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## Joint optimisation of operation and maintenance policies in an urban ropeway transport systems context

Ronald Martinod, Olivier Bistorin, Leonel F Castañeda, Nidhal Rezg

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*Joint optimisation of operation and maintenance policies in an urban ropeway transport systems  
context*

**Abstract:**

For urban transport systems, efficient passenger flows are a key goal in the management of operations. This paper proposes a stochastic optimisation model for integrating service and maintenance policies in order to solve the queueing problem and the cost of maintenance activities for public transport services, with a particular focus on urban ropeway system. We adopt the following approaches: (i) a discrete-event model that uses a set of interrelated queues for the formulation of the service problem using a cost-based expression; and (ii) a maintenance model consisting of preventive and corrective maintenance actions, which considers two different maintenance policies (periodic block-type and age-based). The maintenance policies are then evaluated for their impact on the service and operation of the transport system. The performance of the current maintenance policy is compared against a different maintenance policy. The authors conclude by applying the proposed optimisation model using an example concerning ropeway systems.

**Keywords:** maintenance policy, public transport, queueing theory, ropeway system, urban passenger transport.

## **1. Introduction**

Studies of passenger transport demand in urban public transport systems have increased with a renewed recognition of their role in the economic development of cities. In recent years, transport planning has evolved to place greater emphasis on urban transport to increase the mobility of commuters (Ibarra-Rojas et al., 2015; Shang et al., 2016; Li and Sheng, 2016). Previous works have had different approaches for analysing passenger demand in urban transport systems. Using a dynamic systems approach, Horn (2002) showed a demand-responsive passenger transport system based on a model to analyse the performance of urban passenger transport. By means of an economic theory-based approach, Ison and Sagaris (2016) examined the social, political, regulatory, and operational challenges in providing urban transport. Using a scheduling-based approach, Wang et al. (2015) proposed an event-driven model involving different types of events to obtain a nonlinear nonconvex optimisation problem. There are also studies (Barrena et al., 2014-a; Sun et al., 2014) focusing on a non-periodic timetable that explicitly considers time-dependent passenger demand to reduce waiting time and travel time. Other works (Niu and Zhou, 2013; Barrena et al., 2014-b) reduced the waiting time of passengers looking into the arrival process of passengers in stations with a uniform process or a Poisson process. A detailed review of these approaches is provided by Caris et al. (2013) and Yin et al. (2017).

There has also been a research focus on waiting and queueing phenomena associated with urban transport services, with studies showing that urban transport users are negatively inclined if it involves uncertain waiting time (Ceder et al., 2013). Nesheli et al. (2015) introduced synchronised timetables to reduce the waiting time caused by batch arrivals. Queues with batch arrivals and bulk service are commonly observed in the field of

behaviour in transport systems, and such queues are found with urban buses, trains, trams, railways or ropeways. The queueing process follows the following features (Wang et al., 2014): (i) passenger demand at urban transport terminals consists of people gradually arriving in batches, with demand increasing progressively until rush hour, and then declining in the off-rush hour; and (ii) the service has a bulk-like pattern, given that it is a mass-transport service. Passengers arrive in batches to a terminal where they can be served *en masse* for the transport system. This paper therefore assumes an urban transport system characterised by batch arrivals and bulk service patterns.

Queueing theory applications in transport has led to a number of author to develop queueing systems (Ceder et al., 2013): (i) arrival patterns of passengers –e.g. Poisson, Erlang, Gaussian and others–; (ii) service patterns; (iii) queue discipline –e.g. first-come-first served, priority-based–; (iv) number of servers provided; (v) maximum queue length allowed; (vi) configuration of the transport operators –e.g., in series, in parallel, or mixed. In this work, the theory of compound Poisson processes is used to establish a stochastic model of passenger demand in the stations. The distribution of arrival passengers is obtained with the classes defined by the quantity of users per time unit on the frequency domain (e.g. passengers/minute). Thus, the density distribution function of passenger arrivals follows a Poisson distribution (Dalla-Chiara, 2010); in consequence, it is possible to apply the queueing theory, which allows to evaluate the quality of requested service.

Some authors (May and Keller, 1967; Hall, 2003) have argued that queues in the transport field often tend to be deterministic and predictable because of: (i) the passengers journey generates demands for repetitive patterns; and (ii) queues by random variations in arrivals and service are often deemed to be secondary relative to queues caused by predictable demand patterns. In response, another line of research (Lee and Vuchic, 2005; Nesheli et al. 2015) has defined urban transport attributes as stochastic (e.g. travel time, dwell time, passenger demand, etc.). Ceder (2007) used a formulation for mean passenger waiting time under the assumption of random passenger arrivals, and Newell (1977) assumed that the passengers arrive at stops according to a Poisson distribution and the delay of vehicles according to Fokker-Planck. The hybrid queue-based model of Wu and Mengersen (2014) reflected a Bayesian Network model and stochastic queueing theory, using the properties of the Poisson and exponential distributions. The theory of compound Poisson process is introduced as the main model to deal with the queueing problem on urban public transport (Ceder et al., 2013). Moreover, transport queueing models have been characterised as non-stationary (time varying) systems (Lee and Vuchic, 2005; Parbo et al., 2014).

Following similar lines, several optimisation models have been developed. Lee and Vuchic (2005) proposed an optimal transit system as a compromise among the minimal travel time, the transit operator profit, and minimisation of social costs. Parbo et al. (2014) dealt with timetable optimisation from the perspective of minimising the waiting time experienced by bus passengers; the researchers obtained a bi-level minimisation problem via a non-linear non-convex mixed integer problem. Yin et al. (2017) studied a dynamic passenger

demand in the context of railway scheduling with the goal of minimising the operational costs and passenger waiting time, resulting in a mixed-integer linear programming problem.

Pitsiava-Latinopoulou and Iordanopoulos (2012) is noteworthy for introducing a categorization of urban transport terminals based on journey features. *Intercity terminals* are transit points for passengers traveling relatively long distances between cities or countries, where the chief characteristic is long waiting times and a lack of significant traffic fluctuations. At *commuter transit centres*, the passengers are regular travellers who need advanced accessibility and minimum travel time (Sun et al., 2017); the main feature is the large variation in hourly demand during the day and the need for a quick and convenient transfer between transport modes (Jones et al., 2000). *Interchanges* are intermodal facilities established at connection points for different transport modes forming a co-operative urban transport network. *Park-and-ride terminals* function as stations designed to provide adequate parking, primarily at urban transport terminals (Spillar, 1997). Finally, there are *on-street facilities*, public transport stops that serve different routes or transfers between different modes. The present article is focused on park-and-ride terminals and on-street facilities, as they are the more typical terminals for the integration of passengers into an urban transport network via ropeway. In cities with hills, the ropeways offer an attractive, straightforward and reasonably-priced system for mainstream urban public transport. Ropeway systems provide not only a convenient transportation in hilly terrains, over rivers, harbours and motorways, but also an alternative to connect people over densely populated residential areas (Alshalalfah et al., 2012). Currently, ropeway systems are becoming a popular transport mode and a logical choice for their ability to efficiently move passengers from the tops of hilly metropolitan areas to lower-lying areas. In this way, the ropeways are often the critical initial piece of the system, bringing passengers down to valley areas where they can access other transport modes in the wider integrated urban transport network.

The proposed work analyses the demand for transport, for an optimal service-oriented maintenance plan. The lack of studies evaluating service performance, as impacted by maintenance requirements provided a motivation for the research. In particular, the authors found few studies dealing with the simultaneous optimisation of maintenance and service policies in urban ropeway transport systems. An efficient service should consider the waiting time of users, but on the operational side, decreasing the waiting time increases the cost of service in terms of maintenance actions. The contributions of this work are as follows:

- (i) to the best of our knowledge, this is the first study to simultaneously consider maintenance policy and operational policy in an urban aerial ropeway system, taking up the problem of queueing with particular attention to the unique requirements public transport services;
- (ii) this work analyses ropeway system maintenance and operational policies based on the international regulations, evaluating how fluctuating demand influences the operating conditions; and
- (iii) this paper proposes a method to establish passenger waiting time of in relation to the optimal maintenance policy for an optimal urban transport service. The approach has been developed specifically to take into account passenger demand in urban public ropeway systems.

The paper is organised as follows. Section 2 sets out the mathematical expressions of service and maintenance policies applied to ropeway system operation. In Section 3, a stochastic optimisation model is developed to obtain the optimal service and maintenance actions. The model is applied in Section 4 using a numeric example. Table 1 shows the coefficients, parameters and variables to be used throughout the paper.

**Table 1**

Indices and parameters used throughout the paper.

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$i = \{1,2, \dots, I\}$	indices of the platforms on the ropeway systems;
$j = \{1,2, \dots, J\}$	indices of the components on the ropeway systems;
$k = \{1,2, \dots, K\}$	indices of the vehicles (gondolas) on the ropeway systems;
$m = \{1,2, \dots\}$	indices of the user demand conditions from rush hour to off-peak periods;
$n = \{1,2, \dots, N\}$	indices of discretised time;
$a, b$	instants of time;
$N$	typical (representative) period of working time;
$\eta$	horizon of time, long time window of working-life;
$\Delta t$	discret-time.
Operational parameters:	
$cv$	vehicles capacity [pax];
$fv_n$	passing vehicles frequency in service over the $n$ th discretised time [ $s^{-1}$ ];
$g_{k,i,n}$	available places of the $k$ th vehicle on the $i$ th platform over the $n$ th discretised time [pax];
$h_i$	quantity of discretised time period $\Delta t$ that a vehicle spend to transit between stations [--];
$lv_n$	distance between vehicles [m];
$[qv_{inf}, qv_{sup}]$	lower and upper limit of density of vehicles in service [ $m^{-1}$ ], respectively;
$[sv_{inf}, sv_{sup}]$	lower and upper limit of vehicles speed [ $m/\Delta t$ ], respectively.
Service policy parameters:	
$Cw$	cost associated with the waiting time spend by passengers in the queue [ $mu/\Delta t$ ];
$l_i$	proportional coefficient of $\lambda_{i,n}$ at the $i$ th platform [--];
$Lq_{i,n}$	number of users in the queue on the $i$ th platform over the $n$ th discretised time [pax/ $\Delta t$ ];
$Pa_{i,n}$	probability function of passengers' arrival at the $i$ th platform [pax/ $\Delta t$ ];
$Pe_{i,n}$	probability function of effected services at the $i$ th platform [pax/ $\Delta t$ ];
$Wg_n$	global mean waiting time in the queue over the $n$ th discretised time [ $\Delta t$ ];
$Wg_{sup}$	upper limit of the mean waiting time of the users in the queue [ $\Delta t$ ];
$\lambda_{i,n}$	users that arrive on the $i$ th platform over the $n$ th discretised time [pax/ $\Delta t$ ];
$\sigma_{k,n}$	effected services (disembarking passengers) the $k$ th vehicle over the $n$ th discretised time [pax/ $\Delta t$ ];
$\mu_{i,n}$	passengers boarding the vehicle form the $i$ th platform over the $n$ th discretised time [pax/ $\Delta t$ ].
Maintenance policy parameters:	
$Cc_j$	cost of a repair activity (corrective maintenance) due to the failure of the $j$ th component, which is quantified on monetary unit over failure [mu/failure];
$Ci_j$	cost of an imperfect maintenance by the preventive maintenance actions for the $j$ th component [mu/maint.];
$Cmax_j$	cost of a perfect maintenance (AGAN) for the $j$ th component [mu/maint.];
$f_j, F_j$	probability and cumulative fault distributions, respectively [cycles/fault];
$p$	relationship between the quantity of minor maintenance actions per major maintenance action [--];
$r_{j,n}$	ratio of cycles by the $j$ th component over the $n$ th discretised time [cycles// $\Delta t$ ];
$R_j, Rg$	reliability of the $j$ th component and global reliability of the system [cycles], respectively;
$Rg_{inf}$	lower limit of the global reliability of the system [cycles];
$\alpha$	age reduction coefficient after a maintenance action. To this work: the corrective maintenance policy is a minimal repair action to a failed component, thus $\alpha = 1$ ; and the preventive maintenance policy is an imperfect action, $\alpha = \{\alpha_{p1}, \alpha_{p2}\}$ , whit $\alpha_{p1}, \alpha_{p2} \in (0, \dots, 1]$ , where $\alpha_{p1}, \alpha_{p2}$ are the age reduction coefficient of a major maintenance and a minor maintenance;
$\varphi_j$	probability of failure of the $j$ th component over the finite period of time [failure];
$\omega_j$	current working cycles of the $j$ th component [cycles];
$\omega_0, \omega_A$	working cycles of the last and the next preventive maintenance action [cycles], respectively.

