports.

− Map View

All the bridges taken under consideration are presented through a geographical information system interface, that was built using map objects. This option can be used to select and locate a bridge site, it can also be used to create a thematic map by using a filter or by detailing ranges for the values of some field.

− Detail View

When a site is selected From Table View or Map View may launched the Detail View, that presents a drop-down list of sites and the data about any selected bridge presented in a tree. The Detail View enables to see all the and project-level data, inspections, and inventory associated with a bridge.

OBMS supports the decision-making processes which is provided by the system that includes:

− Monitoring – inventory and inspection updating;

− Needs identification – analysis of the data of a bridge and its elements so as to decide what work is needed;
− Policy development – analysis of the economic aspects of planning models and policies;
− Priority setting – deciding on the timing and order of projects;
− Budgeting and funding allocation – trade-off analysis of performance versus funding, the life-cycle cost analysis in OBMS is performed over a program horizon of 10 years, with long-term effects extending to 60 years.

OBMS provides an assessment on two levels:
− Element level
Detailed Visual Inspection identifies and quantifies defects and assigns the element into one of four condition states. This action is based on performance measures of load capacity, safety, and performance.
− Structure level
Condition of a bridge is evaluated by Bridge Condition Index (BCI) out of 100, based on element level condition (e.g. barriers/railings, curbs), besides it is rated load capacity and compared with load limits.
Moreover it is possible to make an appraisal for fatigue, seismic effects, and flood.

5.1.2. DANBROweb Bridge Management System – Denmark

DANBROweb is Danish bridge management system that focuses on the day-to-day management of bridges or other structures. DANBROweb is a whole web-based system, and nothing needs to be installed before the system will be used. It was designed for using by many people with very different level of education and with different backgrounds. It was put a big pressure on making the system easy to understand and operate. The final effect was achieved in several ways:
− For each user of DANBROweb it is possible to see only functions and the data that are relevant for him, management of this function belongs to the user administration;
− The system makes it possible to adjust the inventory exactly to different types of structures so as to omit filling out the data fields that are not crucial for the considered type of structure;
− Only an individual job is visible for the user who is at the stage of bridge’s life, it is provided by the activity management.
The aim of using DANBROweb is to provide to agencies a tool which let to collect objective data about bridges, help in optimizing the use of the assigned funds, guarantee a technical-economic backup and the safety and functionality of a bridge.

In order to manage the structures by the system there is defined a six-level element hierarchy. Documents may be attached to any element belonging to any level. Categories that are used to divide the documents are following: photos, inspection reports, drawings, and specifications.

A work with DANBROweb starts with carrying out the principal inspection which is a visual inspection of all accessible parts and elements of the bridge. The goal of this action is to get an overview of the condition of the bridges that are taken into consideration, afterwards it is possible to find out more about the main damages and how urgent are works, so as to carry them out in the optimum time. All the data are put into system. The database is divided into following registers:

- system register, that contain data catalogs which are used by the system,
- basic register, containing basic data about bridges,
- bridge information register, in which are accumulated information about the structure geometry, its condition evolution, and administrative data,
- maintenance alternatives register, in which are repair strategies for each bridges,
- budget register, that includes estimations for the maintenance alternatives,
- intermediate registers.

The Principal Inspection Module of DANBROweb assumes that, each bridge and each of its elements’ condition is assessed using ranging from 0 (no damage) to 5 (complete failure of the component), in case if it is important, it should be done a short description of damage and there ought to be added photos. All the needs for inspections and possible repair works are announced as requested works. All these activities may be presented in the inspection screen, that gives an overview of the condition of the bridge and its elements and the activities planned to mend the registered damage. The manager commissions the contractors to do the jobs, and afterwards if result of them is satisfactory, he accepts the completion by changing the job status to “Completed” in the system.
5.1.3. **Eirspan – Ireland**

Eirspan is the Irish bridge management system, that is used to manage bridges which total span is equal to or greater than 20 m, the bridges considered by Eirspan are on the national primary or secondary road networks.

Figure 10 shows the bridge management system organization in Ireland where the flow of information is provided by Eirspan. The NRA is an abbreviation for the National Roads Authority. The important thing is to put the data as precisely as it is possible, because on it depends proper operation of the whole system.

