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ENERGY REPRESENTATION VIA DESIGN FUNCTION STRUCTURE FOR MULTI-ATTRIBUTE OPTIMIZATION OF TRACTION ELEVATOR SYSTEMS

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1. Introduction

The reduction of energy consumption in buildings is a fundamental factor that affects future urban and environmental sustainability in a world where both population and energy cost increase. In that aspect, the design of energy-efficient electromechanical systems, and more specific of elevators, is of major importance. Elevator systems account for a significant percentage of the overall consumption of electrical energy and any effort for reducing that energy should be inspired by a holistic perception of efficiency where the main goal should be the achievement of optimal designs that serve vertical transportation demand without compromises. This is a point of major importance, since the performance of elevators is a factor that could contribute in providing with comfort and good life quality to people living and working several floors above the ground in overcrowded cities.

An extended search of the technical literature has shown that while there is a satisfactory amount of work related to energy consumption reduction via more efficient control systems and to design optimization of certain elevator subassemblies (motors etc.), little worth- to-be-mentioned work has been done considering the successful elevator system parametric design with respect to energy usage and transportation service performance. More specific, VDI company [VDI 2009] propose a method for the estimation of elevator systems energy usage based on energy classification derived from energy measuring in a reference trip cycle of pre-installed elevators. The method is not adequate as it is not based on design methodologies but on measurements in already produced elevator assemblies, so the assumptions are extensive and the elevator design parameters that contribute to the problem are not identified. Furthermore, for the elevator energy classification, the transportation demand and service performance are not taken into account and for those factors, it is not clear wish would be the way for engaging them in a design optimization process. The same inadequacies, in terms of design optimization, characterize the energy simulation model proposed by Barney [2011], as it is based in the use of results produced by the aforementioned measurements. Al-Sharif, Peters and Smith [2004] in their work propose also an elevator energy simulation model that can cooperate with a traffic analysis simulation tool. This model accepts a wide range of parameters as inputs and implements a detailed set of equations referring to elevator kinematics. However, since it is restricted to existing measurements of energy consumption, serious assumptions have been made and the results are highly affected by measurement inefficiencies. Additionally, there is not a systematic procedure for the indication of design variables that affect both energy and service efficiency and for their optimization. To continue, Sweet and Duket [1975] presented also a simulation model, this time based on a theoretical formula. However, this formula is oversimplified after extended assumptions and it is not adequate if examined with mechanics principles, while there is no reference to elevator service performance either to possible optimization. Closer, to the problem posed is the approach of Adak, Duru and Duru [2012]. They propose a simulation model that examines the energy consumption of elevator system and estimates their service performance. However, the energy estimation model they use is again oversimplified with extended assumptions, the results are affected strongly by inefficiencies that could be autonomously optimized, and the simultaneous examination of energy efficiency and service performance is kept to the level of results observation, without any reference to their systematic correlation and optimization. Examining now the implementation of function structures to elevators, and their use for energy efficient design, there is not any previous analytic study that contributes to these issues.

Within this context, in present paper, the concept of a new systematic method for the design of energy-efficient traction elevators is proposed. The basic idea behind the proposed approach arises from the following main points:

a. If for a given building there are two elevator system design alternatives, namely (A) and (B), and alternative (A) performs faster by servicing transportation demands at an average of 20 (%) less time and alternative (B) consumes 15 (%) less energy, which should be the criteria to judge them and which of them should be considered as the most efficient?
b. Consider now that there are again two elevator system alternatives (A) and (B) for the same building. The application of principles of mechanics show that the load motion pattern (velocity, car capacity etc.) in (A) corresponds to less energy usage than in (B), but alternative (B), by featuring a torque transmission subsystem with significantly better efficient factor and a control system with improved stand-by energy consumption, uses overall less energy. In this case, which alternative is better? System (B) or system (A) which, if its motion pattern is combined with the transmission and stand-by function subsystems of (B), will be far more energy efficient?