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Optimisation parameters:

$\Gamma_{wg}$  global penalty cost due to the waiting time spend by passengers in queues [mu];  
 $\Gamma_c$  cost of the corrective maintenance [mu];  
 $\Gamma_a$  cost of the periodic block-type preventive maintenance policy [mu];  
 $\Gamma_p$  cost of the periodic age-based preventive maintenance policy [mu].

Decision variables:

$qv_n$  Density of vehicles in the  $n$ th discretised time [ $m^{-1}$ ];  
 $sv_n$  vehicles speed [m/s];  
 $T_j$  periodicity of periodic block-type maintenance, quantity of maintenances over a full cycle of preventive maintenance [maint./year];  
 $A_j$  range of working between the scheduled preventive maintenances [cycles/maint.].

## 2. Problem description

This section describes the problem by analysing the characteristics of each policy separately: (i) urban transport service policy, and (ii) ropeway system maintenance policy; as follows:

### 2.1. Urban transport service policy

The distribution of passengers that arrive at a ropeway station is obtained by the quantity of users per time unit in the frequency domain (e.g. pax/min), the probability distribution of arrivals on the  $i$ th platform over the  $n$ th instant of time belongs a Poisson distribution,  $Pa_{i,n}$  [pax/ $\Delta t$ ] (Gillen and Hasheminia, 2013), the empirical distribution of the passenger arrivals has been verified using a *goodness of fit* test (Dalla-Chiara, 2010). According to the queuing behaviour of ropeways, the best model for evaluating waiting time is expressed as M/M/1/ $\infty$ /FIFO (Jenelius, 2018). This work assumes the following conditions about service policy and context:

**Assumption 1.** Passengers arrive at the upper ropeway station in order to reach the downtown or connect to another transport mode by means of a transfer station at the bottom of the hill (railway, light-train, bus, etc.).

**Assumption 2.** The stations are characterised by having on-street facilities.

**Assumption 3.** Passengers do not use another transport mode before their arrival at the upper ropeway station.

**Assumption 4.** If the number of waiting users exceeds the capacity of the ropeway system, the operator leaves behind some passengers – just as in any other transportation mode (Kfahraman et al., 2011). The system has therefore a finite capacity to serve users. The demand rate may exceed the capacity of the system in some periods.

**Assumption 5.** The urban transport service policy must correspond to the demand placed upon the system. There must, in other words, be flexibility in the service, allowing it to adapt to variations in demand (Amirgholy and Gonzales, 2016).

Given a Poisson process as probability function of discrete-time and linearly spaced, the sequence  $n = \{1, 2, \dots, N\}$  with  $n \in t$  is used to represent the time sequence between successive events. The discrete-time stochastic distributions make it possible quantify the number users over a finite set of events. The events

depend on the arrival of vehicles on the platform. Using an operative characteristic of the ropeway system (all vehicles are synchronised by the pulling cable, and the vehicles speed,  $sv_n$ , has a constant value over the periods of operation) the discrete-time period can be written as

$$[n, n + 1] = \Delta t = \frac{lv_n}{sv_n} \quad (1)$$

where  $lv_n$  is distance between vehicles (see Fig. 1.a).

The weighted mean of arriving passengers on the  $i$ th platform over the  $n$ th event is represented by  $\lambda_{i,n}$  [pax/ $\Delta t$ ], with  $i = \{1, 2, \dots, I\}$ . It can be expressed as a probability function at the  $i$ th platform,  $Pa_{i,n}$ , over a period of time  $[a, b]$  by means of  $\lambda_{i,n} = (b - a)^{-1} \sum_{n=a}^b Pa_{i,n}$ , with  $a < b$ . Using an analogous definition, the average of effected services during the same period of time is given by  $\sigma_{i,n} = (b - a)^{-1} \sum_{n=a}^b Pe_{i,n}$ , where  $Pe_{i,n}$  is the probability function of disembarking passengers. If the period of time is  $[a, b] = N$ , and  $N$  is defined as a typical service period of time (e.g. full working day), the service capacity of the platform must not overflow in order to ensure the complete outflow of the passengers from the system; i.e., a stability condition of the service must be guaranteed, where  $\sum_n \lambda_{i,n} (\sum_n \sigma_{i,n})^{-1} \leq 1$ .

**Remark 1.** Note that,  $\sigma_{i,n}$  relies on the capacity of the transport system. This means  $\sigma_{i,n}$  [pax/ $\Delta t$ ] is directly related to both variables: the frequency of passing vehicles in service  $fv_n$  [ $s^{-1}$ ] (in the case of ropeway systems, all vehicles have the equivalent of  $fv_n$  value in each instant  $n$ , because pulling cable synchronises the separation –distance– between vehicles), and the quantity of available places in the  $k$ th vehicle  $g_{k,i,n}$  [pax], with  $k = \{1, 2, \dots, K\}$ ; thus,  $\sigma_{i,n} = fv_n g_{k,i,n}$ . Moreover,  $fv_n$  can be expressed according to the density of vehicles  $qv_n$ , and the vehicles speed  $sv_n$ , i.e.

$$fv_n = sv_n qv_n. \quad (2)$$

Two different boarding/disembarking models are considered for the queuing model to describe the service behaviour of a typical ropeway system:

The first model describes the boarding/disembarking process on the single platforms (see Fig. 1.b) belonging to stations between the loops of the line. The model is based on a stochastic service. The service on a platform directly depends on the service behaviour of the previous platform; i.e.,  $\mu_{i,n}$  depends on  $g_{k,i,n}$ . From the point of view of users in the queue, the vehicles in service have different (random) sizes because of user is interested in the available places in the vehicle.

The second model describes the process for boarding/disembarking at terminal stations, located at the ends of the line. This model is based on constant service time (see Fig. 1.c); i.e., the service is constant and established by the operational characteristics. This service behaviour takes place according to two different operating conditions: (i) cases in which the ropeway system starts operating, and each vehicle is empty in order to pick up passengers; and (ii) cases in which the  $k$ th vehicle is located in one of the system's terminal stations (passengers have finished their journey and just disembarked)

According to the both boarding/disembarking models, the quantity of users in the queue on the  $i$ th platform is

$$Lq_{i,n} = \begin{cases} Lq_{i,n-1} + \lambda_{i,n} - \mu_{k,i,n} ; & \text{if first queuing model} \\ Lq_{i,n-1} + \lambda_{i,n} - cv ; & \text{if second queuing model} \end{cases} \quad (3)$$

and  $\mu_{k,i,n} = g_{k,i,n-h} + \mu_{k,i-1,n-h} - \sigma_{k,i-1,n-h}$ , with  $\mu_{k,i-1,n-h}$  representing the quantity of passengers that board the  $k$ th vehicle at the platform before (the vehicle spend  $h_i$  times of discrete-time period  $\Delta t$  to transit between stations), and  $\sigma_{k,i-1,n-h}$  representing the quantity of passengers that disembarked from the  $k$ th vehicle on the preceding platform.

**Proposition 1.** *The general formulation to the mean waiting time is expressed as*

$$Wg_n = \frac{1}{sv_n qv_n} \sum_i \frac{Lq_{i,n}}{\mu_{i,n}} \quad (4)$$

**Proof 1.** By definition, the average waiting time for each platform depends on the ratio between the quantity of users in the queue,  $Lq_{i,n}$ , and the users leaving the queue to board the vehicle,  $\mu_{i,n}$ , adjusted for time they spend waiting in the queue, i.e.

$$Wg_n = [n, n + 1] \frac{Lq_{i,n}}{\mu_{i,n}} ; \quad \forall i = \{1, 2, \dots, I\}; \quad (5)$$

therefore, the total weighted waiting time in the railway system is the sum of the values on all platforms,

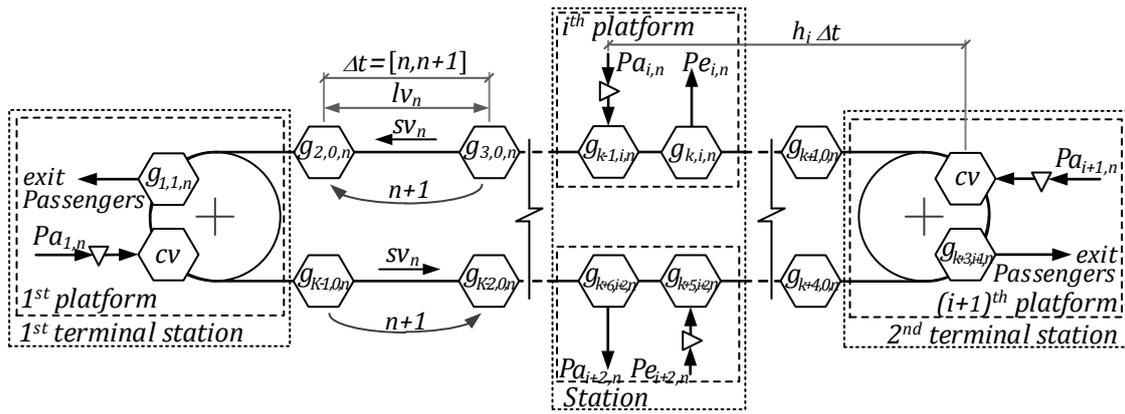
$$Wg_n = [n, n + 1] \sum_i \frac{Lq_{i,n}}{\mu_{i,n}}, \quad (6)$$

then, taking Eq. (1) and considering that  $\Delta t$  is equivalent to the inverse of the passing vehicles frequency  $fv_n^{-1}$

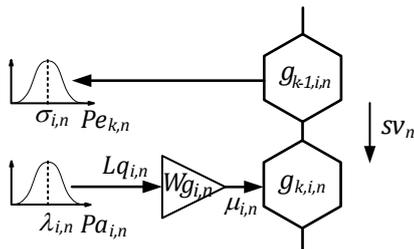
$$Wg_n = \frac{1}{fv_n} \sum_i \frac{Lq_{i,n}}{\mu_{i,n}}, \quad (7)$$

taking into account Eq. (2) the proposition is proved.  $\square$

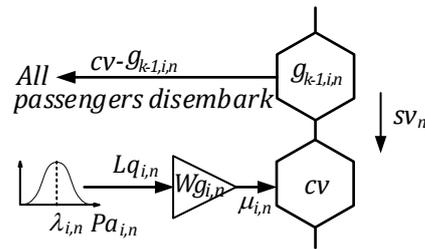
The discrete-event model deals with the analysis of the waiting lines with the objective of determining  $Wg_n$  value, which changes only when the passengers board the vehicle,  $\mu_{i,n}$ —and simultaneously other passengers disembark from the previous vehicle,  $\sigma_{k-1,n}$ . In other words, the proposed model is a composite of queues from a set of stochastic distributions  $\{Pa_{i,n}, Pe_{i,n}\}$ . Therefore, only  $n$  is required to examine the transitory behaviour of the system, and other time points do not affect the data relating to system operation. In Section 3.1., we will develop the formulation of the service problem regarding to the service parameters behaviour  $(sv_n, qv_n)$ .



a. General diagram of urban ropeway systems.



b. Queuing model of a simple platform.



c. Queuing model of a terminal station.