![Eirspan organization chart](image)

**Figure 10. Eirspan organization chart**

The Eirspan BMS is consists of following activities:

- Inventory gathering

The inventory gives users an overview of a structure and at the entire structure stock. So as to print out reports of inventory data may be used the database. It consists of the name, identification number, location of the structure, the type of crossed obstacle, the date of construction and any reconstruction, the types of superstructure and substructure, construction materials, the geometric data (e.g. lengths, widths, skew) and the structure component details (e.g. type of bearing, joints).
– Principal inspection
The principal inspection is a visual inspection carried out in steady time intervals, and its goal is to evaluate all accessible parts of the structure. During the principal inspection are not made any tests. The main aim of them is to assess the need for repairs, moreover to monitor the performance of routine maintenance and observe how are changing in the condition of the structure. There are specified 13 standard bridge components and the condition rating is applied to each of them. An overall rating is given for “structure in general”. The rating’s scale begins from 0 (no or little damage) to 5 (the failed component or a danger of total failure, that may cause implications for traffic safety).

– Special inspection
A special inspections are carried out by a private consultants. Their task is to determine in detail the extent, nature and reason of damage to a bridge. Moreover, the inspection is necessary to make a detailed assessment of the damage and to prepare scheme of the most suitable rehabilitation.

– Optimization
In this module are used the economic analyses based on the special inspections, they consider how significant will be any economic consequences to society, in case if the works were postpone. The costs which may be borne as a result of such a behavior can be divided into two groups: the direct cost (extra repair work which are caused by a further deterioration); and the indirect cost (e.g. costs of road user delays due to, weight restrictions or even bridge closure). The programme requires such parameters like the budget for the first five years of using, and the prices of the repair strategies being result of each special inspection.

– Ranking of repair works
Ranking of repair works includes an overall priority list of bridges that need to be repaired or rehabilitated. Identification of the structures that require repairs takes place during the principal inspections. In Ireland the ranking is carried out by the bridge managers on the regionally level, then they meet annually with the NRA Structures Section so as to choose high-priority schemes for the next year.

– Routine inspection, maintenance and cleaning
Routine maintenance works are executed at regularly intervals and provide such works like for example, removal of vegetation or cleaning the drainage system.
− Price book

Price book provides updating overview of structural repair work’s prices. The prices are used in drawing up cost estimates for repair works, that were required after principal inspections and for pricing repair strategies described after special inspection.

− Budget and cost control

In this module are gathered information about costs and work progress for all of the rehabilitation projects carried out at any time. Users can control the costs of design, construction and construction supervision. Budget and cost control module can be used to prepare a review of total allocated costs as well, what make easier to control budget throughout years.

− Archive

All the important documentation is registered in the archive module registers, besides it can state where original paper copies are kept. From this part it is possible to get a chronological overview (and get it printed) of all of the events and activities in the whole lifetime of a bridge, such as design, construction, inspections and repair works.

− Technical approval

The design of new bridges, and all made structural alterations to get approval need to be put into an independent technical approval database. This module is be used only by the NRA project managers in Dublin, they are responsible for any technical approval.

5.1.4. SMOK – Poland

SMOK is Polish bridge management system that for the first time was implemented in 1997 as a help in a maintenance of bridges located on railway lines. Current version was released in 2007. SMOK is equipped with a number of expert functions that support main decision processes, the Expert functions are following: Data Compatibility, Bridge Evaluation, Diagnostic, Forecasting, Load Capacity, Clearance, Serviceability, Transport Planning, Rehabilitation, Planning, Optimization.

The data collected during the inspections are used for the evaluation procedure. In SMOK exists a uniform system of damage classification and identification, which helps in an assessment process. It has been defined an individual List of damages for each existing combination of the following parameters:
- Type of the structure (e.g. bridge, viaduct, culvert, retaining wall),
- Type of the structure element (e.g. support, main girder, deck),
- Type of the material (e.g. steel, reinforced concrete, prestressed concrete),
- Type of the construction (e.g. plate girder, box girder).

This all gives a lists of about 200 individual damages. In order to provide very precise identification of the damages in the system, there has been worked out the Bridge Damage Album, which can be used by the users of this Bridge Management System. The Album consists of a printed manual and about 1000 photographs of bridge structure damages.

All damages ought to be unified so as to facilitate the work of the bridge management system SMOK. They are classified and described, there are distinguished following main classes of damages: damages of surface protection, material destruction, losses of material, cracks, fractures, deformations, movements, contamination.