In order to provide an answer to the above questions, the method proposed concentrates on the *determination* of the *subfunctions* of the elevator that *support* the performance of its basic overall function (the transportation of a load), *contribute* to both energy consumption and service performance and *do not include* subsystems that *affect energy consumption* due to *energy losses*. The latter are typically represented for each such subsystem via efficient factors and can be reduced by proper improvements that refer to the subsystem per se. For the implementation of the method, the technique of function structure [Otto and Wood 2001], [Eggert 2005] is applied for a traction elevator and is performed in a reverse engineering manner in order to represent energy flows and transformations. Then, a systematic subtractive process transforms the function structure into a scheme that gathers the elevator subfunctions that consume energy for performing its basic function. The design parameters that correspond to these subfunctions and refer to the energy consumption problem are extracted and correlated to the design parameters that derive from the service performance analysis. The latter is based on well established methods for the future estimation of vertical transportation demand in buildings that are in design phase. Then, an appropriate formula is proposed as a vector of the overall elevator system's efficiency and as an objective function for the simultaneous optimization of both the elevator energy consumption and service performance. It is estimated that Genetic Algorithms could serve as an efficient optimization tool. The present approach is novice and considers systematically all design parameters that refer to energy consumption. It results to a proper function structure that represents energy flow and transformation that is subsequently reduced to a schematic net of subfunctions that cooperate for providing the basic function of a system without energy losses. Here, the proposed method is applied for the first time on traction elevators. Its generic potential is also examined for possible future applications regarding the energy efficiency of electromechanical systems.

2. Function structure and energy design in traction elevators

The function structure [Otto and Wood 2001], [Eggert 2005] of the traction elevator system has been developed and is presented in Figure 1. In it, the following chains of subfunctions can be distinguished:

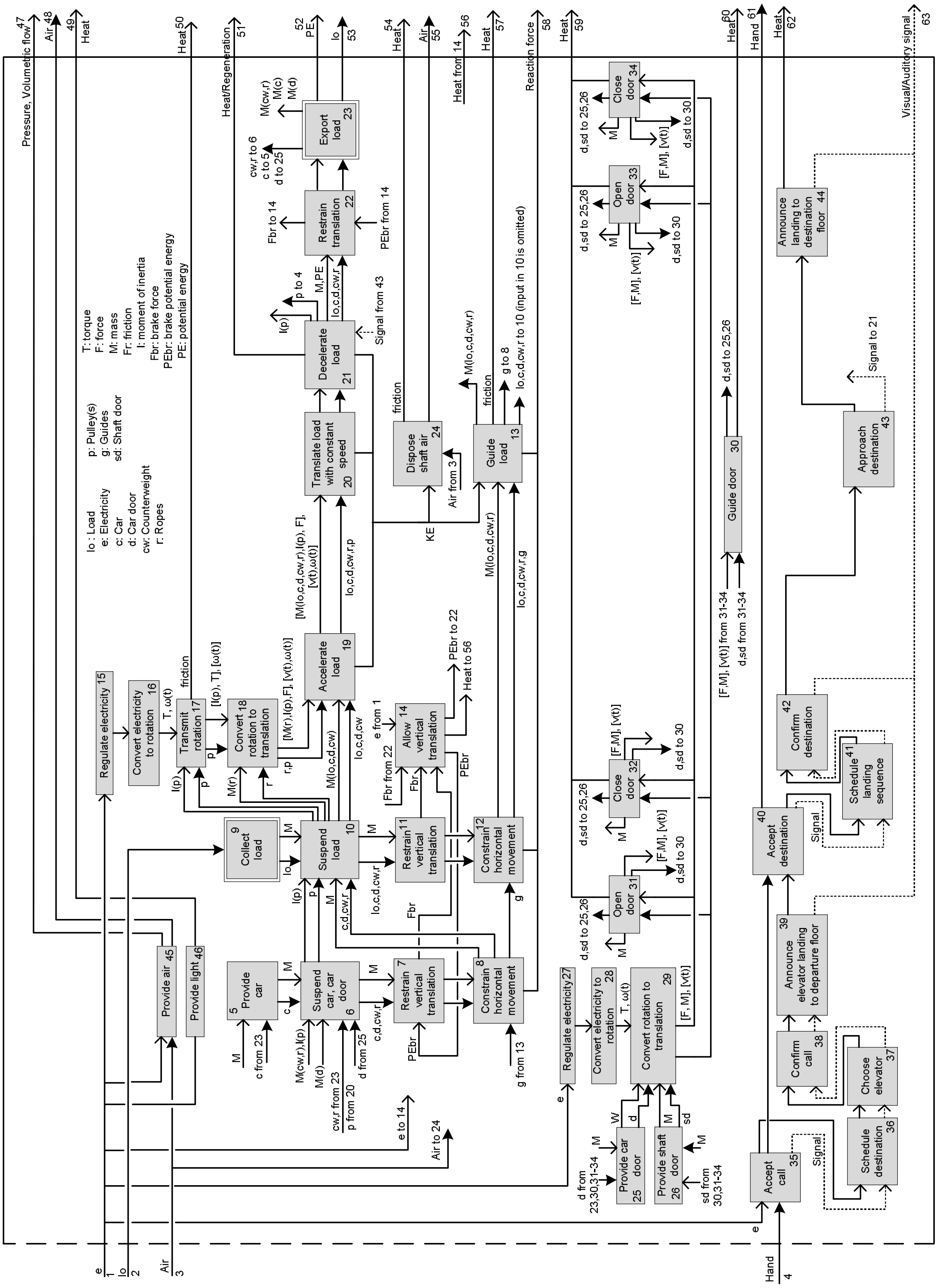

Figure 1. Power - energy representation in the function structure of a traction elevator

- The chain from subfunction 5 to subfunction 23 that represents the vertical handling and transportation of load (passengers or goods). It be divided into shorter chains: a. 5 to 8 (car, car suspension and stabilizing), b. 9 to 12 (load collection), c. 15 to 18 (electric energy conversion to kinetic energy), d. 19, 20, 21 (acceleration, traveling with constant speed and deceleration of the load), e. 22, 23 (car unloading), f. The chain from subfunction 25 to subfunction 34 that describes the door operation (in present study the doors are supposed to be automatic due to European codes for servicing handicapped people)
- The chain from subfunction 35 to subfunction 44 that represents the elevator control operations
- The subfunctions 45, 46 that provide comfortable conditions into the car

For understanding further the provided traction elevator function structure, the following points must be underlined. First, the subfunctions that are mentioned into the boxes are form-independent as they should comply with function structure theory. Second, some material and energy flows are form-dependent (for example the counterweight, pulley, torque etc), because the present function structure analysis refers to an existing elevator configuration and should be perceived within the context of a reverse engineering process [Otto and Wood 2001], focusing on representation and optimization of energy usage. Thus, the basic principle of traction elevator operation must be represented (friction between pulley and ropes), as also the form of materials (masses) that are used for the abstract embodiment of that principle [Eggert 2005]. Second, many material flows (i.e., car, doors etc.) as also energy flows (potential energy in braking system presented by subfunctions 7, 11, 14) are provided and distributed within elevator system's boundaries. These materials and energy flows are represented by flow loops into the system. Finally, for reasons of better understanding of the present function structure, the function boxes are positioned following the time sequence of elevator's operations.

Considering now the optimization of the energy consumption of a system, its function structure can be used for the determination of the subfunctions that configure the most important and necessary system's functions and consume energy. These basic functions describe the reason why the system operates, are not related to any energy losses and from now on they will be called as Basic Energy Subfunctions (BES). On the other hand, the subfunctions that are characterized by inefficiencies from now on will be called as Energy Inefficient Subfunctions (EIS) and can be considered as autonomous that could be further optimized with respect to their own efficiency factors. For the determination of (BES), a method based on the representation of power and energy flow in function structures is proposed. This method is applied in traction elevators and is articulated in steps as follows:

Step 1. The function structure must be so formed that it can provide qualitative information about energy flow. To accomplish that, for every subfunction, all components and subassemblies that are used for implementing that subfunction, as also all the components and subassemblies that are affected by the operation of that subfunction, are clearly defined as material flows. If these material flows refer to more than one subfunctions, this correlation must be defined with the appropriate material flow connections between the subfunctions. Furthermore, in case when some of these components or subassemblies are provided by the system and they do not exit its boundaries, this should be indicated by appropriate material flow loops (see, for example, the loop of elevator car flow between subfunction 23 and subfunction 5). At the same time, the masses and the mass moments of inertia of these components and subassemblies that translate and/or rotate, must be defined clearly as effort analogies [Otto and Wood 2001] in flows of energy. Furthermore, the material that enters and/or exits system's boundaries must be indicated as material flow. Next, in every subfunction, all effort (forces, torques, pressure, etc.) and flow (linear and angular velocities, volumetric flow, etc.) analogies must be referred. It must be also underlined that the principles of conservation of mass and energy must be valid [Otto and Wood 2001]. Also, possible time dependency of flow analogies should be denoted; linear velocity, for example, should be registered as $v(t)$. Finally, in some cases of subfunctions where the energy conversion is obvious and for reasons of simplicity, the energy flow can be noted more generally like e (electrical energy), KE (kinetic energy) and PE (potential energy). The aforementioned notations on the function structure provide the information of what changes in energy states occur when subfunctions are performed and which are the conversions between the different forms of energy. The version of the function structure that is developed after this step, can from now on, be called as Energy Function Structure (EFS).