**Fig. 1.** Service model of ropeway systems.

## 2.2. Maintenance policy of ropeway systems

Technical regulations govern the requirements for passenger installations by cable drives. Directive 2000/9/EC (2000) standardises ropeway installations designed to carry persons (e.g., funicular railways, cable-cars, gondolas, chairlifts and drag lifts) and which are designed, manufactured, put into service, and operated for the purpose of transporting passengers safely. The international standard BS/EN-1709 (2004) establishes general guidelines in relation to the inspection and maintenance required on the component systems: (i) vehicles; (ii) carrier cables and pulling cables; (iii) electro-mechanical devices; (iv) traction and brake equipment; (v) rescue, monitoring and signalling devices; and (vi) installation and infrastructure. Moreover, there are two types of components associated with any ropeway system: (i) a set of mobile components which are driven by the pulling cable –such as the vehicle and its parts– that are influenced directly by  $sv_n$ ; and (ii) a set of structural components, such as supports, installation and infrastructure, that are influenced directly by both:  $sv_n$  and  $qv_n$ .

**Remark 2.** As part of the safety systems governing installations like ropeway systems, periodic preventive maintenance has been introduced as a technical specification on an industry-wide basis. The maintenance managers of ropeways have adopted a periodic preventive maintenance based on a periodic block-type maintenance policy, which provides for maintenance actions to be carried out according a fixed schedule based on linearly-spaced periods of chronological time.

The number of working cycles,  $\omega_j$ , produces wear-out of the  $j$ th component; thus, the ratio of cycles, denoted as  $r_{j,n}$  [cycles/s], defines the rate of deterioration for the  $j$ th component.

**Proposition 2.** *The ratio of cycles is expressed as*

$$r_{j,n} = \begin{cases} \frac{2I sv_n qv_n}{\sum_i h_i}; & \forall j \text{ if } u = 0 \\ \frac{lv_n sv_n qv_n^2}{\sum_i h_i}; & \forall j \text{ if } u = 1 \end{cases}; \text{ with } u = \{0,1\}, \quad (8)$$

where  $u = 0$  in the case which the  $j$ th component be a mobile component,  $u = 1$  in the case which the  $j$ th component be a structural component, and the value  $I$  is the quantity of platforms.

**Proof 2.** Consider the  $j$ th component as a moving component by the pulling cable; then, the component undergoes two cycles each time a platform is crossed (a first cycle entering the platform, and a second cycle leaving the platform), i.e. the quantity of cycles that are applied to a component during a loop journey is  $2I$  [cycles]; moreover, the spent time by a vehicle for whole loop journey is  $\Delta t \sum_i h_i$  [s]; therefore,

$$r_{j,n} = \frac{2I}{\Delta t \sum_i h_i}; \quad \forall j \text{ if } u = 0; \quad (9)$$

then, taking Eqs. (1) and (2) into Eq. (9), the first part of the proposition is proved. Now, consider the  $j$ th component as a structural component belonging to the ropeway system. The component undergoes a single cycle each time that a vehicle crosses the component; i.e., the quantity of cycles that are applied to a component during a loop journey is  $qv_n lv_n$  [cycles]; therefore,

$$r_{j,n} = \frac{qv_n lv_n}{\Delta t \sum_i h_i}; \quad \forall j \text{ if } u = 1; \quad (10)$$

again, taking Eqs. (1) and (2) into Eq. (10), the second part of the proposition is proved.  $\square$

**Remark 3.** Note that the operational parameters,  $qv_n$  and  $sv_n$ , define the quality level of service  $Wg_n$ , and the degree of deterioration in the ropeway components as well,  $r_{j,n}$ .

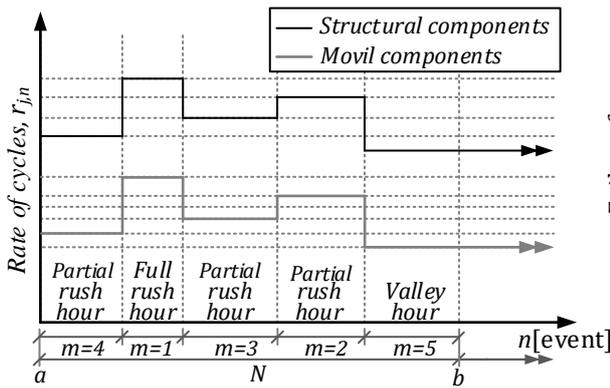
Fig. 2.a shows the relationship between  $r_{j,n}$  and the two types of components (mobile and structural) over a typical service time  $N$ , which is classified by periods of users demand,  $m = \{1, 2, \dots\}$ , where  $m = 1$  represents the users demand of full rush hour, and  $\forall m \neq 1$  represents the users demand of a partial rush hour. Considering the periods of users demand for the ropeway system, the performed working cycle by the  $j$ th component can be expressed as  $\omega_j = \Delta t \sum_n r_{j,n}$ .

Let  $f_j$  be defined as the fault probability distribution of the  $j$ th component – working cycles per fault [ $\omega$ /faults]– (see Fig. 2.b) and  $F_j$  as the cumulative distribution function corresponding to  $f_j$  on a determined working cycle  $\omega_j$ ,  $F_j(\omega_j \leq \omega)$ , see Fig. 2.c. The reliability probability of each  $j$ th component in the transport system is  $R_j = 1 - F_j$  with  $j = \{1, 2, \dots, J\}$  (see Fig. 2.d). The global reliability of the system,  $Rg$ , is directly relied on the behaviour of  $R_j$  as follows

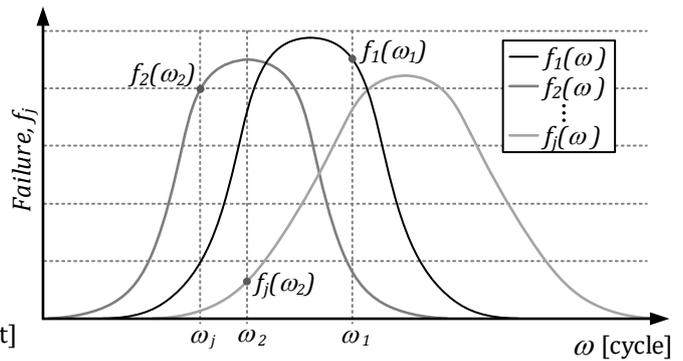
$$Rg = \begin{cases} \prod_j R_j; & \forall j \text{ if } u' = 0 \\ 1 - \prod_j (1 - R_j); & \forall j \text{ if } u' = 1 \end{cases}; \text{ with } u' = \{0,1\} \quad (11)$$

where  $u' = 0$  in the case which the  $j$ th component be in a series relationship configuration over the system, i.e. a failure of the any  $j$ th component will result in a failed function in the whole system; and  $u' = 1$  in the case where the  $j$ th component is in a parallel relationship configuration over the system, i.e. the system performs as long as a single  $j$ th component remains operational.

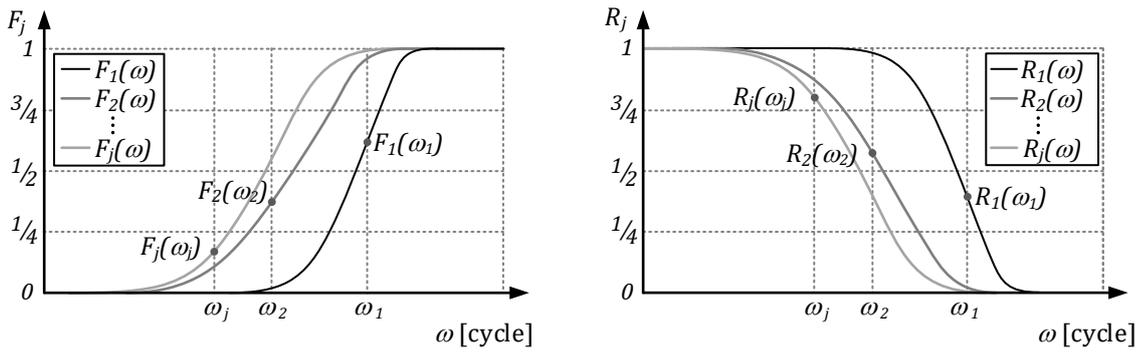
Ropeway maintenance managers may adopt different maintenance policies regarding the repair actions on a failed component ahead of the next scheduled preventive maintenance. The repairing actions affect the technical state of the repaired component in terms of its working life (Khatab, 2013), i.e.  $\alpha \omega_j$ , with  $0 \leq \alpha \leq 1$ , where  $\alpha$  is the age reduction coefficient after the maintenance action. In case of the maintenance manager adopts a maintenance policy with a value  $\alpha = 0$ , the reliability level of the component takes the nominal value  $R_j = 1$ , and the working cycles is restored to  $\omega_j = 0$ . This means that the corrective actions are focused on a *perfect* repair bringing the component to as-good-as-new condition (AGAN). AGAN involves repairing the component using the required resources to obtain the highest repair quality of the component. But, in a case where maintenance management adopts a maintenance policy with a value  $\alpha = 1$ , the reliability level of the component remains the value before the fault  $R_j(\omega_j)$ , meaning that the corrective actions are focused on a minimal intervention to the component, entitled as-bad-as-old (ABAO), which consists in repairing the component using the minimum possible resources to obtain the working component again (Hajej et al., 2012, Martinod et al., 2018). In Section 3.2., we will develop the formulation of the maintenance policy problem regarding to the imperfect preventive maintenance.



a. Rate of cycles to different type of components.



b. Fault probability functions.



c. Cumulative fault probability functions.

d. Reliability probability functions.

**Fig. 2.** Maintenance model of ropeway systems.

### 3. Proposed Model

There are two different methodologies available to address the problem: (i) an aspiration-level model, which works directly with the measure of the queuing performance with the goal of determining an acceptable range for the service level,  $\mu_{i,n}$ , by specifying reasonable limits on the queuing performance (the limits represent the aspiration level); and (ii) a cost-based model, which attempts to balance two conflicting costs: (a) the cost of offering an efficient service, and (b) the cost of delaying the service offer (passengers waiting time). The two types of cost are in conflict because any increase to one automatically affects the other. Both approaches recognise that higher service levels reduce the waiting time in the system, and both models aim to strike a balance between service level and waiting time (Taha, 2011). The proposed work is focused on the cause-effect relationship between the joint service-operational policy and the maintenance policy, a relationship developed in the context of the cost-based model optimisation analysis: (i) penalty cost for passengers waiting time, and (ii) maintenance activities cost.

The paper tackles the problem by developing the formulation in three stages: (i) formulation of the service; (ii) formulation of the maintenance, which is analysed by two different strategies: (a) corrective and (b) preventive; and (iii) formulation of the combined service-maintenance policies.

#### 3.1. Development formulation of the service problem

A discrete-time model is used to describe the queuing situations, in which the passengers: (i) demand the system,  $\lambda_{i,n}$ ; (ii) wait in a queue, if necessary,  $Wg_n$ ; (iii) receive the service,  $\mu_{i,n}$ ; and (iv) arrive at their destination,  $\sigma_{i,n}$ . The discrete-time model is composed of a set of interrelated queues with the objective of determining  $Wg_n$  value.

**Remark 4.** Note that the  $Wg_n$  value constitutes a penalty cost. The methodologies to quantify the penalty cost are directly defined by the operation managers of the ropeway systems. Each can use different criteria to quantify the penalty cost according to its service policy.

In this paper, the relationship used to describe the penalty cost for waiting time is expressed as  $Cw$  [ $\mu/\Delta t$ ] (see Fig. 3.a); thus, the penalty cost for the global waiting time is defined as

$$\Gamma wg = Cw \sum_n Wg_n . \quad (12)$$

**Remark 5.** This work assumes that  $\Gamma wg$  is described as a linear function, where the  $Cw$  value is a constant linear rate. The linear function is adopted because it is efficient and appropriately describe the cost for passengers waiting time. The task of building on these assumptions will be part of future works, according to the correlations highlighted in the literature review.

Section 4.2. will develop an application example of the service parameters behaviour regarding to the penalty cost by  $\Gamma wg$ .

