Integrated Bridge Management from 3D-Model to Network Level

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ABSTRACT: In bridge management, namely in complex networks like e.g. in urban areas, it is of equal importance to consider the condition of the individual building as well as the effects of maintenance measures on network level. In this paper we introduce a concept to integrate a 3D-model based management of single bridges with a maintenance schedule optimization on network level.

The use of 3D-models in building management has some advantages to the mere textual based approach used in most common management systems: The orientation of building inspectors and maintenance planning engineers at navigation through the data is facilitated; the possibility of misplacements and misinterpretation of data is reduced, as all data is attached directly to a 3D representation of the building. Further the current condition (gained from inspection data), as well as prognoses for the future condition trends can be visualized on this 3D-model thus helping to identify weak points in the construction to be subject of special attention in later inspections.

The condition prognosis obtained on building level is input data for finding an ideal schedule of maintenance on network level. This schedule is not only subject to the wish to keep all bridges in the network under good condition and therefore safe, but also to some additional considerations by the building manger: For example, the manager may have a limited budget for maintenance measures each year or may want to steady the amount of money spent on maintenance over the years. It may also be of interest to plan maintenance and thus involved (partial) road closures in such a way, that the impact on traffic flow is as low as possible. Additionally, there may be synergies with maintenance measures by other parties, e.g. streetcar operators, which should also be considered. All these considerations make the task of finding a good schedule a constrained multi-objective optimization problem which we solve using advanced heuristic approaches (e.g. ant colony optimization) which are presented in the paper.

1 INTRODUCTION

Life-cycle management on bridges is a complex task that covers two different levels of view: one single bridge with all its elements that are subject to deterioration on the one side and on the other side the whole number of bridges under operation of one manager where it is desirable to find a perfect schedule when which bridge is to be maintained.

Bridge management on building level means collecting data concerning the building and making a prognosis for the further lifetime of the bridge, particularly to get information when the bridge will get to such a condition that maintenance is necessary.

But to know about the latest possible point in time when maintenance measures should be taken on one bridge does not provide the ideal schedule for all the bridges that are under operation. Therefore other considerations must come into play: Monetary considerations, either to spend as little money as possible or to use each year about the same amount of budget on maintenance, as well as possible synergies with construction sites by other parties (e.g. streetcar operators) may make a maintenance before the deadline of a bridge more advantageous.

If not only the operators view but also the public is considered the problem gets even more complex: Some combinations of construction sites at the bridges have a higher impact on traffic than others, as they might block possible detours. An ideal maintenance schedule will take this into account as well.

In this paper we present a concept that combines the bridge management on building level with an optimization algorithm to find an ideal maintenance schedule on network level.

2 LIFE-CYCLE MANAGEMENT ON BUILDING LEVEL

2.1 *Related works*

There are many works that deal with life-cycle management for bridges on building level. Many countries have developed their own life-cycle management systems.

Examples are SIB-Bauwerke in Germany (Abram 2003), KUBA-MS in Switzerland (Haller & Bascuro, 2006), DANBRO in Denmark (Henriksen, 1999), Eirspan in Ireland (Duffy, 2004), BridgeLife in Finland (Vesikari, 2006 and 2008), Pontis (Robert et al., 2003) and BRIDGIT (Hawk, 1999) in the USA, and Ontario Bridge Management System in Canada (Thompson et al., 1999).

In recent years there has also been high research activity in development of new life-cycle management systems (e.g. Frangopol et al., 2001, Frangopol & Neves, 2003, Hammad et al., 2006, Okasha & Frangopol, 2010).

These systems can be divided into mere data management systems where no prognosis can performed (e.g. Henriksen, 1999; Duffy, 2004) and systems where a condition prognosis is possible, either by deterministic (e.g. Abram, 2003) or more or less complex probabilistic (e.g. Vesikari 2006 and 2008, Frangopol et al., 2001, Frangopol & Neves, 2003, Hammad et al., 2006, Okasha and Frangopol, 2010) deterioration models. For an integrated building management on building and network level as proposed in this paper a prognosis computation is essential.