Furthermore, the main classes may contain subclasses, for example, “cracks” can be divided into subclasses: “vertical cracks” and “horizontal cracks”.

The damages can be described using following basic parameters:
- Type of damage,
- Damage location,
- Damage intensity,
- Damage extent.

Information about this how to define the damage extent is described in the Bridge Damage Catalogue. An extent of the damage should be given as input data for each type of damage detected in the evaluated structure element.

5.1.5. Sistema de Gestión de Puentes (SGP) – Spain

The SGP was created in response to demand of Spanish administration for the tool that will help in conservation and maintenance of their heritage, this tools is constantly being evolved to facilitate the work of the bridge management.

The SGP, that was designed by GEOCISA, includes activities which make it possible to know in any time the whole information about the financial operation of the bridge that were made in the past and about its current situation. This knowledge allows to achieve maximum
utilization of the structure in its whole life and to optimize rationally the finances that are meant for it, moreover SGP can be adapted to the specific needs of each administration.

It is a centralized system with a structure very similar to other systems. The SGP is equipped with a program of inspections, which are structured according to their importance. The program includes papers with instructions and guidelines for carrying out such inspections. There is also accessible the function which detects works whose condition status points to necessity of some works.

There are three factors that are used to assess each damage (extension, intensity and evolution), so as to avoid subjectivity criteria are fixed. Structure and its elements have ascribed an index from 0 to 100, that is based on all their damages. This is called an element index and on it depends assessment considering safety risk assessed from damage. For the index ranges are determined criteria. This index may be changed by the inspector.

The SGP consists of a database which includes existing information about structures, makes it possible to upgrade a system and develop the data. It is divided into four different modules:

- Inventory Module, that provides the information about the location and identify all the structures, besides it collects the basic data relevant to each work.
- Module of Conservation, allows to identify a condition status of the structure at any time.
- Operating Module, that determines possible actions which must be taken depending on the condition status of the structure, taking into account the approximate costs of such actions.
- Economic Control Module, enables to manage the investments that are planned.

The data are put into system manually. There is no need to have an access to the network in that moment, because the data may be later uploaded to the database. It is also possible to put the data directly into the database.

**5.1.6. Pontis – United States of America**

Pontis is a predominant bridge management system in the USA. It is now in its next major version (4.5 Client Server – 2009 and 5.1 Web Version – 2009). Pontis supports the bridge management cycle, including inspection and inventory data collection and analysis, it also
recommends an optimal preservation policy, forecasts bridge life-cycle deterioration and costs, and is used to predict needs and performance measures for bridges.

The whole bridge management cycle is supported by Pontis, and it is possible to make changes in the data at every stage of the process. The most important features of Pontis:

- project planning, inspection, preservation;
- comprehensive bridge data presentations;
- handling with multimedia like links to photos and drawings of a bridge and inspection;
- reporting, data management;
- access to a common bridge database;
- comprehensive help accessible on-line, technical manual, user manual, and other resources that support using.

The main benefits that offers using of Pontis:

- comprehensive support for the whole bridge management cycle;
- the help for agencies to make good, justifiable, and repeatable investment decisions concerning their bridges;
- application of cost-minimizing strategy for the bridge network and estimating the impact of any deferring needed repair, maintenance, and rehabilitation action;
- compatibility with National Bridge Inventory (NBI) data validation and reporting and requirements;
- agencies are provided with a cost-effective, proven bridge management solutions.

Agencies that use the product can define in the Pontis program simulation their own elements of bridge, deterioration models, and agency business process rules. There may be personalized screen layouts, data entry, and reports forms. Moreover, agencies can customize the Pontis database, add database tables, build their own external applications for connecting to the database, besides it is possible to build interfaces between the Pontis database and other databases.

