# UNIQUE CHARACTERISTICS OF DENMARK'S BRIDGE MANAGEMENT SYSTEM

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## ABSTRACT

Bridge Management System (BMS) is an area in rapid development. Although we have been working with this subject for nearly 20 years in Denmark, we are still adding new parts to our system. Experience obtained from working with bridge management in other countries also has influenced our system development. Thus, what we present today is a step forward from what we were able to show a few years ago. Since the last presentation of the work in Thailand, we have developed new modules for optimization and also preventive maintenance, long-term budges and a price book. We are currently working on an experience module. This paper describes the various components of our system and the status of our development. It also describes how the system is used as a tool in the road administration when dealing with the multiple tasks that have to be taken care of in the daily work.

## INTRODUCTION

Three important issues of BMS are: data needs and data collection techniques, data analysis procedures, and decision support. We will try to deal with all three issues. However before we jump into a description of how we are handling these matters in our system, we find it is vital to discuss the background for BMS: why, for whom, and how? Some may find it a step backwards, because now we want to discuss the systems and how they are working. However, it is important to have the purpose of the system in mind always. We have to realize that today is it possible to build in many fancy gadgets into a BMS. This may be very tempting, but without a constant eye on the goal we may end up with a toy and not a tool.

So again, why are we building and using BMS? We normally say that a BMS is a tool that helps us with the following activities:

- Maintaining traffic safety;
- Preserving the road network capacity;
- Minimizing maintenance costs;
- Optimizing allocated funds; and
- Forecasting the budget needs.

It can be answered in many more complicated ways, but it can also be described with the key words *to save money*. Therefore, we should always be able to see the benefit of what we are doing, maybe not shortly but in the long run. This leads to another issue worthy of mentioning. The bridge owners have two main tasks:

- to maintain existing bridges, and
- to construct new bridges.

The system should help us to get the best out of our dollars in both cases. The system will give us experience from the old bridges, so that we can construct the new bridges in such a way that they will last longer for less money. If this is the case, we have to realize that we cannot use the service life prediction from the old bridges on the new ones.

For whom are we making the BMS? The system is made for the bridge owner's use. This has to be taken in the widest sense. It should be a tool that can support everyone who is working with bridge management.

Then comes the "how?" How can we construct a BMS that will fulfil our demands and be so user-friendly that everyone involved in bridge management will use it? First the concept has to be developed in cooperation with the future users. Here we are thinking of practical engineers, who have experience in bridge management. We also believe it be fundamental that it is built up in modules that can be tested as prototypes. Secondly we have to realize that it is not possible to hit the target right in the bull's eye at the first try. We have to go back and modify already developed modules from the experience we get from using the system. Finally, and partly because of the second point, the system has to be dynamic and constantly under improvement and development.

What makes the Danish system unique is the way it combines the project level and the network level. Optimization, budgeting and planning are all done on network level but the basis for these is information collected at the project level. This means that the optimization directly identifies the works to be carried out at project level. The optimization also considers the consequences of insufficient funds, and if necessary selects alternative solutions to keep within the budget.

The system deals with all aspects of bridge management, from preventive maintenance and daily administration to forecasting development of the bridge stock. All activities are described in manuals. Bridge management is thus integrated into one system, which is unusual.

## DATA NEEDS AND DATA COLLECTION TECHNIQUES

### Data Needs

When we look at the data needs, we have to categorize the data according to their future use. The use of the data can be for one of the following purposes:

- preventive maintenance;
- daily administration;
- planning of rehabilitation works;
- forecasting of future budgetary needs ; and
- policy for research and development.

Data can be related to the bridges, or external factors. Some data are static, some are changing over time. According to our experience the collection of data must be kept to an absolute minimum. This because data have to be maintained and this is time consuming. Thus only data we know we need are collected. We may here run into the problem that some data required according to codes or regulations are not very useful for us. If so, the best we can do is to try to have these regulations changed.