Almost all the systems described here are based on mere textual description of the buildings. Some of them, e.g. SIB-Bauwerke (Abram, 2003) and Eirspan (Duffy, 2004) allow the attachment of photographs to illustrate inspection data. Only the system described by Hammad et al. (2006) makes use of a 3D geometric model of the building to assist the user's orientation.

2.2 *3D-model based life-cycle management*

The life-cycle management system proposed in this paper differs from most of the aforementioned systems by using a 3D building model of the bridge. The idea is to store all relevant information for condition prognosis (e.g. environmental loads, data from inspections, etc.) in reference to a 3D geometric representation of the bridge.

In comparison to the mere textual allocation of data used in most life-cycle management systems in use, this approach offers a more intuitive way of allocation and thus reduces the danger of misplacing data.

We propose a five-level vertical structure of the building model as shown in Figure 1 (Schießl & Mayer 2007). These five levels going from the whole building on the highest level down to the sub-element levels of element parts and so-called Hot Spots provide the possibility to do a fine-granular condition prognosis.
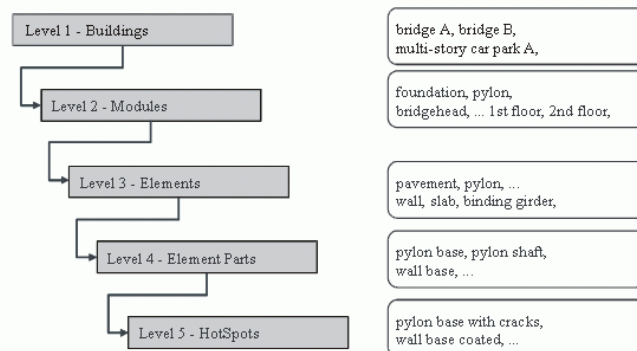

Figure 1: Five-level structure of the building model (Schießl & Mayer 2007)

Instead of doing a prognosis for a whole element (e.g. a pylon) prognosis can be focused on special element parts that are in higher danger (e.g. the pylon base due to de-icing salts). The lowest level "Hot Spots" is reserved for those parts of the bridge that are highly endangered either due to structural settings or because already beginning deterioration (e.g. cracks) is observed in them.

Elements, element parts and Hot Spots can have a geometric representation. The material properties and environmental loads are then added directly onto this geometry (see Figure 2).
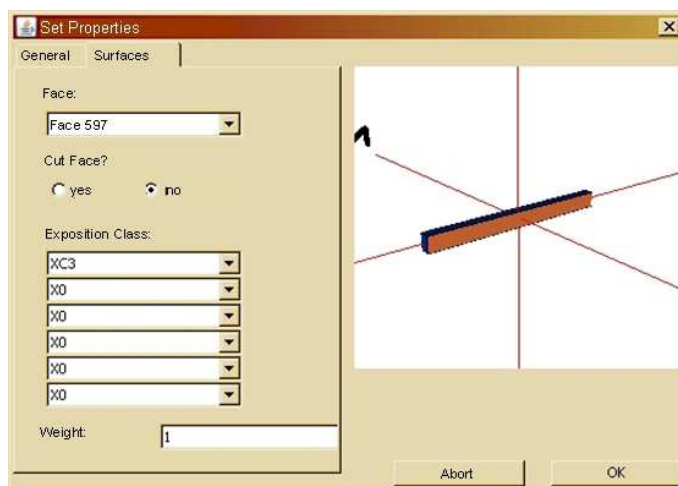

Figure 2: Setting environmental loads on a building element

Inspection data like photographs or data from measurements (e.g. carbonation depth or chloride profiles) can also be added to the geometric representation. This data can be either added as files for documentation or can be preprocessed to be later applicable for later as direct input for prognosis computation.