5.2. Comparison of Bridge Management Systems

Below is presented a table (Figure 11), that includes the main information concerning 18 Bridge Management System that are used in various countries around the world. Some of them were in detail described in previous point. Table is based on information included in paper [14].
<table>
<thead>
<tr>
<th>No.</th>
<th>Country</th>
<th>Bridge Management System</th>
<th>Assessment on element level</th>
<th>Assessment on structure level</th>
<th>Intervention</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Canada</td>
<td>OBMS</td>
<td>Detailed Visual Inspection  - 4 condition states</td>
<td>Bridge Condition Index (BCI) out of 100</td>
<td>- defined treatments (maintenance, repair, rehabilitation, replacement) applied to element condition states, - actions, timing and costs developed from Element Level and selected based on lifecycle cost analysis (as well Structure and Project Level)</td>
<td>- detailed lifecycle cost analysis carried out for 10 years, long term life cycle cost analysis for an additional 50 years - ten year budgets (divided: years 1-5, 6-10) with prioritized projects and based on network performance measure (BCI) using the detailed LCC analysis</td>
</tr>
<tr>
<td>2.</td>
<td>Canada</td>
<td>QBMS</td>
<td>Detailed Visual Inspection  - 4 condition states</td>
<td>Bridge Condition Index (BCI) out of 100</td>
<td>- defined standard interventions for reference strategies - partly LCC – interventions are meant to be cyclic, so as to estimate the long term costs of the intervention strategies is used LCC</td>
<td>- no deterioration models in the system - a partial LCC computation, DANBRO does not generate LCC itself - planned time-frame includes 1+10 year s and used for operational planning</td>
</tr>
<tr>
<td>3.</td>
<td>Denmark</td>
<td>DANBRO</td>
<td>A condition rating (0-5) based on visual inspection.</td>
<td>Aggregated from all elements, worst condition is default.</td>
<td>- inspection handbook characterizes rules for actions that depend on the structure and damages - every recorded damage has selected repair urgency class (immediate, in 2 years, in 4 years, later or no repair)</td>
<td>- deterioration of structural elements is described by age behavior models - LCA and LCC analyses are carried out - repair programs for 6 years</td>
</tr>
<tr>
<td>4.</td>
<td>Finland</td>
<td>FBMS</td>
<td>The nine main structural parts’ condition is evaluated - 0-4 (very good - very poor).</td>
<td>The overall condition is evaluated by inspector, rates 0-4 (very good - very poor).</td>
<td>- for damages and defects are defined warning and threshold values - carrying out cost-benefit-analysis (object level) and prioritization with knapsack-algorithms (network level) - partly LCC analysis</td>
<td>- defined deterioration models (corrosion, chloride intrusion, carbonation) - defined service life model - planning period – 6 years; “prediction period” – 20 years - two scenarios (financial and quality) on network level</td>
</tr>
<tr>
<td>5.</td>
<td>Germany</td>
<td>GBMS</td>
<td>Assessed by stability, traffic safety and durability.</td>
<td>Calculated with information from element level.</td>
<td>- Principal Inspection manual includes a list of standard intervention types for each element - Costs are not stored on Eirspan, but they may be considered at a structure level (comparing repair strategies for major schemes)</td>
<td>- inspection reports define repairs and annual intervention costs of them; unit rates of repair can be provided for up to 6 years (they are inaccurate because of the associated uncertainties) - planning time-frame only for inspections (years 1 to 6)</td>
</tr>
<tr>
<td>6.</td>
<td>Ireland</td>
<td>Eirspan</td>
<td>Ratings 0-5 (best-worst) for each of 13 structural elements.</td>
<td>Condition rating (0-5) given for 14th structural element ‘structure in general’, based on worst condition rating for deck, bearings, piers, abutments or beams/girders.</td>
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</tr>
<tr>
<td></td>
<td>Country</td>
<td>BMS Name</td>
<td>BMS Code</td>
<td>Description</td>
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<tr>
<td>7.</td>
<td>Italy</td>
<td>APT-BMS</td>
<td>APTBMS</td>
<td>On the basis of a procedure Standard Element System (3-5), possibly conditions identified based on visual inspection. Different condition indices (overall CS, apparent age) computed from the condition of the single elements. Effects of standard interventions are defined, and they may be customized by user. LCC for repair and replacement scenarios.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Japan</td>
<td>BMS@RPI</td>
<td>RPIBMS</td>
<td>Condition state criteria (1-5) based on visual inspection, established on 35 different type of element and deterioration. Each element is divided into unit, the inspection is performed on unit basis. The condition of the structure is assessed as an aggregation of unit. The deterioration model curves defined with 4 deterioration speeds (for each type of element and deteriorations) - after interventions (repair, rehabilitation and replacement) is provided the level of improvement for each type of element and deterioration. LCC for the structure level, as well as unit or element level. Time-frame up to 100 years.</td>
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<tr>