The requirement for reliability is different for all data. If we get garbage into the system we also get garbage out. However, to keep the workload at a reasonable level, we should also specify the quality of the data we require, e.g., we should not measure length or width in tenths of inches. For the same reason we should ensure that the updating is done at appropriate intervals.

The static data we need will be information of a technical and administrative nature related to the design and construction of the bridges. These data are collected at the inventory.


Dynamic data required will be data on deterioration, repairs and maintenance connected with the bridges and data such as traffic, accidents, maintenance costs, repair costs, tender prices and budgets connected to external factors. The first of these are collected during inspections, the rest are from other sources.


*Preventive Maintenance*

Preventive maintenance we define as minor works that comprise remedy of pollution effects and aging or wear caused by climate or traffic. They are often neglected or overlooked despite the benefit given by regular planning and execution of these tasks. For this activity we need the information from the following sources:

- inventory, and
- planning of maintenance (budgets includes superficial inspections and costs).

*Daily Administration*

The daily administration of our bridges consists of the tasks that keep the shop running. These are, e.g., updating of databases, tendering, writing of contracts, budget control, quality control, maintaining route maps for special transports, classifying existing bridges and special transports. We use in the daily administration data from:

- inventory,
- principal inspection,
- repair costs,
- tender prices, and
- budget policy.

*Planning of Rehabilitation Works*

Within the given maintenance budget for our bridges a certain part is set aside for preventive maintenance and the rest is used for rehabilitation works. These works are of a size that requires them to be tendered out. The rehabilitation works are planned based on data from:

- Inventory,
- Special investigation,
- Repair costs, and
- Tender prices.

*Forecasting of Future Budgetary Needs*

Both for the near and far term, we have to produce reliable figures for what the budgetary needs will be if we have to keep the bridges at an acceptable standard. The data we use for our forecasting come from:

- inventory,
- principal inspection,
- special investigation, and
- repair costs.

*Policy for Research and Development*

To determine which research projects and development projects on materials to support we need data from:

- inventory,
- principal inspection,
- special investigation, and
- repair costs.

**Data Collection Techniques**

Data can be collected with techniques ranging from simple visual observation to the fully automated one where built-in instruments automatically register the data and transfer them to computers for processing. We believe that there is a place for most of these techniques in a well-developed BMS. Again, we need to use the right technique for the right purpose. We have found that visual inspections are sufficient for our normal superficial inspections and principal inspections. We have tried to build-in detectors under bridge pavements to detect when they were leaking. The sad conclusion was that the detectors failed before the pavements. However we use advanced techniques when we monitor our cable-stayed and suspension bridges. These we have instrumented so than we can follow movements of cables, joints and bearings. On our project in Mexico we are using global positioning system (GPS) instruments to determine the position of the bridges.

We have been using small dictaphones for collection of data in Denmark. During a project in Portugal we used a computer installed in our vehicle. Now we are testing out the use of a video camera where we can collect pictures and data on the sound track. We have also tried using a data logger, which looks like a good solution for specific purposes. If we find severe defects during our visual inspections we call for a special investigation. During these types of investigation all types of testing are used from non-destructive testing (NDT) to retrieving specimens for laboratory tests. Of the NDT tests potential measurement is one of the most used. We are now starting the testing of ultrasonic equipment for special concrete problems.

## DATA ANALYSIS PROCEDURES

The analysis procedures to be used for the various bridge management purposes mentioned above will be discussed in the following. We have the computer part of our system divided into the modules shown.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Inventory | Principal Inspection | Long Term Budget | Experience | Price Catalogue | Optimi-zation | Budget Module | Maintenance Module |

*Preventive Maintenance* is supported by the maintenance module that can be used for keeping accounts on the maintenance works and the maintenance products and writing out work orders. It is also possible to make analysis on the maintenance works on the bridge components.

*Daily Administration* is supported by the Inventory, Principal Inspection, Optimization, and Budget Modules.

