Availability and performance measures for planning maintenance actions on waterways networks

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A today's challenge in civil engineering is to plan maintenance activities on network of infrastructures. Among several difficulties, there is also a communication problem between engineers and managers. In particular, it is of paramount importance that engineers deliver results in a way that managers can understand. Only in this way optimal decision can be met.

Pursuing this scope, and focusing the attention on the German network of waterways, whose infrastructures are affected by aging problems and require maintenance, we resort to queueing theory in order to express the networks performance and availability measures in a compact and analytic way. This approach allows us to easily compare and optimize maintenance plans, also facilitating the communication between engineers and managers. A case study is developed, in which we demonstrate how performance and availability measures can be implemented for planning maintenance intervention on a network of locks. The ultimate scope is to shift the current maintenance practice towards a more mature maintenance management system, in which the waterways networks morphology and the amount of traffic are also considered.

Keywords: asset management, infrastructures network, waterways system, queueing theory, availability, performance.

1. Introduction

The geographical configuration of the German landscape presents an extended network of navigable rivers that has been exploited since the Roman age for the transportation of freight and it represents together with roads, rails and pipelines part of the ground-based traffic route network of the country. Nowadays the network includes about 7300 km of inland waterways, of which about 75% are free-flowing and impounded rivers and 25% canals. The main parts of the network are the river Rhine, representing the north-south axis, the Main/Danube corridor, representing the south-east axis, and the river Elbe, which is interlinked to a network of smaller rivers and canals like the Mittellandkanal and the Odra, and it spans from the Rhine-Ruhr region to the area of Berlin.

The navigability of the network has been improved with the construction of locks, culverts, ports and weirs. Nowadays the waterways system has about 310 locks, 320 weirs, 450 culverts, 45 canal bridges, 2 ship lifts, 2 dams and about 1600 bridges. The fixed assets amount to approximately € 50 billion. Several of these infrastructures have exceeded their design working life and are affected by deterioration phenomena: locks especially raise concerns because most of them have only one chamber and they are around 80-100 years old, showing evident signs of advanced degradation.

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Resulting in a series system of infrastructures, the stall of only one lock may threaten the navigability of the entire waterway. For this reason inspection and maintenance - and in general the management of the asset - are of primary importance for the proper functioning of the entire network, also in view of the continuing transport growth foreseen in the upcoming years. However also during inspection and maintenance the infrastructure should be put out of service; it is thus of paramount importance to plan inoperative periods in such a way that their impact on the transportation of goods is minimized.

The problem of scheduling maintenance interventions on waterways network can be approached with several methods; one way is to resort to queueing theory, a discipline originally born to manage telephone calls (Erlang 1909), but later largely applied whenever the study of waiting lines matters, like in computing and traffic engineering. This paper especially proposes to model the waterways network as a Jackson network with unreliable servers subject to breakdowns and repairs, and to use simple explicit formulae in order to assess the performance and the availability of the system.

2. Scope of the research

Before getting into the issue in question, it is worth to say a few words about the overall scope of this research, and the main actors involved in it.

The responsibility of the management of the entire portfolio of waterway infrastructures is held by the Waterways and Shipping Administration (Wasserstrassen- und Schifffahrtverwaltung (WSV)), which is a federal organization mainly composed by civil engineers with a strong practical experience in hydraulics and waterway infrastructures. Originally, regional administrations of the WSV were in charge with the planning of maintenance actions on the waterways network. However, as the years passed it clearly emerged that this task was becoming more and more expensive and difficult to carry out. For this reason, the Federal Waterway Engineering and Research Institute (Bundesanstalt für Wasserbau (BAW)) was enforced for assisting the WSV and approaching the task from a national perspective. We recall here that the BAW is an engineering and research institute in which researchers not only in engineering but also in other sciences such as mathematics, physics, geoinformatics provide new solutions to the problems affecting the management of the German waterways network. As also Adey et al. (2018) have pointed out, one of the main problems is the different expertise and knowledge owned by the two organizations: from one side, the WSV has practical experience, but lack of a global understanding of the problems. From the other side, the BAW might have the overall view and the theoretical backgrounds, but struggles to provide solutions which can be effectively implemented by the WSV.

Referring to maintenance, important objectives currently pursued by the WSV on which also the BAW is working on are the development of network-wide coordinated maintenance plans and the integration of transportation data in them. A new maintenance management system should be developed, which embodies features like transparency, comprehensibility, user-friendly and practice oriented.