### 3.2. Development formulation of the maintenance problem

The maintenance actions and their associated cost are a well-known topic for ropeways maintenance managers, who must assess the relative merits of preventive versus corrective maintenance policies.

#### 3.2.1. Formulation of corrective maintenance

The repairing actions on a failed component are executed between the scheduled preventive maintenances, i.e. between the working cycles range  $A_j = \omega_A - \omega_o$  (see Fig. 3.b); in addition, the repairing actions have a cost associated for the fault of the  $j$ th component, which is expressed as an cost value on monetary unit,  $Cc_j$  [ $\mu$ ].

**Remark 6.** The corrective maintenance policy (commonly used by the maintenance managers) corresponds to ABAO (Pham and Wang, 1996; Khatab et al., 2013). This work adopts a ABAO corrective maintenance policy, which is defined by the age reduction coefficient  $\alpha = 1$ , i.e. the  $R_j$  value, before the fault, remains (Martinod et al., 2018).

**Proposition 3.** The cost of the corrective maintenance,  $\Gamma c$ , are expressed as the sum of the cost for the fault of the components affected by their probability of fault,  $\varphi_j$ ,

$$\Gamma c = \sum_j Cc_j \varphi_j \quad (13)$$

where  $\varphi_j$  is the average failure probability for the  $j$ th component, from the current lifetime,  $\omega_j$ , to the next preventive maintenance action,  $\omega_A$ .

**Proof 3.** The fault probability of the  $j$ th component is quantified by the mean area value from the probability function of fault distribution

$$\begin{aligned} \varphi_j &= P\left(\omega_j \leq \omega \leq \frac{\omega_j + \omega_A}{2}\right) \\ &= (\omega_A - \omega_j)^{-1} \int_{\omega_j}^{\omega_A} f_j(\omega) d\omega , \end{aligned} \quad (14)$$

with  $\omega_j < \omega_A$ . In addition, the probability average value of the function of fault distribution can be expressed by the mean value of the cumulative fault distribution

$$(\omega_A - \omega_j)^{-1} \int_{\omega_j}^{\omega_A} f_j(\omega) d\omega = F_j \left( \omega_j + \frac{\omega_A - \omega_j}{2} \right). \quad (15)$$

If the relationship  $\omega_j + (\omega_A - \omega_j)/2$  is denoted as  $\phi_j$ , it is possible to express  $F_j(\phi_j) = \phi_j$ ; then, the probability of fault, which affects  $Cc_j$  to get the corrective maintenance cost actions, has been proved.  $\square$

### 3.2.2. Formulation of preventive maintenance

The preventive maintenance actions are adjusted to improve the  $Rg$  value. The imperfect preventive maintenance is well-established the field of engineering (Hajej et al., 2014; Hajej et al., 2015) and has been the preferred approach of the maintenance managers of ropeways (Martinod et al., 2018); therefore, the imperfect preventive maintenance is considered in this study, which is defined by the age reduction coefficient,  $0 < \alpha \leq 1$ . After each preventive maintenance action, the equipment is restored on a lower level than the nominal state of its components, i.e. over the lifetime of the system its components undergo wear and degradation.

Let us define the highest quality maintenance cost as  $Cmax_j$  [mu], which is the cost of the required resources to carry out AGAN maintenance. In other words  $Cmax_j$  represents the cost of the required resources to get the highest quality maintenance and to restore the reliability function of the component to its nominal value,  $R_j = 1$ . As a consequence, when the budget of a maintenance action for the  $j$ th component is equivalent to  $Cmax_j$ , the executed maintenance action consists of replacing the component with a new one; hence, the value of the age reduction is restored,  $\alpha = 0$  (Martinod et al., 2018).

The cost of the imperfect maintenance action is a fraction of  $Cmax_j$ , which is directly related to the age reduction coefficient of the component; thus, the cost of a preventive maintenance action can be expressed as  $Cmax_j (1 - \alpha)$ . The preventive actions are classified according to two types: major maintenance and minor maintenance. The age reduction coefficient associated with the preventive maintenance action is  $\alpha = \{\alpha_{p1}, \alpha_{p2}\}$ , whit  $\alpha_{p1}$  and  $\alpha_{p2} \in (0 < \alpha \leq 1)$ , where  $\alpha_{p1}$  is the age reduction after major maintenance action, and  $\alpha_{p2}$  is the age reduction coefficient after minor maintenance.

**Remark 7.** The cost of the major maintenance action is higher than the cost of the minor maintenance action,  $Cmax_j (1 - \alpha_{p1}) \gg Cmax_j (1 - \alpha_{p2})$ , therefore  $\alpha_{p1} \ll \alpha_{p2}$ .

**Proposition 4.** *The cost of an imperfect maintenance action by the preventive maintenance policy is expressed as*

$$Ci_j = Cmax_j \left( 1 - \frac{\alpha_{p1} + p \alpha_{p2}}{1+p} \right), \quad (16)$$

**Proof 4.** By definition, the cost of the imperfect maintenance relies on the sum of the costs of maintenance actions executed over the period of operating service time; i.e., the cost of the major maintenance and all the minor maintenances over a full cycle of preventive maintenance is

$$C_{i_j} = C_{max_j} (1 - \alpha_{p1}) + C_{max_j} \sum_p (1 - \alpha_{p2}); \quad (17)$$

thus, the relationship between the major and the minor preventive maintenances is defined by means of the parameter  $p$ , which describes the quantity of minor maintenance actions per each major maintenance action, where  $1 + p$  is a full cycle of preventive maintenance over the long-term horizon of time  $\eta$ ; therefore the expression is write as

$$C_{i_j} = C_{max_j} ((1 - \alpha_{p1}) + p (1 - \alpha_{p2})), \quad (18)$$

and after some algebraic manipulations the proposition is proved.  $\square$

This work considers two preventive maintenance policies:

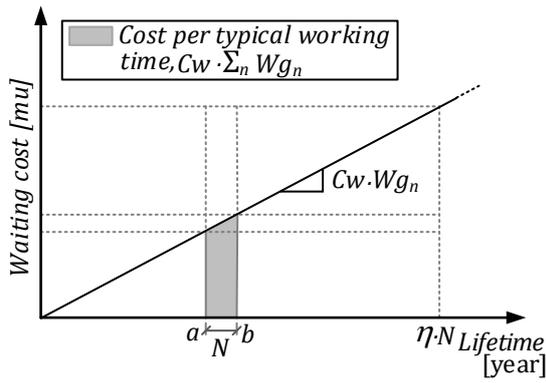
(i) The periodic block-type is the preventive maintenance policy adopted by the ropeways maintenance managers. Given a horizon of time expressed as  $\eta$  with a piecewise linear distribution of time  $T_j$  (see Fig. 3.c) the distribution of time over a full cycle of preventive maintenance is defined as  $T_j \eta = 1 + p$ . The cost of the periodic block-type maintenance policy is expressed as

$$\Gamma p = \sum_j T_j C_{i_j}, \quad (19)$$

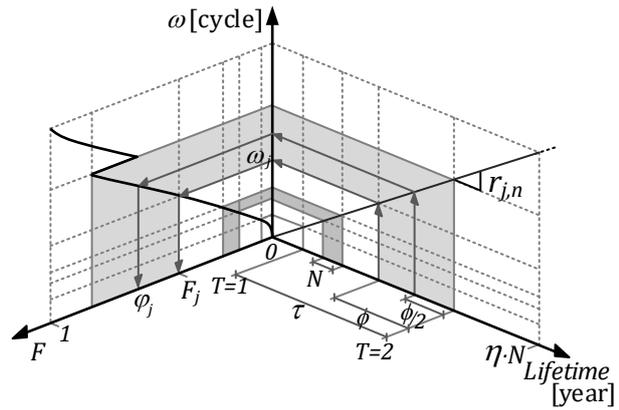
(ii) The age-based maintenance policy is executed as the reliability indices of the components reach a predetermined level (Wang, 2002), i.e. the system undergoes a preventive maintenance whenever its reliability  $Rg$  reaches a given threshold level,  $Rg_{inf}$  (Martinod et al., 2018). Let the working cycles range be expressed as  $A_j = \omega_A - \omega_o$  such that  $Rg(\omega_o)$  is the reliability level of the last preventive maintenance denoted as  $Rg_o$ , and  $\exists \omega_A \in \omega : Rg(\omega_A) = Rg_{inf}$ .  $\omega_A$  represents the quantity of working cycles in which the system reaches the reliability threshold level  $Rg_{inf}$  (see Fig. 3.d). Therefore,  $A$  covers the working cycles executed by the system in response to deterioration between preventive maintenances, and the period between maintenances can be expressed as  $A_j = Rg^{-1}(Rg_{inf}) - Rg^{-1}(Rg_o)$ , where  $Rg^{-1}(\cdot)$  expresses the inverse function of the global reliability. The cost of the age-based maintenance policy is expressed as

$$\Gamma a = \sum_j A_j^{-1} C_{i_j}, \quad (20)$$

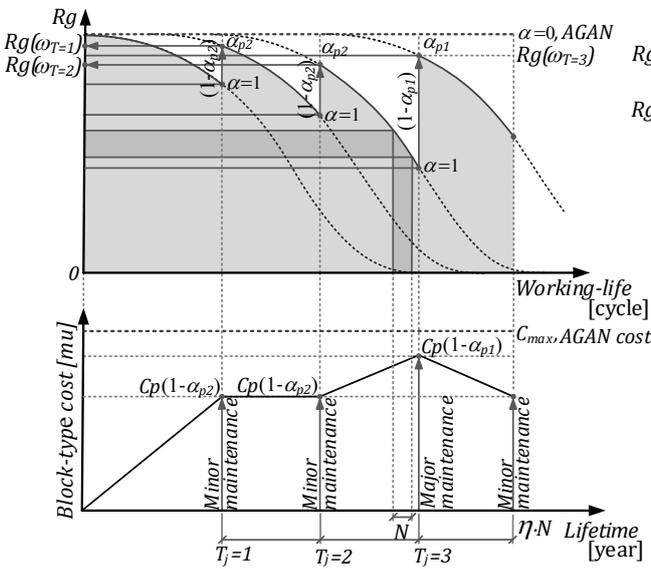
Section 4.3. will develop an application example of the maintenance parameters behaviour regarding types of preventive maintenance policies: periodic bock-type and age-based.



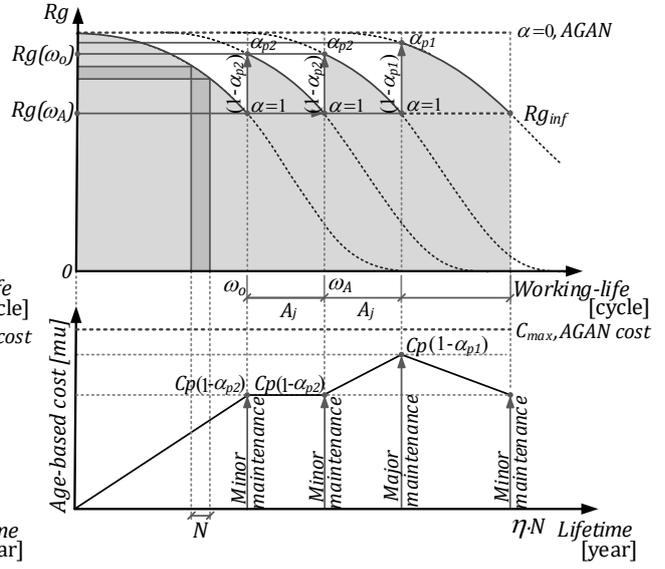
a. Waiting cost relationship.



b. Corrective maintenance parametrization.



c. Periodic block-type preventive maintenance.



d. Age-based preventive maintenance.