Inventory data are among others used to give various overviews of the bridge stock. A new feature in our inventory module is a digital bridge map connected to the databases. It is used to locate one or more bridges with the same characteristics such as type, construction year, load bearing capacity. All bridges are plotted by coordinates but they are also defined in the system by their stationing. Thus, it is possible to find a bridge along a given route.

The principal inspection reports that are automatically printed out from the inspection module contain inventory and inspection data. Now we are supplementing the inspection module with a picture database so video photos from the inspection can be shown on the screen and printed out as part of the report.

Optimization of the repair works is done within given budget limits and the budgets for the works are monitored. The optimization carried out by the system is described in the following, as this subject is considered a key issue by many American engineers. It makes use of both a project approach and a network approach. Road user costs are considered in the optimization.

Because of a special investigation, our consultant works out two to three different repair strategies for the bridge under investigation. The strategies cover a period of 25 years and are of different types, e.g., one may call for a complete retrofit now and a little work later, another for minor works in the first years and a replacement later. The consultants also have to consider the same strategies delayed five years and the consequences of the delay. The system will by a linear interpolation find the costs of the strategies if they are delayed one to four years. We may now end with three time six (3 x 6) solutions for a bridge and the system will now calculate the net present values of these. These 18 values are arranged in order of increasing present values and included further calculation optimization of the structures to be repaired. The present value of the optimum solution $N_1$ is determined within each individual strategy from the formula:

$$N_1 = MIN.\left(\sum_{n=1}^{25} (I_n+T_n)\ (1+r)^{-(n-1)} - R\ (1+r)^{-(25-1)}\right)$$

where,

$I_n$ = Investment in year $n$
$T_n$ = Road-user cost in year $n$
$R$ = Residual value in year 25
$r$ = Calculated rate of interest
$n$ = Actual year

The system will, if we have no budget restraints, select the best solution for each bridge. On network level the system will combine the chosen strategies for all the bridges we have fed into the system. The investment outlay involved in the repair solutions chosen above is determined and placed within the years in which it is to be paid. Only the investments are relevant to the budget limits, so road-user costs are disregarded in these calculations. When the investments are summed up, the optimum temporal distribution of expenses is determined year by year.

If we have budget limits for the first five years it is investigated if the sum of investments in the first five years is under the budget limits. If so, the calculations are completed, and optimum repair is possible under the given economic limits, i.e., the following requirements are fulfilled in all years:

$$\left( B_n - \sum_{i=1}^{A} I_{n,i} \right) \leq 0$$

where,

$B_n$ = Budget limit in year $n$
$I_{n,i}$ = Investment in year $n$ in optimum solution for structure $i$
$A$ = Number of structures

The budget limits are exceeded when the above requirements are not fulfilled. If the budget limits are exceeded, the system will go on working on network level and by an iteration process postpone the bridges where the costs of postponements are lowest until the total budgets for the first five years are below the budget limits. In this process the system may change the strategy for a bridge when the work is postponed. The year with the greatest difference between need for capital and budget limit is determined, i.e., the year with the maximum negative figure. For all structures contributing to the expenditure in this year, the solutions with the second lowest present value are found. For each structure the relative economic additional expenditure for replacement of the optimum solution by the second best solution is calculated, i.e., the calculation includes both investments and road-user costs. The following formula is used:

$$\frac{N_{2,i} - N_{1,i}}{N_{2,i}}$$

where,

$N_{1,i}$ = Present value of optimum solution for structure $i$
$N_{2,i}$ = Present value of second best solution for structure $i$

For the structure with the lowest relative additional expenditure, the optimum solution is replaced by the solution with the second lowest present value. The purpose is to find another temporal distribution of expenses. This is done by first postponing the structures involving a minimum additional expenditure, i.e., reduction of additional expenses, and by investigating whether the economy allows the repair to be carried out in another year. An iteration is performed, and it is again investigated if the budget has been exceeded. The iteration continues until the repair costs of all structures are under budget limits.