The scheduling of maintenance activities in infrastructures networks usually consists of a large combinatorial problem, which can be solved by translating it into an optimization task. The objective function involves several parameters and it has to be maximized (or minimized). The parameters are usually those that characterize the maintenance plan, such as length and starting time of the actions on each structure belonging to the network, and they might be constrained. In order to solve the optimization problem, several approaches could be adopted: bio-inspired algorithms have especially achieved significant success when applied to such problems in recent years (Neumann & Witt 2010). So far the most implemented algorithms have been genetic algorithms, evolution strategies, evolutionary programming, and genetic programming.

Although the BAW could also suggest the implementation of such procedures, their results would hardly be useful to the WSV, lacking of the characteristics previously mentioned. For this reason, other approaches are sought, in which criteria which are relevant for the managers could be expressed in simple and comprehensible ways, and implemented in order to investigate if proposed actions should be taken or deferred.

3. Queuing Theory

Another way to tackle the problem of planning maintenance interventions is based on queueing theory (Kleinrock 1975): a queue consists of a system in which a stream of users demanding some capacity comes, and is served by one or more servers. Queueing systems can be classified according to their features, such as the arrival, waiting line and service facility characteristics. Many parameters are expressed in probabilistic terms; therefore queueing theory belongs to the field of stochastic modelling. Two approaches can be adopted in studying systems of queues: the time-dependent behaviour, based on a set of differential equation, or the limiting behaviour, according to which the steady state of the system is studied. Usually, the average measures that can be obtained through the analysis of queueing systems are the waiting times and sojourn time of customers, the number of customers and amount of work in the system, and the span of the busy period of the server.

In many real-world applications, customers are served in more than one station arranged in a network structure, which is a collection of nodes connected by a set of paths. If servers deteriorate and break down, then nodes are unreliable and they should be subject to maintenance and repair (Morse 1958). For these reasons queueing theory finds also applications in the area of operations management, with the scope of defining the optimal maintenance policy for manufacturing system (Lin et al. 1994) and medical equipment (Lakshmi & Sivakumar 2013).

Since a waterways system can also be modelled as a system of queues in which ships are customers and locks are servers, queueing theory can be considered as a natural model for the waterways network, and it can be applied in order to study the effect of locks congestion on travel time (Dai 1993), the effect of locks interdependence on ships or tows delays (Chien & Schonfeld 1992), the prioritization and scheduling of interdependent locks improvement projects (Martinelli 1993).

However the above-mentioned researches have two main shortcomings: from one side authors resort to simulation, which is a time-consuming approach; from the other side, results are delivered in the form of generic guidelines that should be followed in planning maintenance intervention. The intention of this work is thus to apply queueing theory in order to define a more straightforward strategy based on explicit formulae according to which the best maintenance policy could be defined in detail, clearly determining starting times and duration of maintenance intervention on each structure that belongs to the network.

3.1 The M/M/1/∞ queue

The simplest queueing model involves a single queue, and it is commonly illustrated as in Figure 2. Customers, represented by an arrow, enter from the left and exit at the right; the rectangle represents the server, while the open rectangle represents the waiting line, or queue. We adopt here the standard shorthand notation used to describe queueing systems containing a single queue (M/M/m/n) in which the characters refer to, respectively, the statistics of the arrival process, the statistics of the server, the number of servers and the number of customers that the queueing system can hold. The capital letter 'M' especially means that the statistics are Markovian (given that n is the number of customers in the system, the arrivals follow a Poisson process characterized by rate parameter λ, and service times follow an exponential distribution with rate parameter μ.

Customers finding the server free enter service immediately, while customers finding the server busy enter the waiting room which has an infinite number of waiting places. The waiting room is organized according to the First Come First Served regime (FCFS): if a service expires, the served customer immediately leaves the system and the customer at the head of the queue, if any, enters service and other customers in line are shifted one step ahead. It is assumed that these shifts take zero time.

Given the number of customers in the system, the actual residual service and residual inter-arrival times are independent of the past and independent of another. The random queue length process of the system is denoted by $X = (X(t): t \geq 0)$.

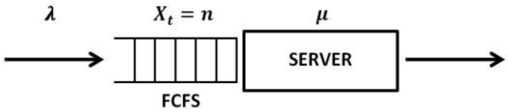

Fig. 1. A single M/M/1/∞ queue, in which the waiting room is organized as First Come First Served regime.