A condition prognosis can be computed for each surface of the geometric model. Input for this com-

putation is gained from the data stored in reference to this model. This consists of material properties, environmental loads and, if available, up to date inspection data.

For this prognosis computation we recommend the usage of probabilistic deterioration models as proposed by Gehlen (2000) and Schießl & Mayer (2007). This model uses a safety concept oriented on that from Eurocode 0 (2009) as illustrated in Figure 3: The resistance of a structure R is compared with the applied loads S. As the exact values for both R and S are not known (both can vary e.g. due to workmanship etc.) both cannot be handled in a deterministic way but as probabilistic distribution functions. Hence the difference of R and S, the reliability Z, is a distribution function. The probability of failure p_f is the probability that R is lower than S which is $\int Z dz$.
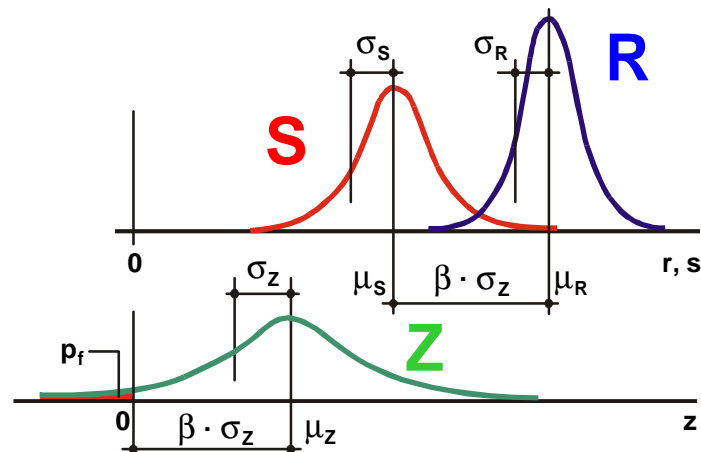

Figure 3: Safety Concept based on Eurocode 0 (2009)

In condition prognosis p_f describes the probability of a change in the condition state; R mainly depends on the material properties while S is described by the environmental loads.

We use a model with six condition states. These states and the functions to compute the transition probability p_f have to be defined for each deterioration mechanism. In Figure 4 the condition states for deterioration caused by depassivation due to carbonation or chloride ingress are illustrated. The equations to describe the transition probabilities are formulated in Fédération Internationale du Béton (2006). For deterioration mechanisms for which no such models exist they can be substituted by Markov Chains.
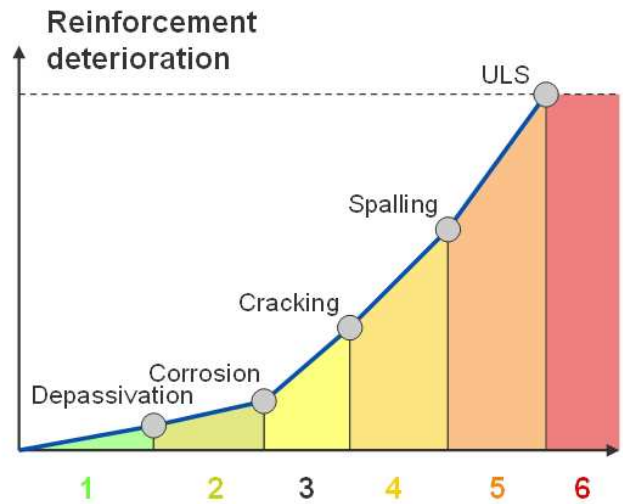

Figure 4: Condition states for deterioration caused by depassivation

When all transition probabilities are known for a surface, the probability of this surface to be in each of the states can be computed. The surface is assumed to have the condition state with the highest probability. If the probability of one of the worse states (4, 5, and 6) is higher then some threshold probability this state is assumed, even if some lower state has a higher probability. If there is more than one deterioration mechanism working on one surface, the worst condition state is assumed.