**Fig. 3.** Relationship of maintenance policy parameters.

### 3.3. Formulation of the joint service-maintenance problem

This work introduces a stochastic optimisation model in order to simultaneously prove a cost-efficient service and maintenance plan. The decision variables are the service rate,  $qv_n$  and  $sv_n$  (adopted for each period) and the periodicity of the maintenance actions,  $T_j$  and  $A_j$  (corrective and preventive). The optimal service plan is obtained by minimising the expected penalty cost for passengers waiting time and the cost of maintenance activities. From that point, the proposed model merges the service policy and the maintenance policy. The maintenance cost increases as a service level increases (i.e. decreasing the cost of waiting time). Formally, the problem is solved through a cost-based model made up of waiting cost,  $\Gamma wg$  (Eq. 12), corrective maintenance cost,  $\Gamma c$  (Eq. 13), and preventive maintenance cost,  $\Gamma p$  (Eq. 19) and  $\Gamma a$  (Eq. 20), as follows

$$\min_{\omega_j} C : \begin{cases} Cw \sum_n Wg_n + \sum_j Cc_j \varphi_j + \sum_j T_j C i_j & ; \text{ if periodic block maintenance} \\ Cw \sum_n Wg_n + \sum_j Cc_j \varphi_j + \sum_j A_j^{-1} C i_j & ; \text{ if age-based maintenance} \end{cases} \quad (21)$$

Subject to the following constraints

$$0 \leq g_{k,i,n} \leq cv, \quad \forall k, i, n \quad (21.a)$$

$$0 \leq \mu_{i,n} \leq \min(Lq_{i,n}, g_{k,i,n}), \quad \forall i, n \quad (21.b)$$

$$0 \leq \sigma_{k,n} \leq cv - g_{k,i,n}, \quad \forall k, n \quad (21.c)$$

$$sv_{inf} \leq sv_n \leq sv_{sup}, \quad \forall n \quad (21.d)$$

$$qv_{inf} \leq qv_n \leq qv_{sup}, \quad \forall n \quad (21.e)$$

$$Rg_{inf} \leq Rg \leq 1, \quad (21.f)$$

$$0 \leq Wg_n \leq Wg_{sup}, \quad (21.g)$$

$$0 \leq \sum_{i,n} \lambda_{i,n} \leq cv \sum_n sv_n qv_n, \quad (21.h)$$

$$\sum_{i,n} \lambda_{i,n} = \sum_{k,n} \sigma_{k,n}, \quad (21.i)$$

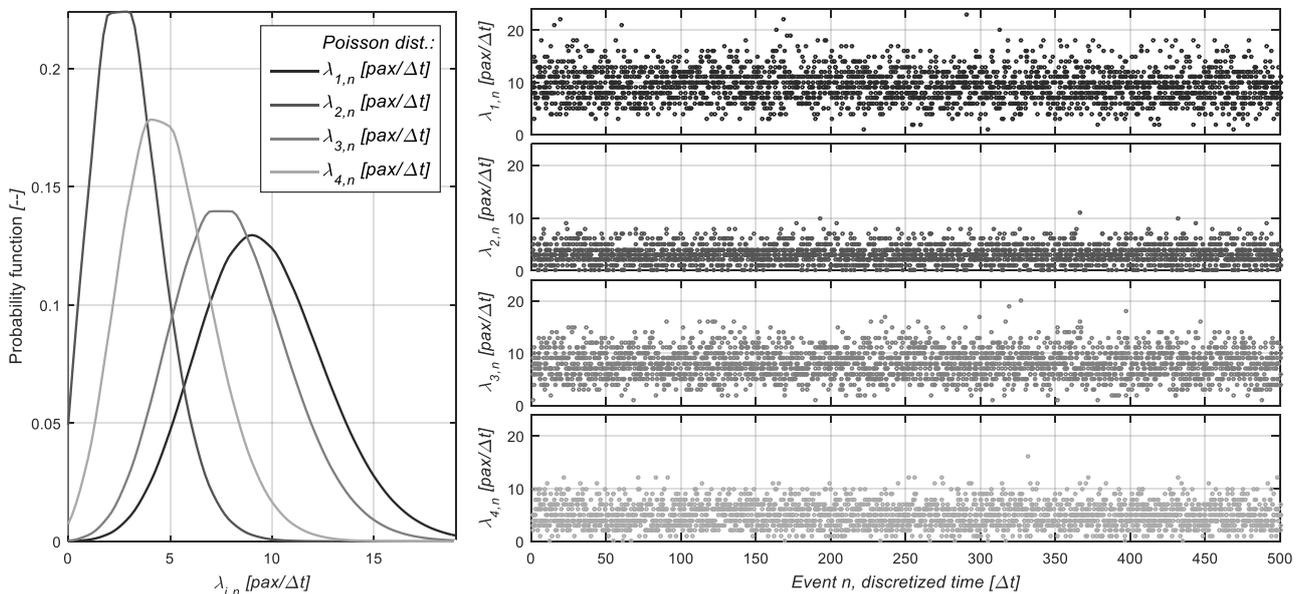
where:

- Eq. (21.a) highlights that the available places of a vehicle,  $g_{k,i,n}$ , must be less or equal to the vehicle's capacity,  $cv$ ;
- Eq. (21.b) means the quantity of passengers boarding the vehicle,  $\mu_{i,n}$ , must be less or equal that the quantity of passengers waiting in the queue,  $Lq$ ; but besides,  $\mu_{i,n}$  must be less or equal that the available places of the vehicle,  $g_{k,i,n}$ ;
- Eq. (21.c) expresses that the quantity of passengers disembarking from the vehicle,  $\sigma_{k,n}$ , must be less or equal than the quantity of the passengers traveling inside the vehicle,  $cv - g_{k,i,n}$ ;
- Eq. (21.d) is related to an operating condition; namely, the speed of the vehicles  $sv_n$  which is limited by a range  $[sv_{inf}, sv_{sup}]$ ;
- Eq. (21.e) refers to another operating condition; namely, that the system must have a range of vehicles in active service (density of vehicles)  $[qv_{inf}, qv_{sup}]$ ;
- Eq. (21.f) is related to the maintenance policy, where  $Rg_{inf}$  is the lower limit of global reliability of the system;
- Eq. (21.g) is related to other service policy, where  $Wg_{sup}$  is the upper limit of global waiting time in the queue;
- Eq. (21.h) implies that the capacity of the transport system,  $cv \sum_n sv_n qv_n$ , must be greater than the total passenger demand for a given time horizon in the transport system,  $\sum_{i,n} \lambda_{i,n}$ ; otherwise, the system is overloaded;
- Eq. (21.i) indicates that the quantity of passengers disembarking from all vehicles on the time horizon  $\sum_{k,n} \sigma_{k,n}$ , must be equal to the quantity of users that arrive on the platforms,  $\sum_{i,n} \lambda_{i,n}$ . It means that with the close of a period of service time at the end of a full working day, all passengers are served and no one remains in the system. In other words, when the system is closed after a working day, the system is empty.

A model of the ropeway transport has been developed in a virtual environment using a programming language, which allows investigating the effects of a wide range of possible conditions and parameters variation. The results obtained from the model provides accurate predictions of the behaviour of the system and its interaction with the decision variables. A ropeway transport system has been defined (see Appendix A). A sensitivity model analysis is executed by mean of 50 sets of test, every test covers 500 events. The input data are  $\lambda_{i,n}$  (a set to each platform) which are defined as a set of variables with stochastic Poisson distribution (see Fig. 4).

Appendix B (Fig. B.1) shows every single mean waiting time  $Wg_n$ , which represents the estimator used to describe the system behaviour over the discret-time; therefore, a relationship can be established between a measure of central tendency such as the average values,  $mean(Wg_n)$ , and the measure of dispersion such as the deviation standard,  $std(Wg_n)$ , to quantify the sensitivity of the model regarding the events. The ratio between  $mean(Wg_n)$  and  $std(Wg_n)$  to each platform is {0.007, 0.065, 0.011, 0.098}%, which represent an acceptable deviation level for the scope of this work.

The model is subjected to a convergence analysis to reach a stable value, Appendix B (Fig. B.2) shows the results of the mean waiting time in the queue to each platform, a lower value of 3% variation represents an acceptable level of deviation from this study. Therefore, in order to fulfil the requirement a total of 18 simulations are necessary.



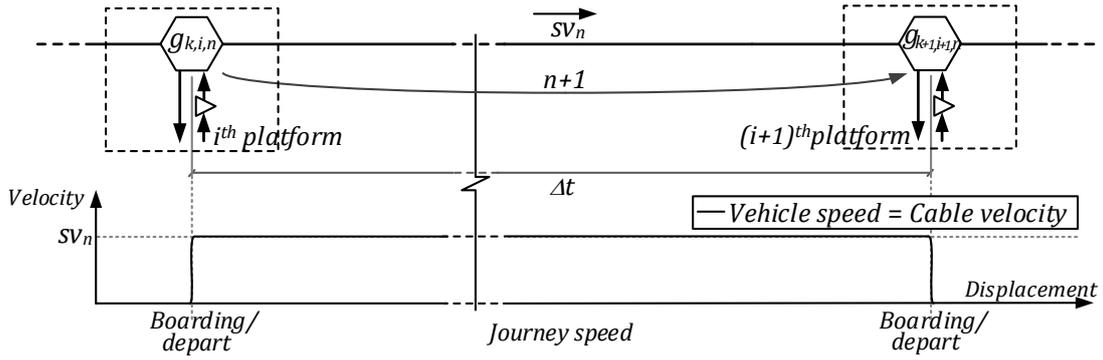
**Fig. 4.** Poisson distribution of users arrival to the platforms,  $\lambda_{i,n}$ .

#### 4. Case study: urban aerial ropeway system

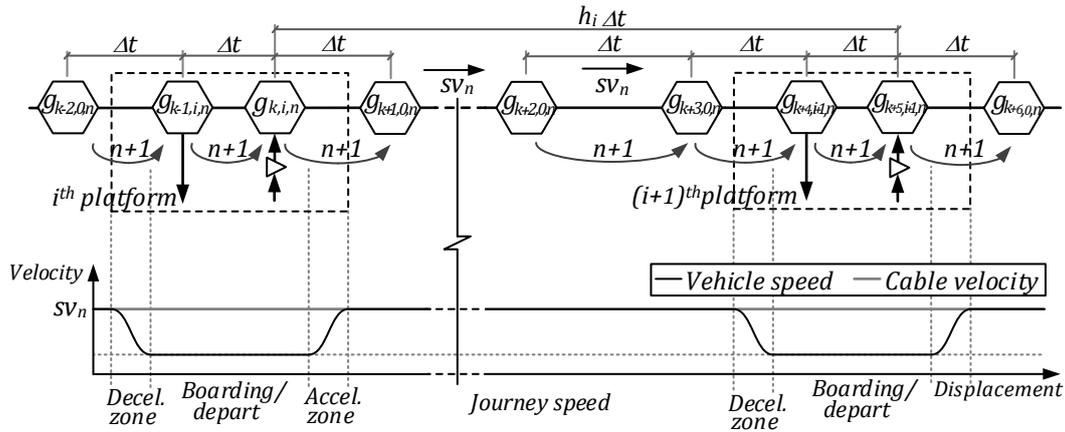
This section provides an application example to expose the obtained numerical results. According to the general operational characteristics of ropeway transport systems, two types of aerial ropeways are identified (Mizuma, 2004; Alshalalfah et al., 2013):

- (i) aerial tramway –*téléphérique*– in this system, two large vehicles (cabins) are permanently attached to each leg of the pulling cable which alternatively turns in one direction. The vehicles stop when they reach the station (see Fig. 5.a). This feature allows vehicle speed and cable velocity to remain the same throughout the journey. In addition, two operational aerial tramway designs are available: (a) an aerial tramway – reversible ropeway system consists of two vehicles suspended from cables, situated at opposite ends of the cable loops –when one is ascending, the other is descending, and they pass each other midway on the cable span–; (b) in a dual-haul aerial tramway system, there are two reversible vehicles that run on parallel tracks. There are two guide ropes and a haul rope loop per vehicle, which allows for single-vehicle operation when demand warrants.
- (ii) gondola –*télécabine*– this system has a pulling cable revolving constantly in one direction; the vehicles (gondolas) are attached and detached when entering and travelling through a platform (see Fig. 5.b). This feature allows the vehicles to be set at regularly spaced close intervals with the cable continuously circulating with the vehicles. The vehicles detach from the hauling rope at the platforms, decelerated, and carried at a very low speed through an embarking/disembarking area, and finally accelerating upon reattachment to the haulage rope for high speed travel on the line between stations. There are three gondola designs: (a) the mono-cable detachable gondola, with vehicles that are suspended from a moving loop of steel cable, (b) the bi-cable detachable gondola, which uses reversible ropeway technology, but the system is detachable, which allows the system to have a high capacity and a detachable circulating systems, and (c) tri-cable detachable gondola –3S– combines features of both gondola and reversible ropeway systems and detachable gondolas.

