METHODOLOGY FOR THE DEVELOPMENT OF RAILWAY OPERATING PLANS

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ABSTRACT

The main objective of this paper is to determine the methodology to be followed for the optimization of railway transport services supply in a railway line selected as scope of the study.

To carry out this optimization, it is vitally important to have a high-quality database, which includes consolidated technical information. This database will be made up of different items, which will refer to aspects related to the infrastructure (equipment, alignments, slopes, speeds, etc.) and to its traffic type (passengers, freights or mixed).

Furthermore, a geographic database must be considered, in order to the railway line will be digitized from a satellite image, and on which all the items included in the database that are relevant for the development of the operating plan will be spatially captured.

Once the data is collected, gear simulations are carried out with commercial times and the calculation of energy consumption for each rolling stock. This allows us to know the commercial times that would be registered on the line with different trains and consumption, in order to determine the optimal material that would be of interest for commercial exploitation.

Through the elaboration of traffic meshes, the economic balance of the operator is calculated for different service offers, until the one that the operator considers optimal is obtained. Likewise, it provides production results and operating costs.

This methodology focuses on the maximization of the railway transport capacity to attract potential passengers from other modes that could be more environmentally aggressive. For this reason, the reduction of the energy consumption by taking advantage of braking energy is a key issue.

The main objective of carrying out a railway operating plan is to promote the use of rail transport by improving the service, both quantitatively and in terms of quality, by reducing travel and waiting times, increasing supply and reducing operating costs.

Therefore, to carry out said optimization of existing or newly created passenger services, an analysis of the current situation of both services and infrastructure must be carried out, an estimate of the demand that would involve the incorporation or elimination services, and finally an economic analysis.

1. ANALYSIS OF CURRENT AND FUTURE SITUATIONS

To perform a good optimization of services, it is vitally important to have a quality database, which includes revised and consolidated technical information. To do this, an analysis of the infrastructure to be exploited and the railway material available or the new material that will be available in the service must be carried out.

This base will be made up of numerous indicators, which will refer to aspects related to infrastructure (equipment, alignments, slopes, speeds, etc.) and to the traffic that develops on it (travelers, goods or mixed).

There must also be the existence of a reference cartographic base, where the layout will be digitized from a satellite image, and on which all the aspects contained in the database that are relevant for the elaboration of the data will be spatially captured.

This allows to create relevant tools so that the operator can optimize and manage the strategy for the operation of the line

2. TRAVEL TIME CALCULATION

Once the type of material destined for railway operations has been analyzed and defined, the commercial times are calculated.

To do this, minimum speed simulations have to be carried out, obtaining the minimum times and energy consumption that each service would have. Once these minimum times have been obtained, the commercial progress must be calculated taking into account the commercial and recovery margin defined in the UIC 541-1.

To obtain these times and consumptions, the simulation model will be based on an integration model. These types of models are basically based on three different approaches to estimate train movement: (i) a function of time, (ii) a function of distance, and (iii) an event-based model.

The best method used is based on the second option (function of distance) for estimating motion as well as energy. For this, it can be stated that energy consumption is the applied force necessary to move the vehicle a certain length:

$$E = \int F(s) \cdot ds \quad (1)$$

From the above formula it can be highlighted that:

- In each process of acceleration of the train there is a consumption of energy, because the positive acceleration implies a tractive force.
- In each deceleration process a certain amount of energy is generated in the brake, because negative acceleration implies a retarding force, which depending on its type can be dissipated in the form of heat or transformed into electrical energy and returned to network.

The way that is chosen to model the movement of a train is to calculate all the forces that act on the vehicle point to point. In this case, it corresponds to each meter, that is, in each meter of a defined line (Origin-Destination) the forces to which it is subjected are determined and / or the forces exerted on it are estimated.

The forces acting on the motion of a vehicle are:

a) Drag (R*av*).

$$R_{av} = A + B \times V + C \times V^2 \quad (2)$$

Where: *V* is the trains speed (km/h). A, B and C are the mechanical, air intake and aerodynamic coefficients that depend on the physical characteristics of the train *(daN, daN/(km/h) and daN/(km/h)^2).*

b) Resistance due to the curve (R*c*).

$$R_c = M_{car} \times \frac{600}{R} \rightarrow R_c = M_{car} \times \frac{800}{R} \quad (3)$$

Where: M_{car} is the mass of the loaded trains *(tons)* and R is the curves radius measured in metres *(m)*.

c) Resistance due to slopes (R*p*).

$$R_p = M \times g \times i \quad (4)$$

Where: M mass of the train *(tons)*, g is gravity *(m/s^2)*, i is the slope *(mm/m)*

d) Traction or brake force (F*t*/F*d*).