The performance measures for the M/M/1 queue described above can be calculated according to analytical formulae. Given that

$$\rho = \frac{\lambda}{\mu} \quad (1)$$

is the utilization factor, the mean number of customers in the system is:

$$L = \frac{\rho}{1-\rho} = \frac{\lambda}{\mu-\lambda} \quad (2)$$

and the mean time that a customer has spent in the system is given by:

$$T = \frac{L}{\lambda} \quad (3)$$

which is also called Little's Law.

3.2 Jackson Network

Many practical systems can be modelled as networks of queues. Performance parameters of networks of queues are in general not simple to compute: however, an exception is represented by the so-called Jackson network, whose equilibrium distribution can be computed in a straightforward manner. A Jackson network satisfies the following properties (Daduna 2001):

1. Given that N is the number of servers (nodes), station i, $i = 1, \dots, N$, is a multiserver with $s_i \geq 1$ service channels and an infinite waiting room under FCFS regime.
2. At node i there is an external Poisson $\lambda_i \geq 0$ arrival stream; customers arriving at node i from the outside or from inside of the network request for an amount of work (service time) which is exponentially distributed with mean $\mu_i \geq 0$. All requested service times and interarrival times constitute an independent family of random variables.
3. The movements of the customers in the network are governed by a Markovian routing mechanism: a customer on leaving node i selects a) with probability $r(i,j) \geq 0$ to visit node j next, and then enters node j immediately, commencing service if he finds an idle channel there, otherwise he joins the tail of the queue of node j; b) with probability $1 - \sum_{j=1}^{N} r(i,j) \geq 0$ to leave the network.

Let $\boldsymbol{\sigma} = (\sigma_1, \dots, \sigma_N)$ be the vector of total job arrival rates at the N nodes. These rates are obtained as the unique solution of the set of linear equations

$$\boldsymbol{\sigma} = \lambda + \boldsymbol{\sigma} R. \quad (4)$$

The ergodicity condition for this network is that the total arrival rates should be smaller than the corresponding service capacities, i.e. $\sigma_i < \mu_i$ for all i.

For describing the network's evolution over time the following processes are used: let $X_i(t)$ denote the number of customers present at node i at time t; either waiting or in service (local queue length at node i), then $X(t) = (X_j(t): j = 1, \dots, N)$ is the joint queue length vector of the network at time t. $X = (X(t): t \geq 0)$ denotes the joint queue length process of the Jackson network.

The Jackson theorem states that for a system with single servers ($s_i = 1$) and general network topology the probability distribution of the number of customers in the system has a product form:

$$\lim_{t\to\infty} P(\{X_1(t) = M_1, X_2(t) = M_2, \dots, X_N(t) = M_N\} = \prod_{i=1}^{m} \left(\frac{\sigma_i}{\mu_i}\right)_i^{n_i} \left(1 - \frac{\sigma_i}{\mu_i}\right). \quad (5)$$

This means that the long-run steady state number of customers $X_i(t), i = 1, \dots, N$ in the system behaves "as if" each job center was independent of each other.

The beauty of this result is that for single-server tandem systems, the key elements of our system performance analysis can be expressed with a
closed-form expression which affords optimization problems, i.e., average number of customers within the system is (Smith 2018):

$$L_s = \sum_{i=1}^{m} L_i = \sum_{i=1}^{m} \frac{\sigma_i}{\mu_i - \sigma_i}. \quad (6)$$

3.2 Jackson network with unreliable servers

We assume now that the server at node i goes through alternating operative and inoperative periods, distributed exponentially with parameters ξ_i and η_i, respectively (i =

$1, 2, \ldots, N$). These periods are independent of the states of other nodes and of the number of jobs in the queue. Transitions from the operative to the inoperative state are called breakdowns, while those from the inoperative to the operative state are repairs. If a breakdown occurs during a service, the latter is resumed from the point of interruption after the repair. Incoming jobs continue to join the queue during inoperative periods.

The behavior of queueing system when the servers are unreliable is difficult to be analysed, notwithstanding that the network satisfies the Jacksonian properties. Unreliable networks pose significant mathematical difficulties, and approximate solutions offer the best hope of obtaining performance measures. According to Chakka & Mitrani (1996), a simple approach is represented by the reduced work-rate approximation, in which unreliable servers are replaced by reliable ones that have the same overall service capacity. The advantage of the reduced work-rate approximation is that the resultant network maintains a product-form solution and its performance measures are easily calculable. However this approach has a major drawback: since the work-rate approximation depends only on the ratio of ξ_i and η_i and not on their separate values, it is insensitive to the frequency of breakdowns and repairs.