Our case study is concerned with a fleet supporting an urban mass-transport system; in particular, a gondola-type aerial cable system running on a continuous cycle, see figure 5(b), mono-cable (simple ring) with a detachable release clamp device (Martinod et al., 2015). The urban transport system in our case study is similar in design and construction to those used for tourist passenger transports in winter regions (e.g. Daemyung, Korea; La Clusaz, France; Donovaly, Slovakia) (Estepa et al., 2014), but it does not share the tourist purpose of these other examples (Mizuma, 2004). Therefore, the transport system in question is required at high levels of service demand that have not been supported by similar systems, causing highly elevated wear rates (Hoffmann, 2006); it will be hence the aerial cable transportation system with highest level of demand, in terms of wear hours of components and service (Martinod et al., 2015). The general features of the application example are illustrated in Table A.1.



a. Aerial tramway (téléphérique) fixed cabins.



b. Gondola (télécabine) with a detachable release clamp.

**Fig. 5.** General operational characteristics of ropeway transport systems.

#### 4.1. Service parameters behaviour

A set of tests has been developed in which the decision variables ( $sv_n$ ,  $qv_n$ ) were considered; thus, a set of combinatory tests was performed based on the ranges de operation of the ropeway system,  $qv_n = \{50, \dots, 66\}$ [veh] and  $sv_n = \{1.5, \dots, 5.5\}$ [m/s]. With each combination run, the quantity of simulations was defined by the convergence analysis to check the stability of results (Section 3.3).

The weighted mean of users that arrive on terminal platforms ( $\lambda_{1,n}$ ,  $\lambda_{3,n}$ ) and the half-way-platforms ( $\lambda_{2,n}$ ,  $\lambda_{4,n}$ ) reflects the different levels of demand at these locations (e.g. the typical demand service of the terminal platforms are higher than the half-way-platforms). The relationship between the different levels of the passenger demand can be expressed as  $l_i \lambda_{i,n}$  where  $l_i$  is the proportional coefficient between platforms; as such,  $l_1 \lambda_{1,n} = l_2 \lambda_{2,n} = l_3 \lambda_{3,n} = l_4 \lambda_{4,n}$ . In the proposed example, the relationship between the passenger demand at each platform can be written as  $\lambda_{1,n} = 1.87\lambda_{2,n} = 1.25\lambda_{3,n} = 2.13\lambda_{4,n}$ . In addition, the tests are structured by the conditions of user demand from rush hour to off-peak periods; see figure 2(a). A set of five demand conditions are established  $(l_i \lambda_{i,n})_m$  with  $m = \{1, \dots, 5\}$  where  $(l_i \lambda_{i,n})_1$  represents the demand conditions of full rush

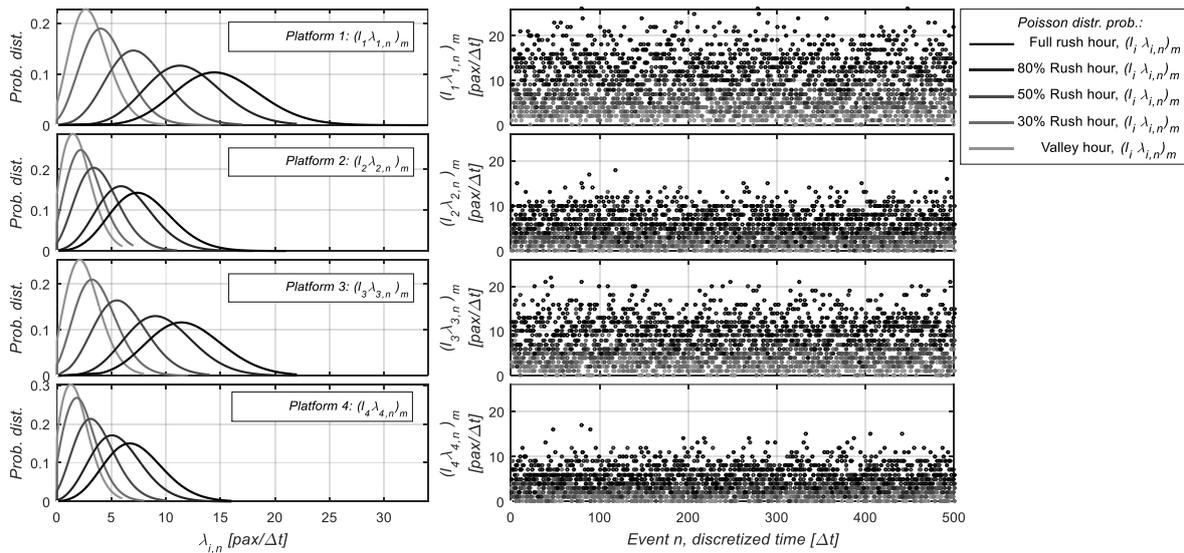
hour, and  $(l_i \lambda_{i,n})_5$  represents the demand conditions of off-peak periods; thus, a total of 8.917 tests were executed. Table 2 shows the  $m$ th Poisson parameter of  $(l_i \lambda_{i,n})_m$  to the  $i$ th platform (see Fig. 6).

The results of these tests are synthesised on Fig. 7. An initial analysis was carried out to identify the combination of the values  $sv_n$  and  $qv_n$ , that must be provided by the transport system to reach a service policy without incurring passenger waiting time; i.e.,  $Wg_n = 0$ . Fig. 7.a shows the boundary values of  $sv_n$  and  $qv_n$  in each demand condition. If the manager chooses a set of values equal to or higher than to the boundary, the users can board the vehicle without waiting in a queue. A second analysis is focused on assessing the values of  $sv_n$  and  $qv_n$  at which the transport system can offer a service with an acceptable waiting time of passengers defined by the service policy, i.e.  $Wg_n \leq Wg_{sup}$ . Fig. 7.b shows these boundary values. If the manager chooses a set of values  $sv_n$  and  $qv_n$  equal to or higher than the boundary, the users face a shorter waiting time that the waiting limit,  $Wg_{sup}$ . A third analysis is the quantification of  $\Gamma wg$  according each user demand conditions  $(\lambda_{i,n})_m$ , see Fig. 7.c.

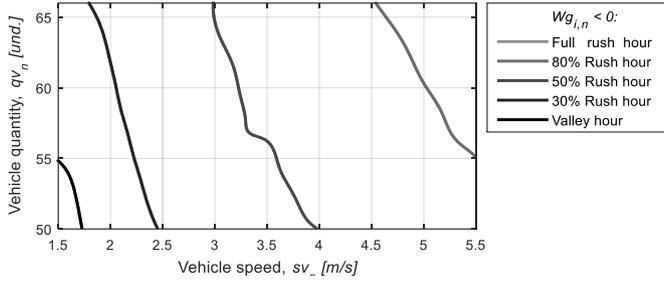
**Table 2.**

Poisson parameters of the users demand to each platform,  $(l_i \lambda_{i,n})_m$  [pax/ $\Delta t$ ].

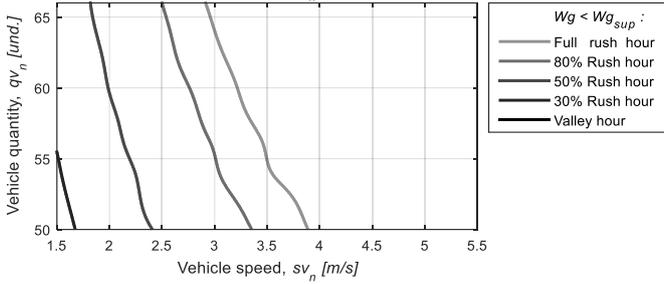
		Rush hour				Off-peak
		Full	80%	50%	30%	periods
		$m = 1$	$m = 2$	$m = 3$	$m = 4$	$m = 5$
Platform 1	$(l_1 \lambda_{1,n})_m$	15.0	12.0	7.5	4.5	3.0
Platform 2	$(l_2 \lambda_{2,n})_m$	8.0	6.4	4.0	2.4	1.6
Platform 3	$(l_3 \lambda_{3,n})_m$	12.0	9.6	6.0	3.6	2.4
Platform 4	$(l_4 \lambda_{4,n})_m$	7.0	5.6	3.5	2.1	1.4



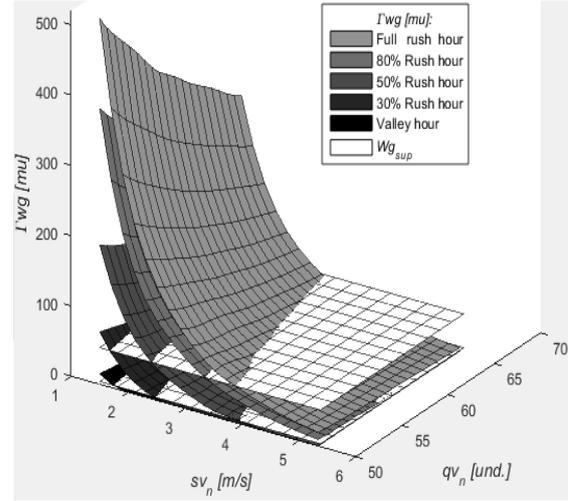
**Fig. 6.** Dataset of users arrival conditions,  $(l_i \lambda_{i,n})_m$  [pax/ $\Delta t$ ].



a. Waiting time level,  $Wg < 0$ .



b. Waiting time exceeds the waiting level,  $Wg < Wg_{sup}$ .



c. Waiting time cost,  $\Gamma wg$  [mu].

**Fig. 7.** Service parameters behaviour,  $Wg$  [ $\Delta t$ ] and  $\Gamma wg$  [mu].

#### 4.2. Maintenance parameters behaviour

The example is focused on the maintenance conditions of two sets of critical components for the exploitation of ropeway transport: (i) the conveyor-track system, and (ii) traction system.

The conveyor-track system has of the ability to decelerate/accelerate the vehicles around each platform; there is one independent system per platform. The conveyor-track system is considered one of the structural components (according to the section 2.2). The ropeway system requires that very conveyor-track works, or else the system must stop until the failure is fixed, this affecting the service policy; thus, the sets of conveyor-track systems have a series configuration on the ropeway transport, with a set of reliability functions expressed as  $\{R_1, R_2, R_3, R_4\}$ .

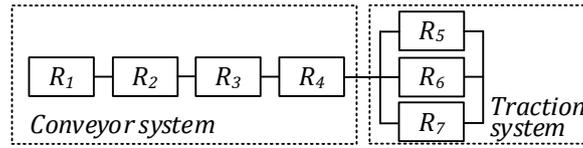
The traction system is composed by three independent and redundant systems  $\{R_5, R_6, R_7\}$  (see Fig. 8). There are two sets of electric motors, with each motor joined to a different gearbox. The ropeway system requires just one working motor-gearbox, and the second, standby motor-gearbox is available for maintenance actions. The third redundant traction system is a set of engine-gearbox; this traction system works in the case of the electrical network undergoes a cut off. Thus, the sets of traction systems have a parallel configuration on the ropeway transport.