The traction curve and the brake curve are in function of the speed (effort-speed curve) and depend on the train power and the adherence. Both curves are parameters provided by the manufacturer.

Next, it is showed an actual example of the effort-speed curve.

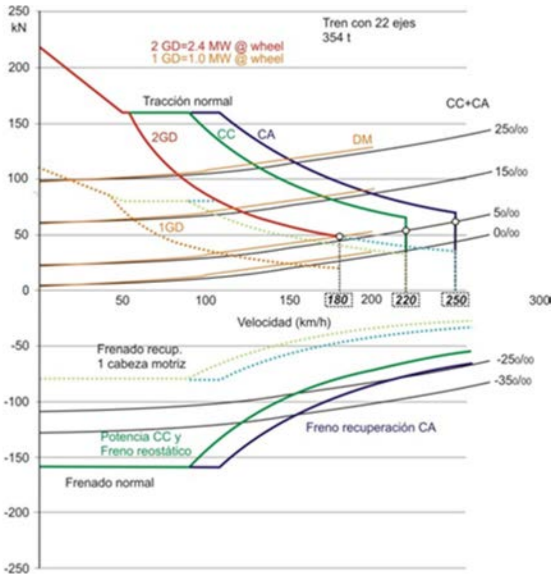

Figure 1. Example of the effort-speed curve

Knowing the forces exerted by the vehicle, both traction and braking, the energy consumption and the energy dissipated in the brake, essentially, are estimated with the following equations:

$$E_c = \int F_t(s) \cdot ds \;\; o \;\; E_R = \int F_d(s) \cdot ds \qquad (5)$$

Where: Ec is the energy consumed by the train (kWh), Er is the energy dissipated in the brake (kWh), Ft Tractive force (daN), Fd is the force exerted by the brake (daN), and ds is the differential of length.
The resultant of all the forces exerted and / or applied on the vehicle is the force used to estimate the acceleration (or deceleration)

$$F_{tot} = R_{av} + R_c + R_p + F_t + F_t = M_{tot} * \frac{dv}{dt} \qquad (6)$$

The M_{tot} parameter corresponds to the total mass of the vehicle considering the rotating masses.

Knowing the total force at a point, the acceleration, the speed, and the travel time are calculated using the equations of uniformly accelerated rectilinear motion.

This allows us to know the commercial times that would be recorded on the line with different trains and their consumption, in order to determine the optimal material that would be of interest for commercial exploitation.

3. DEMAND

Once the new travel times and the services to be implemented are known, it is essential to have a demand study for the different means of transport that currently serve this corridor, and to know the induced demand that will be captured from them. thanks to the improvements and possible changes proposed.

In order to carry out this demand study and find out the number of travelers they will have on the new services implemented, the current demand for the different media, their travel times and their frequencies is first analyzed.

In passenger transport there is a differential factor of the utmost importance, since, to move from one place to another, the traveler must not only pay the price of the ticket, but must also “contribute” their own time. People perceive that their time has value, and they implicitly “monetize” it or convert it into the equivalent of money. This total cost is what is called generalized cost, and it is what allows us to determine which means of transport each traveler will use.