The social consequences of not carrying out repairs at the optimum time are calculated as additional costs. The following formula is applied:

$$\sum_{i=1}^{A} (N_{n,i} - N_1)$$

where,

| | | |
|---|---|---|
| $N_i$ | = | Present value of optimum solution for structure *i* |
| $N_{n,i}$ | = | Present value of chosen repair solution for structure *i* |
| i | = | Actual structure |
| A | = | Number of structures |

The correct way to find the optimal solution is by using integer programming. However, even large computers use an unacceptable amount of time for this type of calculation. Therefore, the simplified model has been developed which gives the results in a few seconds. This simplified model consistently given results close to the optimal found by integer programming.

The budget module controls the spending from the first day when a price is calculated to the day the rehabilitation work is completed. The budget for the single bridge is constantly updated when a change in the basis of the price occurs. Thus, it is possible any time to get a printout of the budget and take action if needed.

*Planning of Rehabilitation Works* is done with the inventory data, the price catalogue, the data from the special inspection and the final list from the optimization.

*Forecasting of Future Budgetary Needs* is done in different stages. During our principal inspections the inspectors estimate rehabilitation works to be done in the next 10-year period. They have to estimate the quantities and select the repair type. The system will then calculate the costs from the built-in prices. This gives us the first rough forecast. They have had an extensive training in these works, and the procedures to follow are described in detail in manuals and a handbook for inspection. Approximately 40 standard repair methods are incorporated in the system, but it is possible to use a lump sum for nonstandard works. We get a better but shorter forecast from our optimization module. With the data from the special investigations this module gives us the needs and the consequences if our needs are not covered.

Finally our long-term budget module gives us a forecast for a long period, say 50 years. This module based on deterministic forecasts, contains all bridges divided in the standard components we use. Quantities and construction data for the bridges are funneled into the module from the inventory module. By adding estimates for service life and maintenance costs for all bridge components it is possible to get the forecast from the system. These estimates are based on statistics from the inventory part. However it is the intention to use the experience module to establish better service life predictions, from exact knowledge of the bridge components, their quality and the influence of the environment. It is possible to integrate the data from the principal inspections in the long-term budget module.

The quality of the different types of forecasts matches their purpose. The data from the special investigation used in the coming years' budgets are the most reliable. The data from the principal inspections cover the following years and are, as in the first type, based on findings in the field. They are used for short term prediction. The data from the long term module are based on statistics only and therefore the most unreliable. For the long term prediction, we only need the approximate level of the budget.

*The Policy for Research and Development* is founded on the data on service life for bridge components that we obtain from our experience module. In this module bridge data from construction and from later stages as they are found during special investigation are combined with data on the impact from traffic and environment. Models to estimate interaction between the internal and external factors are set up. The module is still under development, but we find the work promising.

**DECISION SUPPORT**

The processed data from BMS supports decisions in bridge management. Lists for activities due to be carried out help in the preventive maintenance.

- The daily administration follows procedures planned for the activities that are part of our BMS. Information on problems that need special attention show up in reports and statistics. As a result actions are taken to prevent accidents and change inexpedient ways of constructing and maintaining structures.