Following the example, the set of reliability function is  $\{R_1, \dots, R_J\}$  with  $J = 7$ , and the global reliability expression is  $R_g = \prod_{j=1}^{J-3} R_j \cdot (1 - \prod_{j=5}^J (1 - R_j))$ . A previous study (Trujillo, 2013) developed an evaluation and analysis focused on components of a ropeway system based on reliability, maintainability, and availability

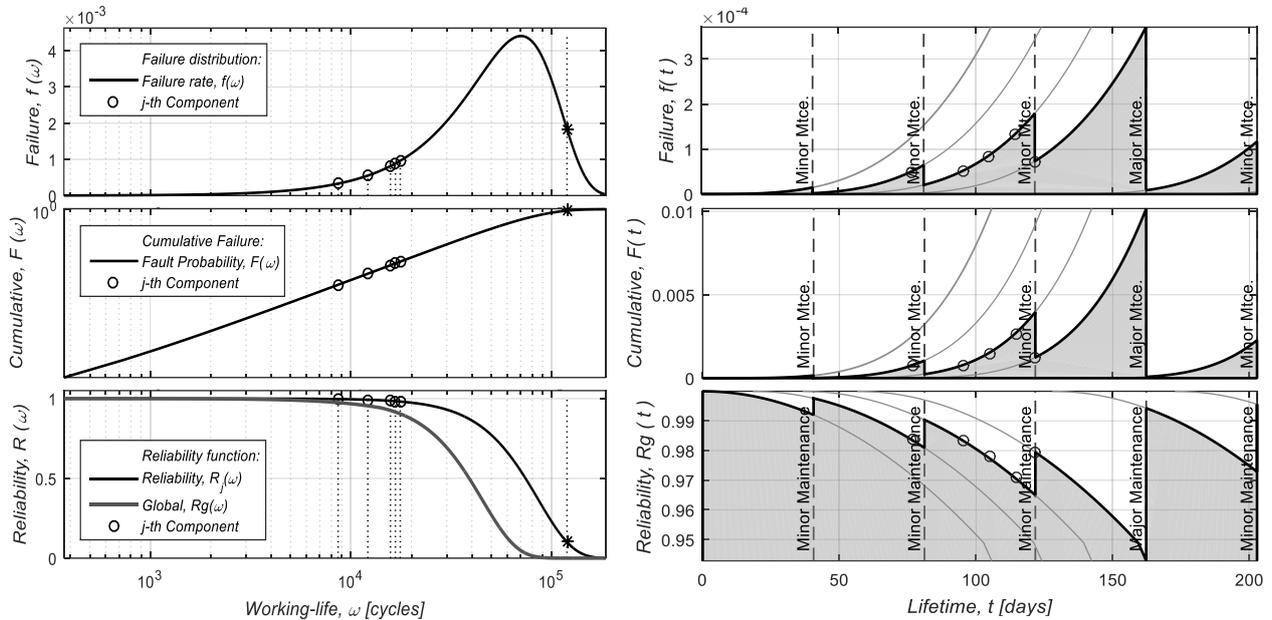
(RMA). That study measured the fault probability distribution of the detachable grips, and its reliability probability. The author made a Kosmogorov-Smirnov test and found the distribution of the faults belong to Weibull distributions.

The example considers all analysed components,  $j = \{1, \dots, J\}$ , belong to the same type of components (in this case, the components belong to the structural elements in the system), the same maintenance policy is applied to the same type of the components. An analysis of the failure probability progress on the transport system is made. Deterioration of the system is computed in three stages: (i) the functions  $f_j$ ,  $F_j$  and  $R_g$  are calculated to obtain the progressive degradation of the system according to typical operation conditions. Considering just the corrective maintenance actions, it means a reactive maintenance policy is applied, without preventive maintenance actions, see Fig. 9.a; (ii) the effect of the preventive imperfect maintenance action to each period of time is calculated; and (iii) the degradation system is found by the superposition principle, to get the mixed effect due to the corrective and preventive maintenance actions on the system (see Fig. 9.b). Two scenarios are considered for application example:

- (i) maintenance cost calculated according to periodic block-type preventive maintenance. This is the current maintenance policy applied by the maintenance managers of ropeways systems and it is the traditional maintenance policy established by the international regulation. The decision variables  $(T_j, sv_n, qv_n)$  have been considered as a combinatorial tests based on the range  $T_j = \{3, \dots, 12\}$ [maint./year] and the working cycles  $\omega(sv_n, qv_n) = \{1.18E4, \dots, 4.56E4\}$ [cycles]. Each combination was run and the quantity of simulations was governed by the convergence analysis to check the stability of results. Fig. 10.a shows a synthesis of the results. The cost of the periodic block-type preventive maintenance do not rely on the degradation of the components, but it is directly proportional to its periodicity,  $T_j$ . The cost of the corrective maintenance increase with the degradation of the components, but decrease with the periodicity of the periodic block-type preventive maintenance.
- (ii) age-based preventive maintenance. This scenario can be used to quantify the effectiveness of the applied current maintenance policy used by the maintenance management. Fig. 10.b shows a synthesis of the results. The cost of the age-based preventive maintenance depends on the degradation of the components. As such, quantity of maintenance actions is in function of  $R_g$ . Note that the quantity of preventative maintenances corresponds to 7 maintenance actions per year, the cost of the corrective maintenance changes of tendency; i.e., the cost behaviour of the corrective maintenance for the age-based preventive maintenance can be classified in two performances: (a) the value of the corrective maintenance cost decreases until a defined quantity of preventive maintenances, and (b) after the defined quantity of preventive maintenances, the value of the corrective maintenance cost remain almost constant.



**Fig. 8.** Components configuration on the ropeway system.



a. Failure probability at frequency domain.

b. Effects of preventive maintenance actions.

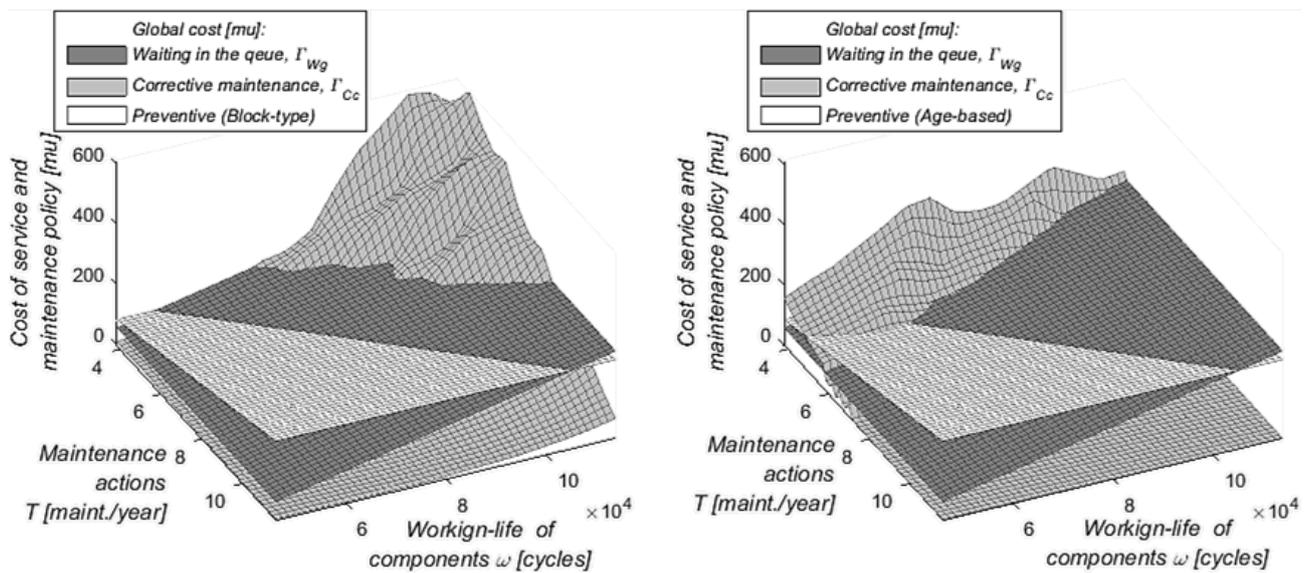
**Fig. 9.** Failure probability progress of the system.

#### 4.3. Cost of service and maintenance policies

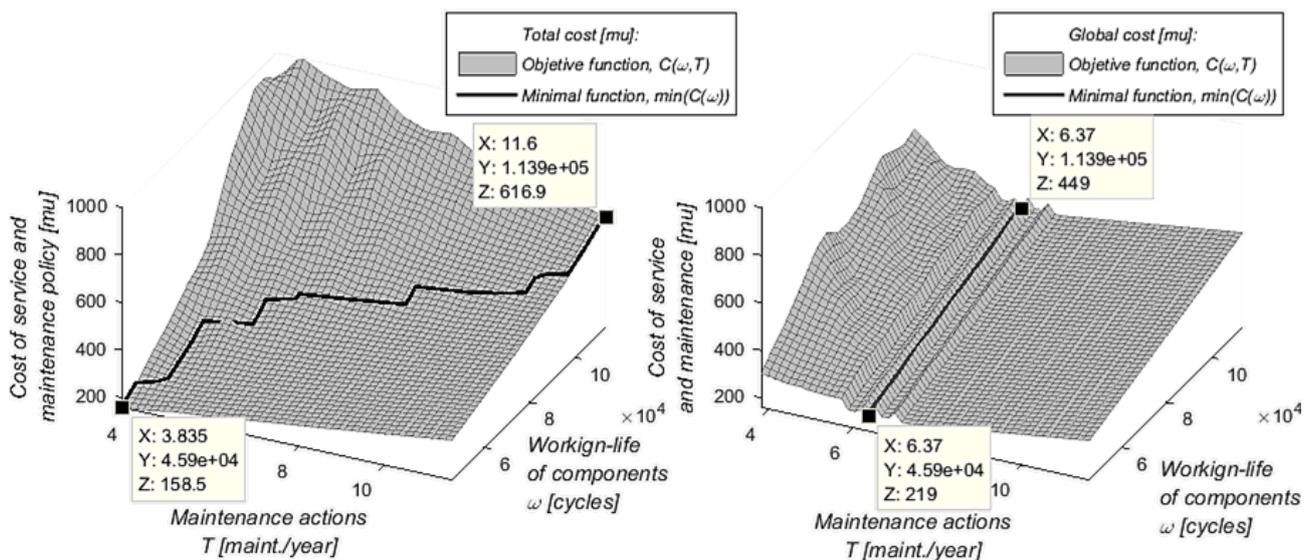
By using Eq. 21, which relates the cost of the service and maintenance policies, it is possible to get two independent objective functions  $C(T_j, \omega)$ : (i) an objective function regarding to the periodic block-type maintenance policy (see Fig. 10.c), and (ii) an objective function regarding to the age-based maintenance policy (see Fig. 10.d).

An analysis of  $\min(C(T_j, \omega))$  belonging to the periodic block-type maintenance policy shows the lowest cost is obtained through quarterly preventive maintenance actions for a working-life of 4.59E4 [cycles]. Once the working-life reaches a value of 1.139E5 [cycles], however, the lowest cost is achieved with a monthly preventive maintenance action. The function  $\min(C(T_j, \omega))$  belongs to the age-based maintenance policy. It indicates that the periodicity of the preventive actions have a constant value over the working-life of the system. The lowest cost is gotten with a two-monthly preventive maintenance action.