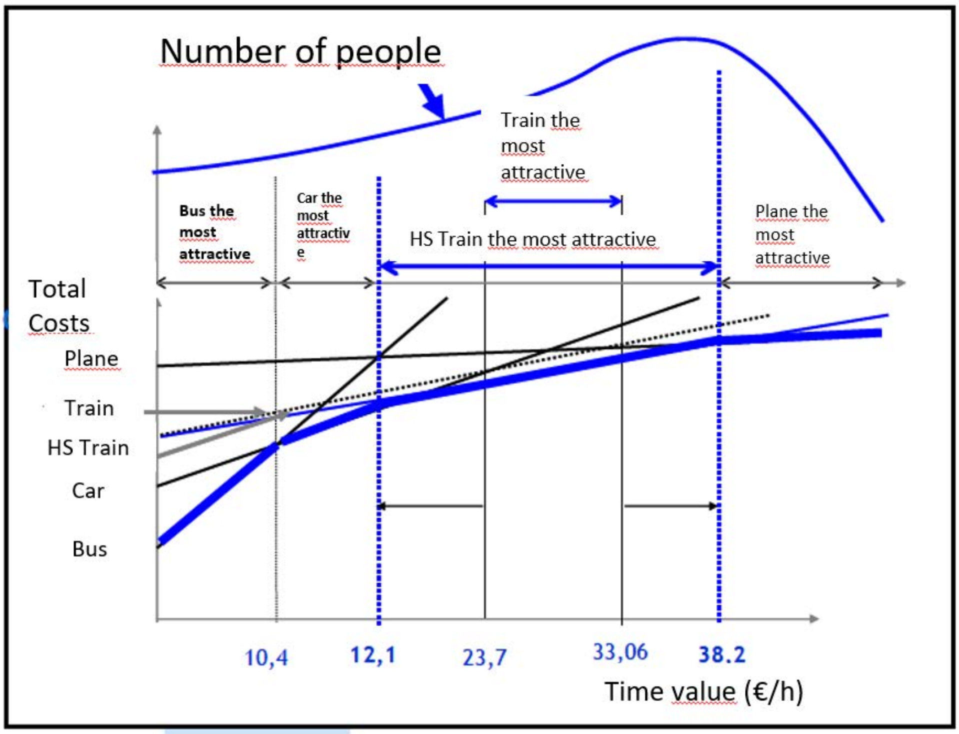

Figure 2. Generalized cost in various modes of transport as a function of the value of time. Effect on the competitiveness of the train of an increase in its speed.

To verify the demand data obtained, a study of generalized costs has been carried out, which is detailed below.

The parameters to take into account for the calculation of said generalized cost are:

a) Frequency
b) Time

To make the trip, in addition to the travel times of each means of transport, the waiting times, information and ticket purchase, travel and terminal times are taken into account.

$$Tt = Tb + Tdt + Te + Tv \quad (7)$$

Where:

Ticket time (Tb): It is the time used to get informed, get the tickets ...).
Travel time and terminal (Tdt): It is the time used to arrive and leave the terminal and to travel through it. The centrality of the stations and their limited dimensions will be taken into account.
Waiting time (Te): It is the time taken to wait for a transport offer. On average, the wait time is the inverse of the frequency.
Travel time (TV): The bus and car travel times will include the possibility of traffic jams, considering an average of 5 minutes throughout the journey.

c) Perceived Time

In each of the phases of the trip, time has a different value for each person, which coincides with personal experience. For example, the time is longer when the user has a bad time or is uncomfortable.

In this way, a modulation coefficient of perceived time is applied to the times, which introduce comfort, ergonomics, the perception of safety, etc. into the model.
The formula for the total perceived time would then be:

$$Tptot = \beta \times Tb + \delta \times Tdt + \Phi \times Te + \upsilon \times Tv \quad (8)$$

These coefficients depend on physical, utility or psychological factors:

- Physical factors: If the user is uncomfortable, without air conditioning, with noise.
- Useful factors: If you can take advantage of the time during the trip.
- Psychological factors: fear, uncertainty, insecurity.

The coefficients will have a value greater or less than 1 to homogenize the duration of time.

The higher these coefficients, the time "gets longer"

The cost of the time spent on the trip is calculated by multiplying the total time by the Value of time, VT (€ / hour).

Ct(€) = Tptot x VT (9)

The total cost of the trip is the sum of the monetary costs and the cost of the time used, so the total general cost will be:

Ci = (Cmd + Cmo) + Ct (10)

Cmd: Direct monetary cost (€).
Cmo: Cost related to the station. They are considered transports from the origin and to the destination.
Ci: Generalized cost

Next, the modal split is calculated according to each mode of transport and its generalized cost:

Pi = e (−γ ∗ Ci) ∈e (−γ ∗ Ci) (11)

Pi: Probability of choosing the medium "i"
Ci: Generalized cost of the trip in the medium "i"
n: Number of means of transport
γ: Model calibration parameter

Once the number of travelers per year is known, it is necessary to make a daily distribution, taking into account the usual oscillations such as weekends, times of greater load, oscillations between roundtrip directions, etc., in order to be able to size the fleet for the biggest daily commuter tip.