Sommer et al. (2017) proposed another approach, according to which breakdowns of the servers and their repair are integrated into the very first Markovian system description. This model allows a simple and explicit expression for the availability measure. Given the Jackson network of service stations $\bar{J} = (1, \ldots, N)$, the stationary joint point availability at time $t \geq 0$ for the subnetwork of unreliable servers $\bar{K} \subset \bar{J}$ is:

$$A_\nu(\bar{K})(t) = 1 - \sum_{\bar{K} \subset \bar{I}} \pi(\bar{I}) \quad (7)$$

where $\pi(\bar{I})$ is the probability that exactly the nodes in set $\bar{I} \subset \bar{J}$ are under repair, given by

$$\pi(\bar{I}) = c^{-1} \frac{A(\bar{I})}{B(\bar{I})} \quad (8)$$

where

$$c = \left(1 + \sum_{\substack{\bar{K} \subset \bar{J} \\ K \neq \emptyset}} \frac{A(\bar{K})}{B(\bar{K})}\right) \quad (9)$$

$A(\bar{K}), A(\bar{I})$, resp. $B(\bar{K})$, $B(\bar{I})$ are rather general functions which define the breakdown intensities, resp. repair intensities.

4. Case study

We show now through an explicative example how the theory regarding waiting lines illustrated in Chapter 3 can be used in order to plan maintenance actions on waterways networks. Before entering into the merits of the example, the model adopted is described. We assume that the system of locks subject to interruptions can be modelled as a series system of queues with degradable servers and alternating operative and inoperative periods. Limiting our attention to 1-chamber-locks, the system is composed by two-ways tandem queues, each one modelled as $M/M/1/\infty$, while the waiting room is characterized by FCFS regime. The assumption of Poisson arrivals and exponential departures has been proved by Leutzbach (1963). Let us assume that customers arrive in both directions at approximately the same rate $\lambda_1 = \lambda_2 = \lambda/2$, which is realistic. This fact has two effects: from one side the two-ways tandem queue can be transformed into a one-way queue with arrival rate $\lambda = \lambda_1 + \lambda_2$; from the other side it is possible to assume that customers arriving from each direction will alternate (Fig. 2).

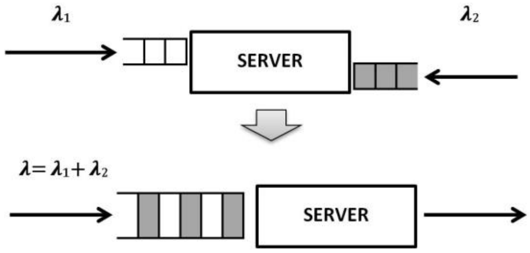

Fig. 2. A two-ways tandem queue (above) and the model that has been chosen (below).

This assumption is reasonable because it corresponds to the arrival pattern which optimizes locks services, and thus it will be also promoted by the administrative authorities, which are able to interact with the incoming ships. It is also supported by data regarding ships trajectories and fleet structure collected in TRAVIS, an online database developed by the BAW which also allows visualizing this information.

The service time of a lock corresponds to the sum of the times required to:

– entering of the ship;
– closure of the gate;

– filling/emptying operation;
– opening of the gate;
– exit of the ship;

The total time corresponds in average to 30 minutes. Assuming that locks are operating both day and night, it corresponds to a service rate $\mu = 48$ ships/day.

Servers are degradable, in the sense that they are subject to service interruptions due to sudden breakdowns and consequent corrective maintenance. Operative and inoperative periods are exponentially distributed, characterized respectively by rate parameters ξ_i and η_i.

We propose now the following applications:

1. Availability-based choice of the predictive maintenance plan.
2. Optimisation of service interruptions on a system of locks;

The applications have respectively the following motivation:

1. Maintenance plan should be prioritized in such a way that the consequences of disregarded maintenance are minimized, and these consequences should be evaluated at network level.
2. Maintenance actions should be planned in such a way that their influence on transportation is minimized. Currently this aspect is highly underestimated: for example, the entire Main, Main-Donau Canal, and Donau (which all together form a long waterway from the Black sea 'till the Rhein) is closed every year for circa 3-4 weeks because of maintenance works. However going from east to west, locks are characterized by an increasing arrival rate; it goes without saying that service interruptions have also increasing impact on transportation. In these circumstances could be interesting to study when differentiating interruption periods could make sense.