The condition indices of the surfaces can be aggregated for volume elements (building elements, building element parts and Hot Spots) and for the whole building (Figure 5). The condition indices 4 to 6 that indicate a higher level of danger propagate directly to the higher levels. On building level one can observe when the bridge will reach a critical state; following down through the levels of the 3D model the building element and also the surface that is responsible for this critical condition can be located.
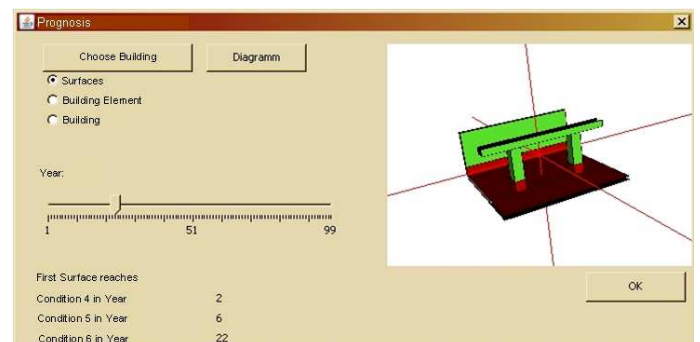

Figure 5: Condition Prognosis

3 LIFE-CYCLE MANAGEMENT ON NETWORK LEVEL

3.1 *Problem description*

The condition prognosis on the surfaces of a bridge described in 2.2 provides an outlook in the future of the bridge. Through this outlook one can forsee when the bridge will reach such a critical condition where maintenance is essential.
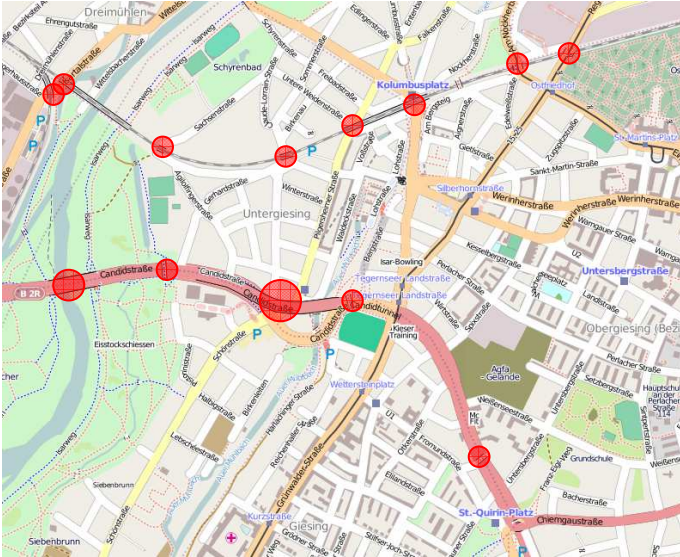

Figure 6: Bridges on network level

But for a manger (public or private) of a high number of bridges it is not always desirable to make this maintenance at the latest possible point in time. Several considerations influence the decision making to choose which bridge to maintain when:

Limited budget for each year and limited availability of project managers and working crews restrict the number of bridges to be maintained each year; the consideration of the influence of construction sites on the traffic makes some combinations of bridges to be maintained at the same time more attractive than other combinations. In addition there may be synergies with maintenance done by third parties, e.g. street car operators, that can be utilized.

Considering the safety of the bridges, i.e. the constraint that the bridges have to be maintained before they reach a critical condition, it will not be sufficient to plan an optimal schedule for only one year: Such an approach would be far to short-sighted as it does not consider whether it is possible for every postponed bridge to be scheduled before its individual deadline. Therefore a schedule for the next several years has to be generated.

To construct such a schedule is a highly complex combinatorial problem. It may be beneficial to schedule a bridge with a high deadline so early that the date of its reparation falls into the considered time frame. Therefore more bridges than those that will be part of the solution have to be considered. Additionally the impact on the traffic as objective

function is non-linear as the simultaneous (partial) closure of a number of bridges will have a highly different effect on the traffic than the sum of the effects by singular closures.