<td>10.</td>
<td>Latvia</td>
<td>Lat Brutus</td>
<td>Lat Brutus</td>
<td>Elements have a condition rating (1-4) based on visual inspection. Aggregated from all elements in a structure. There are defined standard interventions on element level for reference strategies - interventions on structure level composed by user from element level. Information used for budget preparation - no information considering improvement, cost and planning time-frame.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>Netherlands</td>
<td>DISK</td>
<td>DISK</td>
<td>A condition rating (1 - 6) based on visual inspection. Aggregated from all elements in a structure; worst condition is default. Standard interventions are defined for reference strategies - interventions are considered to be cyclic, so as to estimate the long term costs of the intervention strategies it is used LCC, replacement costs of the structures are not included. In DISK is no deterioration model - a partial LCC computation - planning time-frame includes from year +1 to year +10 (later years are in the system, but they are not used for operational planning).</td>
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</tr>
<tr>
<td>12.</td>
<td>Poland</td>
<td>SMOK</td>
<td>SMOK</td>
<td>Condition rating of elements (scale 0-5) based on visual inspection and test results. Supported by the Bridge Evaluation Expert System. Aggregated from all elements by means of the predefined formula. The predefined list of actions can be used to define interventions - intervention costs are defined by user - intervention strategies are based on the ranking list (defined by the user). Information that are collected in the system can be used for planning of the interventions, assessment of their cost, and budget planning - they are collected in the system are used for 1-10 years planning.</td>
<td></td>
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</tr>
<tr>
<td>13.</td>
<td>Poland</td>
<td>SZOK</td>
<td>SZOK</td>
<td>Condition rating of elements (scale 0-5) based on visual inspection and test results. Aggregated from all elements by means of the predefined formula.</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Country</td>
<td>System</td>
<td>Description</td>
<td>Advantages</td>
<td>Disadvantages</td>
<td></td>
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<td>-----------------------------------------------------------------------------</td>
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</tr>
</tbody>
</table>
| 14. | Spain                   | SGP      | An index (0 - 100) based on all damages (element index). Each damage is evaluated by three factors (extension, intensity and evolution). | - catalogues in the database include repair recommendations  
- SGP recommends intervention strategies for each element and for the structure  
- prioritization repairs according the elements state  
- the database contains costs catalogues - calculation of repair budgets and cost forecast (evaluate the current damages) | - no information considering improvement, cost and planning time-frame  
- evolution models are not implemented                                                                 |
| 15. | Sweden                  | BaTMan   | Physical condition - the measurement variable defined for each method of measurement. Functional condition - a condition rating (0 - 3). Based on visual inspection. | - studies of alternative action strategies (economic impacts)  
- the alternative with the lowest current value cost is chosen  
- a database of unit prices for technical solutions  
- the optimal strategy calculation based on LCC | - there are simple deterioration, maintenance policy, and cost models  
- planning time-frame includes 1-20 years  
- among organizational regions is provided estimation of total needs |
| 16. | Switzerland             | KUBA     | 5-state condition rating (1-5) based on visual inspection.                  | - there are evaluated all possible condition based intervention strategies  
- inspection cost can be entered and estimated on the element and project level | - probabilistic deterioration models are based on the physical processes affecting the elements, and the impact of the interventions likely to be performed  
- optimal life cycle intervention strategies are chosen (based on condition evolution) on the element level and project level  
- interventions may be generated for up to 100 years, it is suggested to use in the first 5 years for planning on the operational level |
| 17. | United States of America | ABIMS    | A condition rating (1-9) based on visual inspection.                      | - recommendation is posted when conditions are 4 or less  
- inspection costs are stored by structure | - necessary repairs are determined for each structure  
- cost estimated by activity and stored for each structure  
- annual planning for maintenance, replacement done on 5 year plan (later years are stored)  
- information used for budget planning |
| 18. | United States of America | Pontis   | Yes                                                                         | - there are generated interventions recommended by Pontis (is possible recommendation from inspectors)  
- LCC used in cost estimation | - Pontis provides information useful in improvement and cost planning  
- information for budget preparation |