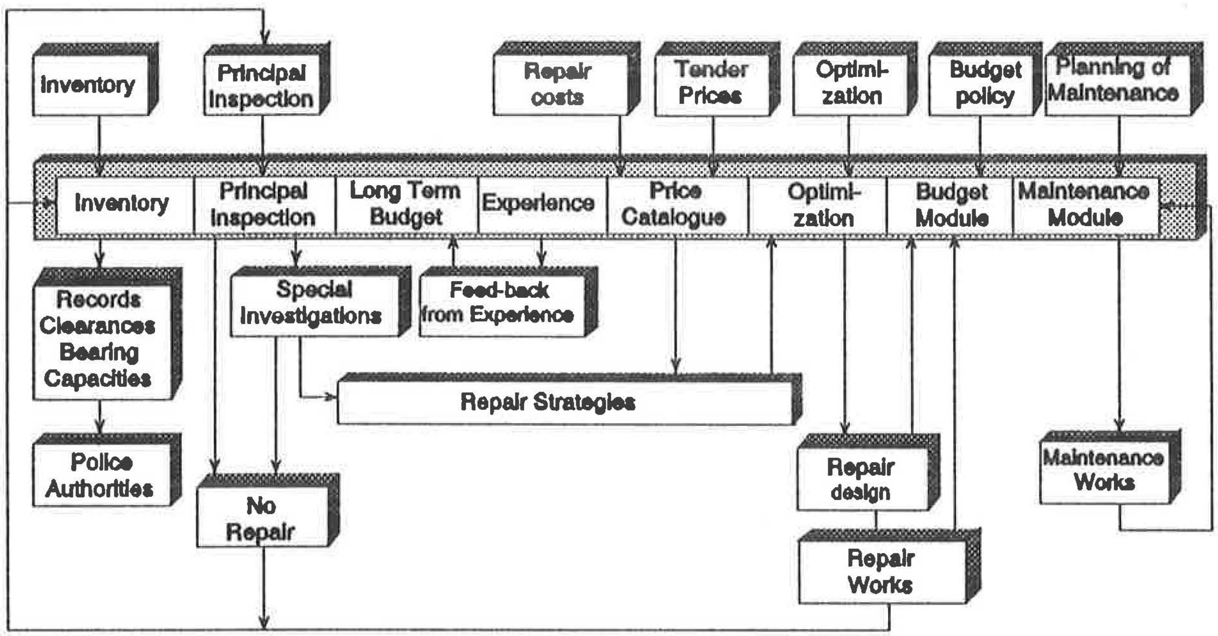


FIGURE 1 Flowchart of bridge management system.

- Rehabilitation works are based on the strategies proposed by the system. The optimized list of works to be carried out gives the head of the maintenance department a support for his planning.
- The forecasts on future budgetary needs are presented for our decision makers as a background for their budget planning and for their dialogue with the politicians.
- Finally we plan our research and development on the digested data from the experience module and the long-term budget module.

The ways data flow through the system and how activities are combined are shown on the flow chart below:

## FURTHER DEVELOPMENT OF THE SYSTEM

Now we are working on a module for special transports. It is the intention that the hauler who has to make a transport from *A* to *B* should be able to get a permit and a route map written out from a computer, when contacting the local authorities with the specifications of his transport. This will be a development from our digital map. The major problem in this project, as far as we can see, is to ensure that the system is always updated when conditions on the roads are changed.

## CONCLUSION

Our system has been installed on highways in Denmark, Thailand, Saudi-Arabia and Mexico, but each country uses its own tailor-made version. We have different applications due to different local conditions and different organizations. The organization and the system have to fit each other. Our experience from working abroad has been that most countries have good engineers who are willing to work with BMS. However, it has taken time to get bridge management organization established to take care of the daily works after a system has been implemented. Also preventive maintenance has been neglected, as it has taken some efforts to convince the authorities that funds for this purpose are essential.

Collecting data and maintaining them are far more costly than the cost of the development of the system. Thus only needed data should be collected and maintained. On the other hand the system should be designed so that we can easily incorporate new types of data into the system if the need arises. The system should be dynamic and not static. However, new applications should be released only so often that the users feel it is a pleasure.

In the introduction we risked saying that all efforts with BMS are made *to save money*. We believe it is true today, because we can only compare needs and requirements if we use money as a common denominator. This may not be so in the future. Research projects have been started where fuzzy logic will be used to interpret and compare the different requirements in another way. If they succeed, a demand may arise for another modification to our system, which will be another challenge. While we are waiting for the result, we will stick to our well-proven denominator.