4.1 Availability-based choice of predictive maintenance plan

One way of planning predictive maintenance is to consider the risk of neglecting it. Risk is usually given by the failure scenario, the probability of failure and the magnitude of the consequences, which also comprise the additional costs due to corrective maintenance process and the disruption on transportation due to the unplanned locks out of service. However in case of system of infrastructures, risk should be considered at network level. Bearing this in mind, we suggest as a possible risk indicator the availability of the network in case of breakdown. The availability depends on the rate of breakdowns and the rate of repairs of the unreliable locks, and can be calculated according to Eq. (7). Here the rate of breakdown is determined by the damage life cycle, while the rate of repair is given by the length of the corrective maintenance process.

Let us consider a system constituted by a series of 3 locks, which can be modelled as the queueing network represented in Fig. 3. The queueing network satisfies the properties of the Jackson network. The locks are unreliable: each lock is affected by two damage processes, I and II (Table 1).

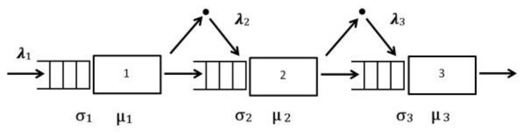

Fig. 3. Queueing network.

Table 1. Breakdown and reparing rates ξ_i and η_i for the damages processes I and II affecting the locks 1,2 and 3.

	Lock 1		**Lock 2**		**Lock 3**	
Damage process	**I**	**II**	**I**	**II**	**I**	**II**
ξ_i	0,0005	0,001	0,001	0,001	0,0005	0,0005
η_i	0,023	0,067	0,048	0,017	0,034	0,067

We assume that when predictive maintenance is carried out, the damage process is totally removed, and their rate of breakdown and repair becomes negligible with respect to the remaining damage processes. However, due to limited resources, not all the damage processes can be eliminated at the same time. For this reason, maintenance plan should be compared, and the one which corresponds the highest system availability should be selected.

Given the available resources, two maintenance plans are possible:

- Plan I: repair of damage processes I. The availability is determined by damage processes II;
- Plan II: repair of damage processes II. The availability is determined by damage processes I;

Possible breakdown and repair scenarios are: $I = \{\emptyset, \{1\}, \{2\}, \{3\}, \{1,2\}, \{2,3\}, \{1,3\}, \{1,2,3\}\}$. We assume that breakdowns happen independently, while a mean time for repairing is considered for each scenario. For each maintenance plan we determine the availability A_v of the network, which corresponds to one minus the probability that the locks are under repair because of the disregarded damage processes. In order to compute it, we need first the breakdown-repair process stationary distributions $\pi(.)$ and the constant c:

$$c = 1 + \frac{\xi_1}{\eta_1} + \frac{\xi_2}{\eta_2} + \frac{\xi_3}{\eta_3} + \frac{\xi_1\xi_2}{\bar{\eta}_{1,2}} + \frac{\xi_2\xi_3}{\bar{\eta}_{2,3}} + \frac{\xi_1\xi_3}{\bar{\eta}_{1,3}} + \frac{\xi_1\xi_2\xi_3}{\bar{\eta}_{1,2,3}} \quad (10)$$

$$\pi(\emptyset) = c^{-1} \quad (11)$$

$$\pi(\{1\}) = c^{-1}\frac{\xi_1}{\eta_1} \quad (12)$$

$$\pi(\{2\}) = c^{-1}\frac{\xi_2}{\eta_2} \quad (13)$$

$$\pi(\{3\}) = c^{-1}\frac{\xi_3}{\eta_3} \quad (14)$$

$$\pi(\{1,2\}) = c^{-1}\frac{\xi_1\xi_2}{\bar{\eta}_{1,2}} \quad (15)$$

$$\pi(\{2,3\}) = c^{-1}\frac{\xi_2\xi_3}{\bar{\eta}_{2,3}} \quad (16)$$

$$\pi(\{1,3\}) = c^{-1}\frac{\xi_1\xi_3}{\bar{\eta}_{1,3}} \quad (17)$$

$$\pi(\{1,2,3\}) = c^{-1}\frac{\xi_1\xi_2\xi_3}{\bar{\eta}_{1,2,3}} \quad (18)$$

$$A(\{1,2,3\}) = 1 - \sum_{\bar{K}\subset\bar{I}} \pi(I) \quad (19)$$

The results for both plan I and plan II are summarized in Table 2.