4. ESTABLISHMENT OF SERVICES

When preparing the best services according to the expected demand, it is necessary to define the analysis scenarios, calendars, service periods and patterns-types of schedules.

- Calendars: the "service calendars" of seasons of the year (for example, vacation, non-vacation) will be defined, indicating the number of weeks per year for each; as well as the peak, valley and flat periods defined for each season for standard days:

a) Monday to Friday; b) Saturdays, and c) Sundays and holidays. In the case of tips, it will indicate which is the dominant traffic direction at the tip.

- Hourly periods: Four time periods can be defined according to the classification of the hours: a) peak (with distinction of the two senses); b) flat; c) valley; and d) super-reduced.
- Service patterns: Various patterns (origins-destinations of trains and stops) to be associated with each of the time periods will be defined by technical assistance. These patterns will be defined for one hour and one direction, considering in principle that the schedules are cadenced and symmetrical. The most suitable minute of symmetry will be analyzed to optimize the rotations in all the headers.
- Types of services:
  - Stops service: This type of service is characterized, as its name indicates, by making stops at all stations on the line.
  - Semi-direct Service: It is characterized by making stops only at certain stations on the line. These stations have been determined based on the demand of each one of them, in order to support the dependencies that have the greatest demand.
  - Direct service: Direct services are those that are performed only between the main stations

In addition to the type of services mentioned above, it is also necessary to analyze whether it is convenient to establish optional stops

These stops are characterized by making it only in those dependencies in which passengers are going to get on or off.

With this type of service, which was in force at Renfe in the 1980s, it is intended to guarantee the reliability of the line's services by eliminating the stoppage of the train in those dependencies in which, in that specific service, there were no passengers who were to get on or off the train. In this case, the drivers, through the controller, will know those optional stops in which it is necessary to stop the train to allow passengers to get off. As for the ascent, it will be the driver, as the stations pass, who will make the stop depending on the presence of travelers on the platform.

- Thanks to this type of service you get:
- - The survival of those stops whose number of passengers is small or even null, which have the possibility of disappearing.
- - Reduction of travel times that can translate into margins for economical driving.
- - Fuel savings that may be due both to economical driving, as well as to the reduction of braking and acceleration due to the reduction in the number of stops, in case of switching from a service with stops to a service with optional stops.

- - Reduction of CO2 emissions, which is given by the reduction of energy consumption.
- - Savings in maintenance of both the rolling stock and the track, due to less wear and tear due to reduced braking and acceleration.

It should be noted that each time a service is modified, the demand analysis must be carried out again, since each small change can cause an increase or decrease in the number of travelers on the operation.

5. SCHEDULE COORDINATION

Schedule design is a method by which energy consumption can be reduced at no additional cost. This makes this measure one of the best methods to reduce energy consumption.

It should be clarified that, in order to achieve these energy savings, in addition to applying the compatibility of schedules, the use of the regenerative brake is a crucial condition for any energy reduction in terms of schedules.

There are three aspects to be taken into account to reduce energy consumption. The first of them is related to (i) time frames and their compatibility with eco-driving previously explained; while the second and third are related to the (ii) coincidence between the departures, or between (iii) the departures and arrivals of the trains at a station respectively.

These aspects are described below.

- Time frames used to perform eco-driving:

Carrying out efficient and economical driving consists of exploiting advantages offered by the existing time frames in the schedules, in order to reduce energy consumption.

On the other hand, train schedules need "regularity margins" to be more robust and reliable.

That margin is often longer than the time required to perform eco-driving, therefore, it is possible to allow a small amount of time to do an eco-driving in the sections where there are no time requirements, and distribute the rest of the time between the points of the sections that require punctuality. Another possibility is to reduce the times in the stops in order to add these times to the margins necessary to carry out economical conductions.

- Avoid simultaneous departures:

The different tracks of the same station are normally fed by the same substation, even in some cases several stations are fed by the same substation. Therefore, if there is a simultaneous output of different trains, there is an increase in the peak power required in the substation, as shown in the following figure.