Step 2. All parallel chains of energy for subfunctions must be identified. These are the chains that their subfunctions – that transmit or convert energy - do not interact with the same type subfunctions of other chains. These chains must be examined separately for contribution to (BES). In the present case of traction elevator, the energy parallel chains are five: the chain of the main function, the chain of the operation of the doors, the control chain and finally, the two subfunctions that provide light and air.

Step 3. All loops of energy flows that exist within the limits of the system are distinguished. For the present case, such a case is the potential energy stored in the braking system described in subfunction chain 7, 11, 14. This type of energy flows are not taken into account.

Step 4. All subfunctions that produce energy losses and are characterized by efficiency factors with value less than 1 ($\eta \leq 1$), are identified as (EIS). In Figure 1, these are the subfunctions 15, 16, 17, 13, 14, 24, 27, 28, 30, 45, 46 as well as the control chain because its subfunctions are performed by non ideal electrical circuits.

Step 5. The subfunctions that do not have as inputs or outputs flow analogies (velocities, currents etc.), or notations of energy (e, KE, PE etc.), are considered as not producing work and are properly identified (see subfunctions 5-12, 25 and 26 in Figure 1).

Step 6. The energy flow outputs that exit the system are examined and every one that comes from subfunction with $\eta \leq 1$, is omitted from next step (in Figure 1 these are the outputs 47, 49, 50, 54, 56, 57 and 61). Additionally, every energy flow that represents force not producing work is also excluded from further energy examination (see output 58). After that, the outputs that should be examined in next step are the 51, 52 and 59.

Step 7. The subfunctions with $\eta \leq 1$ and their inputs are deleted from the system. Correspondingly, the subfunctions that do not produce work and their inputs are deleted too.

Step 8. The remaining system's energy flow outputs are examined in a backwards manner. The remaining subfunctions so located during that backward examination form the chain of (BES) and their energy flow inputs and outputs indicate qualitatively the parameters that affect energy consumption and the relations between those parameters. From these parameters, the energy flow inputs in the very first subfunctions of the remaining chains (for example torque T in function 18) should be excluded because they correspond to the energy consumed by the whole chain and their values are provided after the registration of values to the rest parameters. The function structure that is formulated by the remaining subfunctions and flows can be named as Basic Energy Function Structure (BEFS) and, for the case under consideration, is presented in Figure 2.

According to (BEFS), the (BES) of the system consists of subfunctions 18, 19, 20, 21, 22 and 23, which are related to the translation of the load, and the subfunctions 29 and 31 to 34, that are performed when the shaft and car doors operate (see Figure 2). By taking into account all input and output flows in (BES), the design parameters that affect the energy consumption when the elevator operates are:

- The load mass M_{lo} (Kg) that is related to elevator's rated capacity ca
- The mass of the car M_c (Kg) that contains the mass of the car, the frame and all auxiliary equipment
- The mass of the car door M_d (Kg) that depends on door type and opening width
- The mass of the counterweight M_{cw} (Kg)
- The mass of wire ropes M_r is not taken into account in present approach, as they are supposed to be compensated. However their selection affects the energy consumption of the elevator because the mass moment of inertia I_p (Kgm^2) of a wire rope pulley depends not only on the pulley mass, but also on the wire rope thickness that affects pulley's radius. The selection of wire ropes depends on the suspended masses that determine their number and type as well as their diameter. Then design parameters related to wire ropes are the following:
- Number of wire ropes n_r

- Type (qualitative parameter)
- Diameter $w_r\,(mm)$
- Number of pulleys n_p
- Mass of each pulley M_p (Kg)