Following these considerations we decided to use meta-heuristics to construct near-optimal schedules.

In a first step a single-objective problem is considered with the impact on traffic as the only objective. This objective is evaluated by simulating the scenarios for all the years of a schedule with a traffic simulator (VISUM by PTV, PTV AG, 2009). A limited budget per year, a fixed number of maintenance projects per year and safety considerations (i.e. the maintenance of all bridges before getting to a critical condition) are formulated as constraints.

3.2 *Approach*

One approach to solve this optimization problem is to use Ant Colony Optimization (ACO). This technique developed by Dorigo (1992) is based on the behavior of natural ants (Goss et al. 1989, Bonabeau et al. 1997). It has been successfully used on the very similar problem of scheduling pavement maintenance (Lee 2009).

The idea is to let artificial agents (ants) construct solutions for combinatorial optimization problems by searching a path through a graph representing the problem. At this construction they are guided by some knowledge about the problem and information gained from earlier iterations.

A graph representing the bridge management problem is shown in Figure 7: The layers of the graph resemble the years that are considered in the construction of the schedule. Per layer there are as many nodes as there are bridges in consideration.
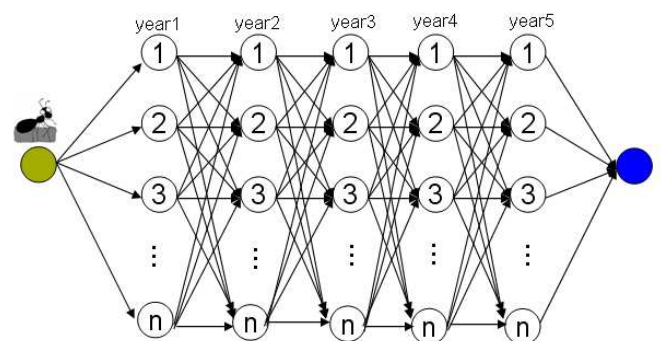

Figure 7: Graph representing the optimization problem

To model the parallel maintenance of several bridges we are using teams of ants as proposed by Lee (2009). So in constructing a schedule an ant team chooses the same amount of bridges like the number of its ants for the first year. After that it does the same for the second year and so on until the last year is reached. Bridges that are already chosen by one ant of a team are tabu for all the other ants of

this team and also for the following layers of the graph (but not for the ants from other teams).

3.3 *The algorithm in detail*

The most time-consuming step of the algorithm is the evaluation of the objective function by the traffic simulator. Taking this into perspective we choose a dialect of ACO that shows good performance with a relative low amount of evaluations of the objective function.

Ant Colony System (ACS, Dorigo & Gambardella 1997) works with a low number of ant teams. Therefore the number of objective function calls per iteration step is reduced, which makes it faster than other ACO dialects.

Each ant team now chooses a route through the graph. Thereby it follows some rules: A team standing in the start node can choose from all nodes in the first layer. For each node the desirability of its choice is computed by

$$d_{1j} = \tau_{1j}^{\alpha} * \eta_{1j}^{\beta} \qquad (1)$$

where α and β are fixed constants, τ_{1j} is the amount of pheromone on node j of layer 1 and η_{1j} is a heuristic value for this node describing additional knowledge.

In the first iteration the amount of pheromone τ_{ij} is the same initialized value τ_0 for all nodes; it changes during the algorithm. η_{ij} depends on the condition of the bridge j in the year i: η_{ij} is computed as the inverse of the time between year i and the first year in which bridge j will reach a critical state. Thus bridges which should be maintained earlier are preferred to be chosen.