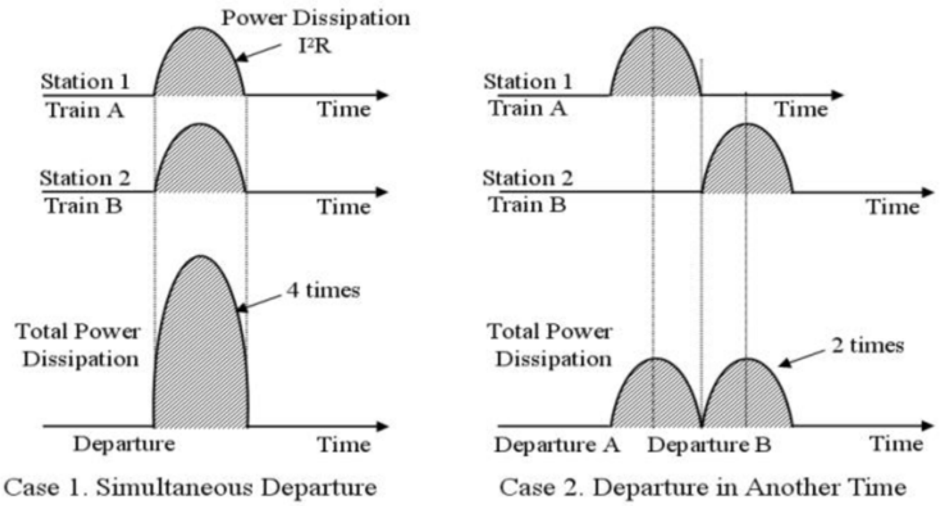

Figure 3. Power peaks due to train departures. Source: K.M. Kim et al. (2010).

This also implies an increase in ohmic losses, and therefore an increase in the energy required. In addition, the installation of a higher capacity substation is required, which translates into an increase in investment costs.

- Simultaneous arrivals and departures at the same station:

On a line with frequent stops and trains with regenerative braking, if trains depart and arrive at the same time at the same station, greater energy savings would be achieved, since the energy regenerated by the brake of the incoming train at the station can be used by the trains leaving said station in their acceleration process, as shown in the following figure.

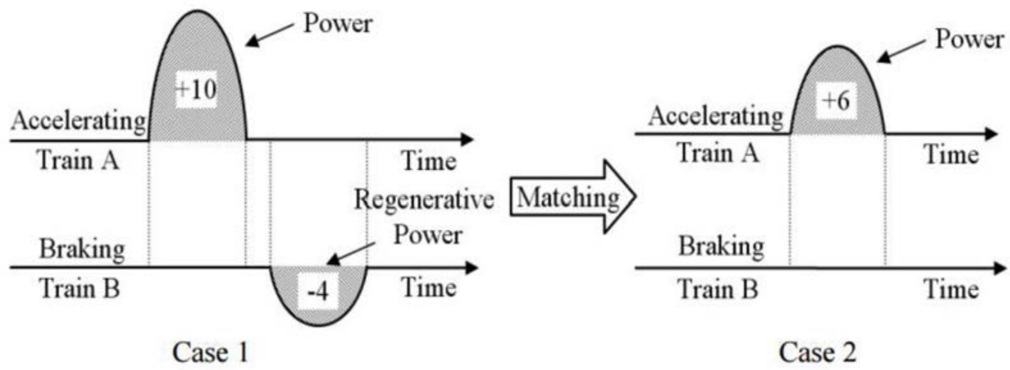

Figure 4. Power peaks in substations due to departures and arrivals. Source: K.M. Kim et al. (2010).

Timetable compatibility can help reduce energy consumption and costs, both energy and facilities, with similar travel time and almost no investment.

6. MESH CREATION

Once the services have been created and the demand known, multiple different supply scenarios configured with different type patterns (calendars, time periods, service patterns, schedules, symmetry minutes) will be carried out in order to obtain a range of possible solutions to achieve an optimal exploitation plan.