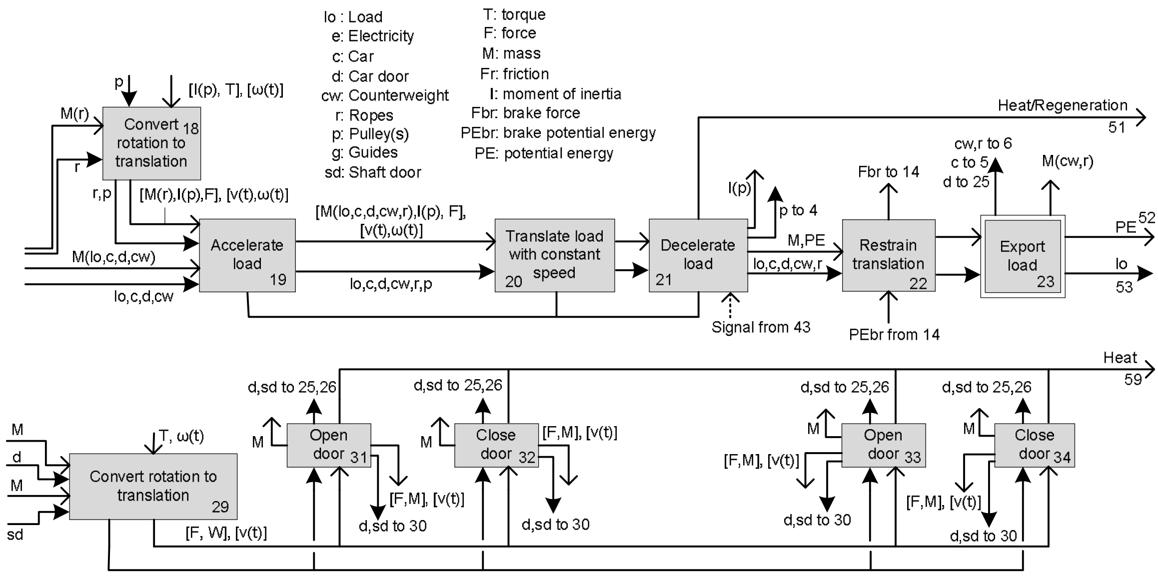

Figure 2. Basic energy function structure of a traction elevator

The linear velocity of the elevator $v(t)$ is a design parameter that affects crucially the consumed energy. The time dependency and the observation of subfunctions 20, 21 and 22 in (BES) lead to the definition of the following design parameters:

- The constant linear jerk ratio j (m/s^3)
- The linear acceleration a (m/s^2)
- The constant (rated) speed v_{cons} (m/s)
- The ability of regeneration (yes/no)

The force F (see subfunctions 19, 20, 21) is transmitted through the wire ropes to the suspended masses and, according to Newton's second law, it depends on variables 1 to 7, 10 and 11 and it can be easily calculated, given that values have been provided to those variables.

The conversion of torque T to force F in subfunction 18, is affected by the roping factor rf. The angular sizes such as jerk ratio j_{rot}, $a_{rot}(t)$ and constant velocity ω_{cons} of friction pulley are correlated to the parameters 10 to 12 with the radius of the friction pulley and the roping factor rf and they don't contribute to the design parameters that affect energy consumption.

Examining now the door operation subfunction chain, the following parameters that affect energy consumption are distinguished:

- The mass of the car door M_d (Kg)
- The mass of the shaft door M_{sd} (Kg)
- The time-dependent door velocity $v_d(t)$, which can be analyzed as jerk ratio, acceleration rate and constant speed
- The conversion ratio between the torque provided by door's electric motor and the linear force applied to the car and shaft door in every landing.

Despite the possible value that an extensive analysis of the door operation energy may have by applying the proposed method, it is redundant – within the framework of the current approach - since any further optimization of the door's components and subassemblies leads to negligible gains. So, a

more general approach for the door energy consumption will be followed based on safety codes that establish the maximum value of 0.29 joule [Strakosch 1998] for the kinetic energy of door panels. For the present study, this amount of energy is assumed to be consumed after opening and closing of the doors no matter their opening width and type are.
For the set of all design parameters that have been extracted from (BES), a number of them - with respect to the energy consumption - are under the control of the designer and can be considered and named as *Design Variables* (DVs) [Eggert 2005]. For the traction elevator, according to the analysis in previous paragraphs these are: elevator's rated capacity ca, door type and opening (that affects M_d), mass of the counterweight M_{cw}, number of ropes n_r, type of ropes, diameter of ropes w_r, number of pulleys n_p, mass of each pulley M_p, linear jerk ratio j, linear acceleration $a(t)$, constant (rated) speed v_{cons} and finally, the roping factor rf.