With a probability q_0 an ant chooses the node j with the highest value d_{1j}, otherwise the node is chosen by a roulette wheel decision where the probability p_{1j} for node j is the ratio between the desirability of this node relative to that of all other available nodes:

$$p_{1j} = \frac{\tau_{1j}^{\alpha} \cdot \eta_{1j}^{\beta}}{\sum_{l} \tau_{1l}^{\alpha} \cdot \eta_{1l}^{\beta}} \qquad (2).$$

After all the ants of the team have thus made their decision for the first layer, the same process is done for the next and so on until the nodes of the last layer are selected. These steps are repeated for all other ant teams.

After the construction of schedules is finished for all ant teams, the quality of these schedules is evaluated. For each year of the schedule a scenario in the traffic simulator is created where the roads with bridges scheduled for this year have a reduced capacity in respect to their basic capacity. These scenarios are evaluated by the traffic simulator. As quality criterion we use the highest value of vehicle hours over all years of the schedule but this criterion can be replaced by any other quality measure for the scenarios.

The best feasible solution according to the quality criterion is compared with the best feasible solution that is known until now, the elitist solution. In case a solution is better then it will replace the elitist solution. A schedule is feasible when all bridges are maintained before their individual deadlines and all monetary constraints are fulfilled. Monetary constraints can be, that in no year of the schedule the costs exceed a given value or that the cost every year lies between given lower and higher boundaries (to steady the budget).

Then a global update on the pheromone values of all nodes belonging to the elitist solution is performed:

$$\tau_{ij} \leftarrow (1-\rho)\tau_{ij} + \rho\Delta\tau_{ij}^{elitist}, \quad \forall(i,j) \in T^{elitist} \qquad (3).$$

Here ρ is a factor $0 < \rho < 1$, $T^{elitist}$ is the schedule of the elitist solution and $\Delta\tau^{elitist}$ is inverse proportional to the quality criterion computed for the elitist solution. This allows the algorithm to forget older elitist solution and guides the search to the promising regions in the neighborhood of newer (and therefore better) elitist solutions.

To encourage the ants to try different paths and thus avoiding the algorithm to be trapped in a local optimum the pheromone amount on a node is reduced by a local pheromone update as soon as an ant selects it:

$$\tau_{ij} \leftarrow (1-\xi)\tau_{ij} + \xi\tau_0 \qquad (4)$$

where ξ is a parameter $0 < \xi < 1$. This makes nodes that are already chosen by other ant teams less attractive. So not only the solutions found in one iteration will be of higher diversity but also the strong encouragement on the elitist solution is somewhat modified, so that the risk of premature convergence to local optima is reduced.

When the global pheromone update is performed the next iteration starts. The tabu lists of all ant teams are cleared and the ants start constructing schedules based on the new pheromone values.

The algorithm is terminated after a fixed number of iterations.

3.4 *Considering additional objectives*

To define the ideal maintenance schedule is often not only a question of the traffic impact but also other considerations may be of similar importance to the manager.

Often the relative importance of these objectives is not known in the beginning so that a linear combination is not possible. The manager rather wishes a set of good compromise solutions to choose from as

a result of the optimization. Thus the problem becomes a multi-objective optimization problem.

In multi-objective optimization the result is not a single solution but a set of Pareto-optimal solutions. A solution is Pareto-optimal if there is no other (feasible) solution that has better values for all objective functions.

As Ant Colony Optimization works with a population of solutions it is suited to find a set of Pareto-optimal solutions. There are many different approaches to use Ant Colony Optimization on multi-objective problems (García-Martínez et al. 2004). For the bridge maintenance problem we propose the Pareto Ant Colony Optimization (P-ACO) by Doerner et al. (2004).

P-ACO is very similar to the ACS described in the previous section. Also here the Ants perform a local pheromone-update by removing pheromone on their walking path and the global pheromone-update is performed only by a small number of ants.