Figure 11. Comparison of Bridge Management Systems – based on [14]
6. Conclusions

Structures, bridges, and other buildings, are designed and built with intent for a long service life, many of them are meant to exist for over 50 or even 100 years. Such an attitude assumes that a significant attention is paid on the performance of an engineered system over its life span. The stance should assure a required level of reliability of performance, which ought to be carried out by inspections, repair, and even replacement. The Life Cycle Assessment is a method that can be used to completely evaluate all the aspects connected with the construction industry and the associated environmental impacts during its entire life span, including such phases like materials acquisition, creation, transportation, use, and finally disposal of the products. Life cycle assessment provides a holistic evaluation methodology and a coherent framework for helping in making better informed decisions. Results obtained in the LCA analysis may even be used as input for policy decisions, corporate management, marketing, product development, environmentally preferable purchasing programs, and carbon or greenhouse gas reporting.

The most widely used attitude of the LCA analysis is an approach described in the International Standards ISO 14040, that assumes four phases of the LCA: Goal and scope definition, Inventory Analysis, Impact Assessment, and Interpretation. Each of these phases has assigned tasks, that should be completed, so as to correctly carry out the whole process of evaluation. Besides an approach that is presented in the ISO 14040, literature describes also other approaches of LCA, for example GDCPP or RIBA Plan. Nevertheless, main rules of LCA method remain the same. There are many LCA and LCC software tools. Most of them is based on ISO standards, and some of them uses the same resources, as for example the Ecoinvent database, which make results comparable.

There exist a few variants of life cycle assessment, namely example cradle-to-grave, cradle-to-gate, cradle-to-cradle or gate-to-gate. For analyses in a building industry the most common is cradle-to-grave approach, which in the best way can present all significant issues connected with buildings.

Strongly connected with the Life Cycle Assessment is an issue of the Life Cycle Costs. The LCC is used to help making decisions in all the phases of building’s life. The LCC method is often thought to be difficult and complicated. Sometimes, the idea of carrying out the LCC analysis is given up because of too time-consuming approach and too big expanses. Nevertheless, in long-term thinking such a attitude is much stronger justified. Construction
costs are only the beginning, and there should also be taken into consideration operation and management costs, or even special costs as for example taxes. There are some formulas that describe costs of deteriorating structures, which among others are used in the whole Life Cycle Costs analysis.

In recent decades, interest in management of bridges has increased significantly. As a result, many different Bridge Management Systems, which are based on the LCA and LCC methods, have been developed so as to help in managing resources effectively and to maintain bridges in an satisfactory condition. For rational bridge management, necessary is an assessment of bridge systems under various uncertainties. Bridge Management Systems assumes not only the assessment of performance but they also are meant to predict future of bridge performance. The prediction procedure ought to encompass such time-dependent factors as resistance deterioration or increasing loadings. Furthermore, there should be taken into account the effect of future events, as maintenance interventions. Bridge Management Systems are meant to serve such functions as bridges recording, technical condition assessment and graphical data presentation, reports creation, scheduling inspections, and providing database of evaluations from inspections.

Using the LCA methods has its advantages and disadvantages as well, therefore using of it has both followers and opponents.

The desire of using the LCA tools is usually justified by the environmental protection. Major benefits are connected with possibility of systematic estimation of the environmental consequences. The LCA provides quantification the emissions into land, air and water which occur in every phase of life cycle, besides it can detect significant changes in the environmental during the life cycle phases. It cannot be left out feature of comparison of the consequences of many various competitive products, which make it easier to take justified choices. Furthermore, the LCA can be used to create a flow of quantitative information between different committed entities, as researchers, customers, governmental agents, local communities. It can be used for technology selection, process improvement, or reporting.

Nevertheless, the LCA techniques reveal some disadvantages which cannot be passed over. First of all, a LCA study is demanding economically, and high costs are deterrent for many of the organizations interested in using it. The reason of this follows from data-intensive and time-consuming procedure included in the whole LCA method. The more complete a LCA is the more time and expenses it will take. Secondly, there is not one imposed LCA
methodology for everybody, so around the world are used many different ones which differ and some of them have smaller or larger imperfections in some points. Some of the assumptions made in the LCA analysis may be subjective or they can change over the years, it might be hard to determine the boundaries, besides it must be chosen the most reliable source of data and the impact assessment choice. In general, the outcomes of such analysis are focused on national, or alternatively on regional level, and consequently they may not be adequate for local issues. Thirdly, some of the studies do not include the whole life cycle of the analyzed product, and hence it is confined to selected stages. Therefore, the shown environmental performance of the product may not be authentic and consequently the usefulness of the results is not completed. Finally, the precision of LCA studies depends on the availability of the essential data and the quality of them. In case if the data are not exact enough, the precision of the study is limited, and the final results are affected by this accuracy.
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