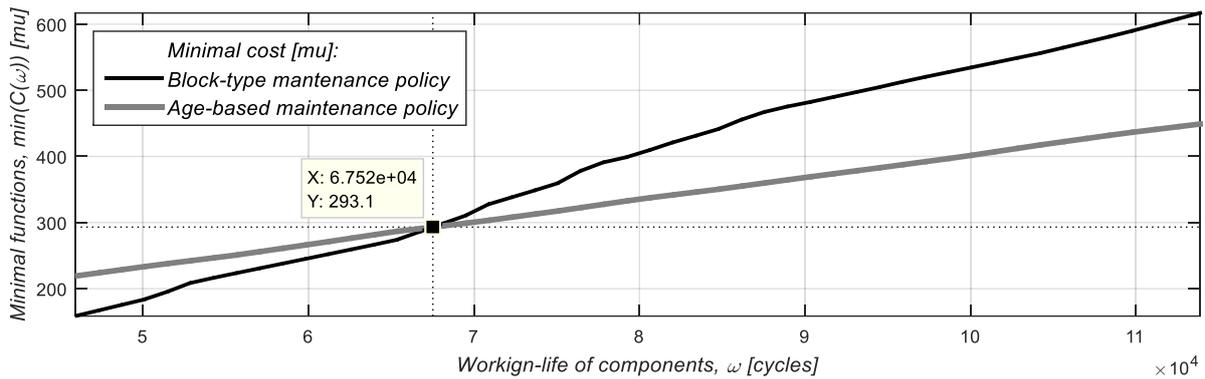
Fig. 10.e shows the relationship between the functions  $\min(C(T_j, \omega))$  in each of the maintenance policies. Note that if the components of the system have a low working-life value, the appropriate policy is the periodic block-type maintenance (the cost of the periodic block-type maintenance is 27.62% lower than the age-based maintenance). However, if the components of the system undergo wear and a decline in performance, due to the high demand on the system, the appropriate policy is the age-based maintenance (the cost of the periodic block-type maintenance is 37.40% higher than the age-based maintenance). Therefore, there is an optimal working-life value for a change in the maintenance policy. This value ensures minimal cost (considering the operational service and the maintenance actions) during the service life of the transport system. The optimal working-life value is calculated as  $6.75E4$  [cycles].



a. Cost of service and periodic block-type maint. policy.    b. Cost of service and age-based maint. policy



c. Objective fn. with a periodic block-type maint. policy.    d. Objective fn. with an age-based maint. policy.



e. Minimal functions of different maintenance policies.

**Fig. 10.** Cost of service and maintenance policies.

## 5. Conclusions and discussion

In this study, a mathematical framework is developed to integrate service and maintenance policies in order to solve the queueing problem and the cost of maintenance actions in public transport services. For this purpose, the authors have proposed: (i) a stochastic discrete-event model composed of a set of interrelated queues for the formulation of the service problem using a cost-based mathematical expression; and (ii) an imperfect preventive maintenance based on two different maintenance policies (periodic block-type maintenance and age-based maintenance).

In the first stage of the analysis, a mathematical model of the service policy was proposed to determine the values of the operational parameters ( $sv_n, qv_n$ ) in which the transport system offers different levels of service quality: (i) users get the service they need without waiting in a queue; and (ii) an *acceptable* waiting time for passengers, defined on the basis of the service policy. Further on in our analysis, the penalty cost in terms of global waiting time,  $\Gamma wg$ , was considered as a term of the optimisation model based on cost,  $C(T_j, \omega)$ . In a later stage of the research, this work developed a stochastic model of maintenance that considers the degradation for a multi-component system with a dependence relationship between the components. Through our analysis, the model cost of maintenance (which includes the corrective and preventive maintenance action) completes  $C(T_j, \omega)$ . An optimisation model  $C(T_j, \omega)$  has been formulated to bring together the service and maintenance policies, making it possible to determine the optimal cost function  $\min(C(\omega))$  such that the cost over a long-time window of working-life was minimised.

This work developed an optimization model that integrates the service and operations policies with the maintenance policy of a transport system. We show that neither periodic block-type maintenance nor an age-based maintenance are necessarily the best maintenance strategy over a long system lifecycle. The optimal strategy must consider both policies; at the beginning of the working-life, applying a periodic block-type is

likely the most advantageous, but as the components of the system undergo age and deteriorate, an age-based maintenance policy is likely the preferable option.

Currently, maintenance managers of transport systems apply a single maintenance policy during the working-life cycle. This paper provides strong support to the idea that an optimal maintenance policy is a mixed policy. Therefore, current maintenance strategies should be reconsidered in order to improve service and the maintenance activities.

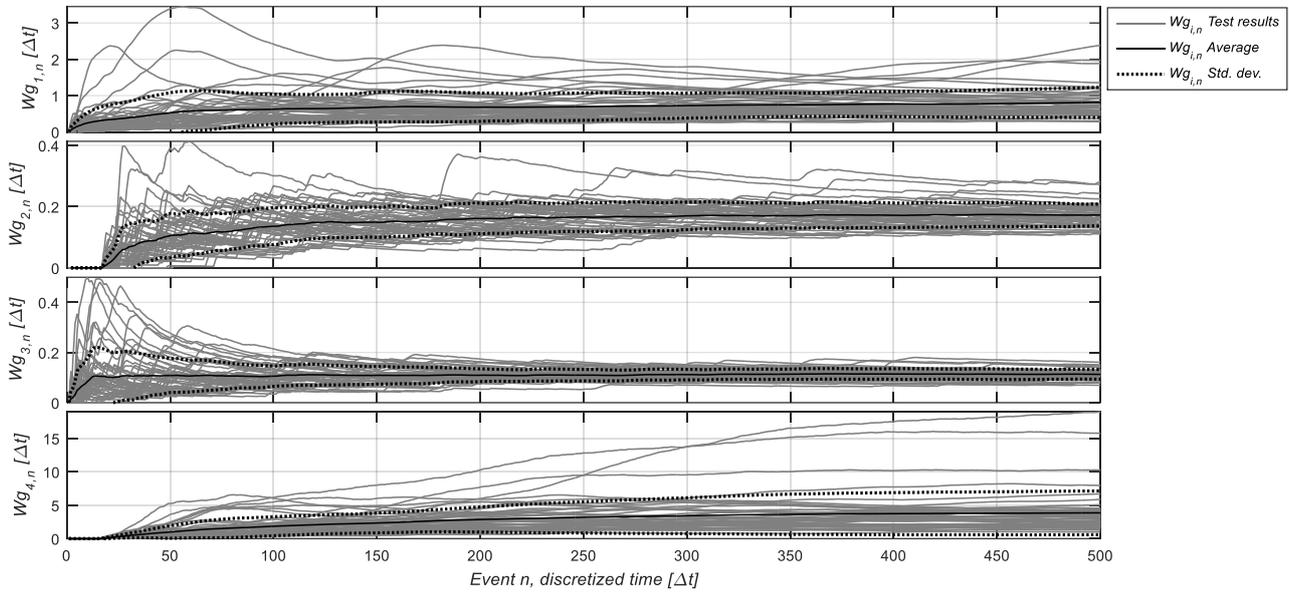
Future research will focus on the four major aspects. From the perspective of passenger demand, transport systems are not independent, they are interconnected and inter-modal. Further analysis of service delivery and the passengers' facilitation process can be undertaken with regard to a ropeway system's connection to an intermodal transport network. This calls for a more robust algorithm to speed up the data processing for solving larger-scale problems. Secondly, it is possible to propose other study, in which broaden different relationships of the penalty cost for the global waiting time –polynomial functions, hyperbolic functions, exponential function, etc.– where an analysis of the system characteristics and its implications is considered. The present work has only considered a linear function for this relationship and for the implications for the service policy. Third, it is perceived that urban transport undergo a remarkable intensity of passengers flow in one direction over defined periods –people go to work, students go to schools, etc.– generating a strong asymmetric demand of passengers over the ropeway system. This urban transport characteristic can be further embedded into the formulated model. Fourth, this work provides an analysis which considers the user requirements and the company profit. Building on that, it possible to propose a further analysis that includes the social cost and the environmental cost; thus, an approximation of sustainability model can be proposed. Finally, this work assumed that all analysed components belong to the same type of elements, and therefore the same maintenance policy is applied to the components, and in addition the preventive maintenance actions are performed on all components at the same time. As such, it would be possible in future to develop a maintenance model which considers components affected by multiple types of independent degradation processes.

## Appendix A. General features of the ropeway transport model

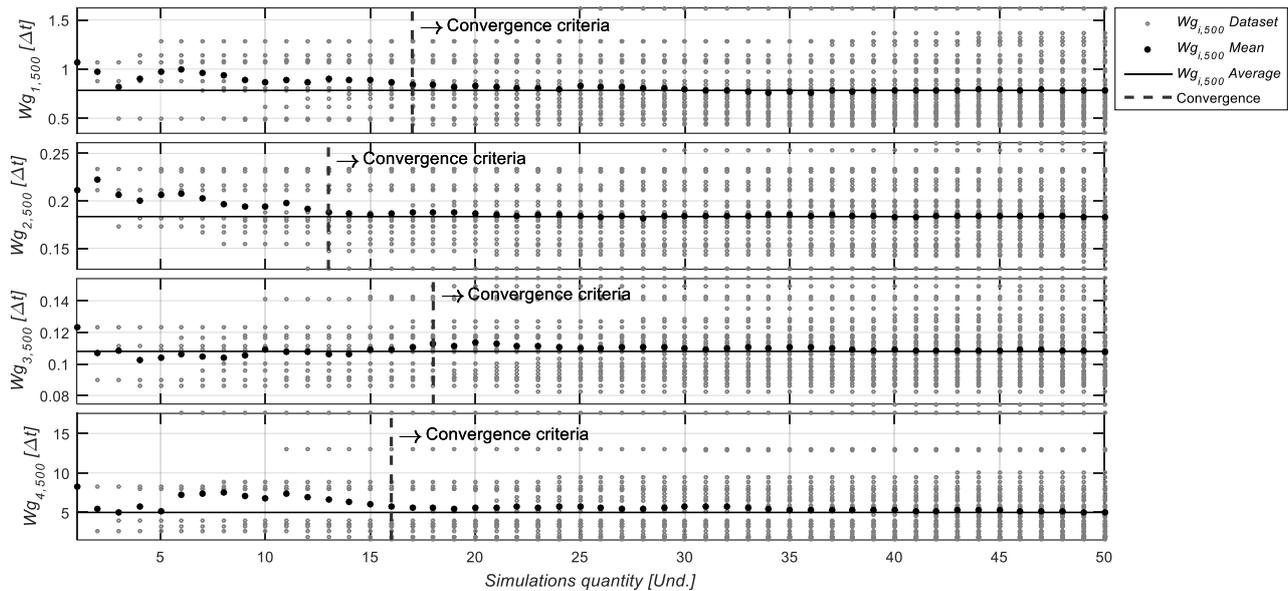
**Table A1.** Parameters of the transport ropeway system.

Operational parameters		Value			
Vehicle (gondola) capacity, $cv$ [pax/veh]		10			
Quantity of vehicles, $qv_n$ [unit]		60			
Commercial speed, $sv_n$ [m/s]		5.00			
Distance between vehicles, $lv_n$ [m]		61.67			
Frequency of vehicles, $fv_n$ [s]		12.33			
Quantity of stations [unit]		{1, 2, 3}			
Quantity of platforms, $i$ [unit]		{1, 2, 3, 4}			
Discretised time, $n$		{1, 2, ..., 500}			
Travel between platforms (start-end)		1-2	2-3	3-4	4-1
Inter-platform length [m]		750	900	900	750
Inter-platform vehicles [veh]		14	16	16	14
Inter-platform travel time [s]		170	200	200	170
Service policy parameters		Value			
Travel between platforms (start-end)		1-2	2-3	3-4	4-1
Users arrival to platform (Poisson distribution), $\lambda_{i,n}$ [pax/ $\Delta t$ ]		9.0	3.0	8.0	5.0
Effectuated services, $\sigma_{i,n}$ [pax/ $\Delta t$ ] (uniform distribution)		--	--	--	--
Maintenance policy parameters		Value			
Cost of preventive maintenance action, $Cp$ [mu]		60			
Cost of corrective maintenance action, $Cc$ [mu]		$10 Cp$			
Age reduction coefficient (major maintenance), $\alpha_1$ [--]		0.1			
Age reduction coefficient (minor maintenance), $\alpha_2$ [--]		0.3			
Quantity of minor maintenance per major maintenance, $p$ [--]		3			

## Appendix B. Results of sensitivity of the model



**Fig. B1.** Mean waiting time in the queue,  $Wg_{i,n} [\Delta t]$ .



**Fig. B2.** Convergence analysis result of the numerical model.

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