Table 2. Breakdown-repair process stationary distributions $\pi(.)$ and availability measures A corresponding to maintenance plan I and II.

	Plan I	**Plan II**
	$\boldsymbol{\pi(.)}$	$\boldsymbol{\pi(.)}$
1	0,021255230	0,0138558047
2	0,019838214	0,0554232188
3	0,014170153	0,0069279023
1,2	0,000026215	0,0000415674
2,3	0,000019130	0,0000207837
1,3	0,000014170	0,0000103919
1,2,3	0,000000015	0,0000000185
c	0,055323126	0,0762796873
A_v	0,944676874	0,9237203127

The results reveal that the availability corresponding to plan I is higher of the availability corresponding to plan II. Therefore, from the networks availability point of view, maintenance plan II should be preferred.

4.2 Optimisation of service interruptions on a system of locks

Now we determine the length of preventive maintenance in such a way that the effect of the service interruption on transportation is minimized. As we can see from Fig. 3, in between the locks there are harbors or points of charge/discharge. Each lock is thus characterized by a ship arrival rate σ_i, which in turns depends on the external arrival rate, as well as from the proportion of ships abandoning the network, as expressed by Eq. (4). Taking $r(0,j) = \lambda_i/\lambda$ and $r(0,0) = 0$, we assume that the extended routing matrix $R = (r(i,j) : i,j \in \bar{J} \cup \{0\})$ is irreducible (Table 3).

Table 3. Routing matrix $r(i,j)$ regulating the flow through the network.

$r(i,j)$	**1**	**2**	**3**	**0**
1	0	0,8	0	0,2
2	0	0	0,9	0,1
3	0	0	0	1
0	$\frac{\lambda_1}{\lambda} = 0{,}32$	$\frac{\lambda_2}{\lambda} = 0{,}29$	$\frac{\lambda_3}{\lambda} = 0{,}39$	0

According to Eq. (3) and Eq. (6), the mean number of ships in the system after the repairing times t_i is:

$$Z = \sum_{i=1}^{3} \frac{\sigma_i}{\mu_i - \sigma_i} + \sigma_i t_i \quad (20)$$

where

$$C = \sum_{i=1}^{3} t_i \quad (21)$$

$$t_{min} \le t_i \le t_{max} \quad (22)$$

because of limited maintenance resources (limited personnel and limited machines) and logistic reasons (ships are impatient customers characterized by a timer $T \approx 3$ weeks). We assume that $t_{min} = 15$ days, $t_{max} = 25$ days, $t_i = 21$ days (3 weeks of interruption), which corresponds to $C = 63$ days.

Our linear programming problem with time constraints is thus to minimize Z subject to C.

The arrival rates λ to each lock are $\lambda_{1,2,3} = [16; 14{,}4; 19{,}2]$ ships/day ($\lambda = 49{,}6$ ships/day). In Table 4 we have reported the value of the function Z considering $t_i = 21$ days ($Z = 1923{,}9$), and the minimized value, which can be obtained for $t_1 = 25$ days, $t_2 = 23$ days and $t_3 = 15$ days ($Z_{opt} = 1769{,}4$), and at which corresponds a reduction of the mean number of ships in the system of circa 8%.

Table 4. Optimized locks service interruption $t_{i,opt}$ obtained minimizing Z.

Lock	$\frac{\sigma_i}{\mu_i - \sigma_i}$	t_i (days)	$\sigma_i t_i$	$t_{i,opt}$ (days)	$\sigma_i t_{i,opt}$
1	0,5	21	345,2	25	411,0
2	1,4	21	586,8	23	642,7
3	23,3	21	966,6	15	690,4
Z			1923,9		1769,4

5. Conclusion

In this paper, we presented availability and performance measures which allow to take decision about maintenance plans for network of infrastructures in general, and the German waterways system in particular. The availability and performance measures are derived from queueing theory, assuming that the waterways network can be modelled as a Jackson network with unreliable servers. Finally a case study is developed, in which the proposed measures are applied in order to choose maintenance actions and optimize their duration. The aim of this paper is twofold: from one side, it should facilitate the communication between managers and engineers in the framework of infrastructures management; from the other side, it should promote a network-wide maintenance management system.

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