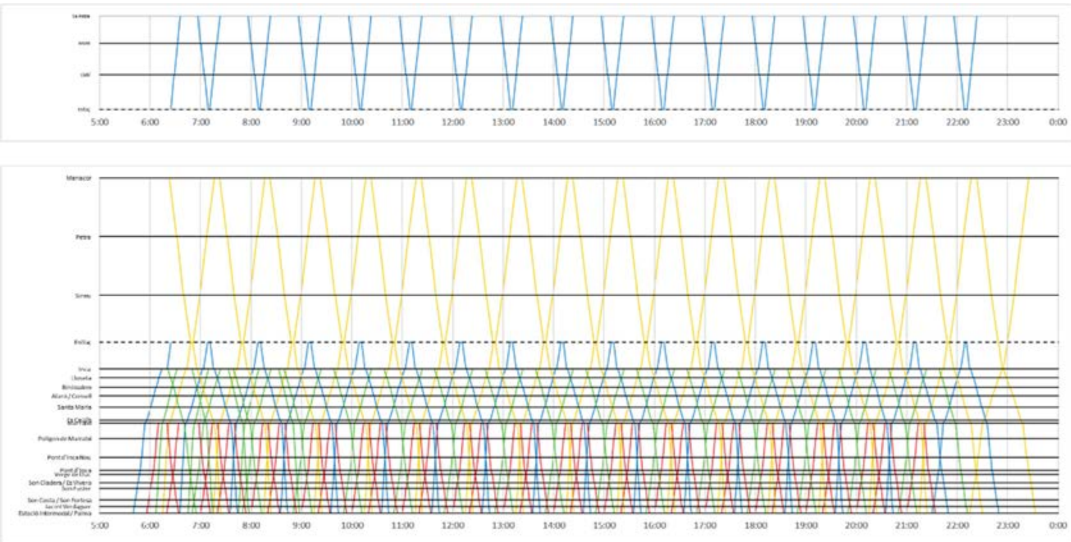

Figure 5. Daily mesh of an exploitation plan

Finally, with the N different scenarios, having a range of solutions (different meshes), a comparison will be made between them, in such a way that the advantages obtained with each one are revealed, keeping the mesh whose offer in squares meets with the planned mobility.

Through the elaboration of circulation meshes, the economic balance of the operator is calculated for different service offers until the one that the operator considers optimal is obtained. Similarly, it provides production results and operating costs.
In addition, apart from seeking a maximization of transport capacity to attract travelers in other more aggressive ways with the natural environment, other objectives are prioritized such as reducing energy consumption by taking advantage of braking energy.

The (annual) results to be obtained for each scenario are as follows:

- Production data: trains, trains.km, cars kilometer, seats, seats.km. Minutes of driver driving and minutes of accompanying personnel.
- Matrix of seats offered for each relationship

7. ECONOMIC ANALYSIS

Each calculated scenario assumes costs and monetary income that will be influenced by the following parameters:

- Energy cost: It is the cost of the energy that would be needed to carry out all the services. For this, the characteristics of the train and the reference prices for the cost of energy are taken into account.
- Maintenance: It will be taken into account whether it has its own workshop or not, and the cost of fixed and variable maintenance of the trains, the latter influenced by the number of kilometers carried out annually.
- Personnel costs: It is a cost closely related to the increase or decrease in services, since if there is a facility with many frequencies, it will be necessary to incorporate more personnel on the staff.
- Other costs: These are those related to financial expenses, possible contingencies and compensation, cleaning costs and all those costs related to the operation.
- Fare income: are those obtained from the sale of tickets either at the box office, agencies or on the internet portal.
- Special income: These are those related to advertising on the internet portal, on tickets and on the trains themselves.

With these parameters obtained and knowledge of all the previously known variables, the final income statement will be made, obtaining a balance between Expenses and Income for each of them.

COSTS		
Fixed costs	**Total**	**%**
Train Maintenance	240.197,13 €	50%
Energy	94.089,60 €	20%
Rolling Stock Amortization	4.429.571,99 €	919%
Financial expenses	2.214.786,01 €	460%
Variable costs	**Total**	**%**
Variable Maintenance Trains	481.889,70 €	100%
Energy	1.720.579,07 €	357%
Personnel cost	732.390,53 €	152%
Selling Costs	385.240,89 €	80%
Other Costs	308.962,35 €	64%
TOTAL COSTS	**10.607.707,27 €**	

INCOME		
Income	**Total**	**%**
Fare income	12.646.444,50	97%
Special income	194.918,35	3%
TOTAL REVENUE	**12.841.362,85 €**	

Earnings Before Interest and Taxes (EBIT)	**2.233.655,58 €**

Figure 6. Example of an income statement

Therefore, the optimal scenario to implement will be the one in which the Benefit for the operator is the highest possible, that is, the one in which the income is greater than the expenses.

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