But unlike in single-objective optimization there is a separate pheromone matrix τ^1, τ^2,..., τ^n for every objective 1, 2,...,n. In every iteration each ant gets random weighting factors p_1, p_2,...,p_n for the pheromone matrices and computes the desirability of the available nodes by

$$d_{ij} = (\sum_{k=1}^{n} p_k \tau_{ij}^k)^\alpha \cdot (\eta_{ij})^\beta \qquad (5)$$

where n is the number of objectives.

Afterwards the ants construct the schedules as in ACS by choosing with a probability q_0 the node with the highest value d_{ij}. Otherwise the next node is chosen by a roulette wheel decision where the probability for the choice of each node is determined similar to equation (2) by

$$p_{ij} = \frac{(\sum_{k=1}^{n} p_k \tau_{ij}^k)^\alpha \cdot (\eta_{ij})^\beta}{\sum_{l}((\sum_{k=1}^{n} p_k \tau_{il}^k)^\alpha \cdot (\eta_{il})^\beta)} \qquad (6).$$

During the construction of the schedules the ants perform a local pheromone-update by applying equation (4) on the nodes it selects.

When all ants in an iteration have finished constructing their schedules for each objective the ants with the best two solutions are determined. Only these ants perform a global pheromone update. The best and the second-best ant for objective k update the pheromone-matrix for objective k performing

$$\tau_{ij}^k \leftarrow (1-\rho)\tau_{ij}^k + \rho\Delta\tau_{ij}^k \qquad (7).$$

$\Delta\tau_{ij}^k$ is following the suggestion of Doerner et al. (2004) 10 units for the best solution for objective k and 5 for the second-best.

Non-dominated solutions are stored in a separate set that is updated after each iteration.

For the bridge maintenance problem we formulated two objectives in addition to the minimization of the traffic impact:

One is to model the wish that arterial roads should not be subject to maintenance in subsequent years. Therefore groups of bridges are created; bridges belonging to the same road are ordered into the same group. The objective chosen here is to minimize the number of bridges that are scheduled in another year than the main part of their group.

The other considered objective is the usage of synergies with other parties, e.g. street car operators, using the bridges. As these also have to do maintenance it is beneficial for both sides to synchronize the maintenance schedules in order to share the costs for barriers and detours. The other party may be a little flexible with its planning. So as for an objective function we choose the minimization of the differences between the schedules by both parties.

Other objective functions can be formulated following those examples. As the pheromone, and therefore the optimization, does not depend on the absolute values for the objective functions, the single objective functions can be of different dimensions and don't need to be scaled to become comparable. It is also possible to combine objectives to be minimized with such to be maximized.

As a result of the optimization the user gets a set of Pareto non-dominated solutions i.e. good compromise solutions to choose from. Other than with a pre-defined weighted objective function the user so is able to see the consequences of his decisions and thus can find the solution that complies best with his wishes.

4 SUMMARY AND OUTLOOK

In this paper we have shown a concept of combining bridge management on building level with an optimization of maintenance schedules on network level.

On building level we propose the usage of 3D building models of the bridges to store relevant data and to perform prognosis for the future development of the condition of one bridge. This 3D model makes the handling of building data more intuitive. By structuring the model in a level-of-detail approach a fine granular prognosis can be performed thus identifying the parts where and the time when maintenance should be performed.

The condition prognosis on building level provides the input for the creation of maintenance schedules on network level. The ideal schedule does not only take safety of all bridges into account but also additionally the budget, traffic impact, etc. The safety can be guaranteed by requiring that the maintenance of each bridge shall be performed before the condition state predicted on building level reaches a certain value.

The other goals form an optimization problem. In this paper we present a method to solve this problem by the use of Ant Colony Optimization. This method can be used on a single-objective as well as on a multi-objective problem.

The schedule optimization algorithm can be easily adapted to other maintenance scheduling problems, over all to pavement maintenance. Further research with test-runs on different real problems is necessary to find the best parameter settings for the optimization algorithm.

For the practical use it will be necessary to identify and formulate additional objectives defining ideal maintenance schedules so that the optimization results will fit even better with the wishes of the building managers.

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