3. Elevator system planning and performance

According to the technical literature [Strakosch 1998], [CIBSE 2005], the most important goal to be achieved during the design of an elevator system for a building is the efficient handling of the vertical transportation demand. The parameters related to that issue are the following:

- The type of the building (commercial, residential etc)
- The number of building's floors served above the main terminal N
- The effective population in every floor i, U_i (in persons)
- The height of every floor i, h_i (m)
- The total height of non-served floors in express zones (if there are any) (m)
- The number of elevators L
- The rated load of elevators, or rated capacity ca (Kg)
- The average passenger mass m_{per} (m)
- The capacity factor of elevators $CF\%$, that is, the percentage of their rated load that is actually loaded due to ergonomic issues (minimum needed area by a passenger etc.).
- The rated linear velocity v (m/sec)
- The maximum linear acceleration a (m/sec^2) (limited due to passenger comfort issues)
- The jerk ratio j (m/sec^3) (limited due to passenger comfort issues)
- The door type and opening width (qualitative parameter)
- The advanced door opening time t_{ad} (s). This parameter describes the overlapping of the leveling operation with the first part of the opening of the doors.
- The starting delay time t_{sd} (s). This parameter represents the delay time in every departure due to the fact that motor is unready, the doors must be locked etc.

The aforementioned parameters are correlated in routines with probabilistic and time calculating mathematical expressions [Strakosch 1998], [CIBSE 2005], which, for certain transportation demand patterns, that are generated by established theoretical methods or by simulation, estimate the trip of each elevator (highest reversal floor, travel distance to the highest reversal floor, number of stops, travel distance between stops, travelling distances and periods where the elevator(s) are loaded or are empty etc). Then, using the estimated data, these routines examine the elevator system's operation against several traffic conditions (up-peak, down-peak, inter-floor traffic, mid-day traffic) and calculate specific vectors that describe and evaluate its performance. These performance vectors are:

- *The Round Trip Time (RTT)* (s) which is the average period of time for a single car trip, measured from the instant the car doors start to open at the main terminal, until the instant the car doors start to reopen at the main terminal, when the car returns to it after the trip around the building.
- *The Interval (INT)* (s) which is the theoretical longest time the elevator system takes to respond to the landing call registered by an arriving passenger.

- *The Average Waiting Time (AWT)* (s) which is the average time a passenger waits until the elevator system responds to its call. (AWT) depends on the (INT) and the traffic demand pattern.
- *The Handling Capacity (HC)* in persons, which is the amount of people serviced by the system in five minute periods where the transportation demand reaches its peak.

The smaller the (RTT), (INT) and (AWT) are, the better is the performance of the elevator system, while on the other hand the (HC) should be as bigger as it is possible.
The Design Variables (DVs) related to the performance prediction problem are the parameters: *L, ca, %CF, v, a , j*, door type and opening width and, finally, the advanced door opening time t_{ad}.

4. Basic energy function structure and energy consumption calculation – multi-attribute optimization

After extracting the related to energy consumption (DVs) from (BEFS) and after correlating them with basic principles of mechanics, the consumed energy during the operation of the system can be calculated. Focusing on the traction elevator, the torque that is applied in traction pulley before the conversion of rotation to translation (subfunction 18), is given, in (*Nm)* and for $rf = 1$, by the following expression:

$$T = \frac{n_p \cdot I_p \cdot a(t)}{r_p} + \frac{\left(M_{lo} + M_c + M_d - M_{cw}\right) \cdot g \cdot a(t)}{r_p} \tag{1}$$

Now, when the elevator is moving, the power that is consumed can be calculated in (*KW*) by the expression:

$$P_k = \left[n_p \cdot I_p \cdot \frac{dv(t)}{dt} + \left(M_{lo} + M_c + M_d - M_{cw}\right) \cdot g \cdot \frac{dv(t)}{dt} \right] \frac{v(t)}{r_p^2} \tag{2}$$

and the energy consumed in a period of time $(t_2 - t_1)$ is in (Ws):

$$E_k = \int_{t_1}^{t_2} \left[n_p I_p \frac{dv(t)}{dt} + \left(M_{lo} + M_c + M_d - M_{cw}\right) g \frac{dv(t)}{dt} \right] \frac{v(t)}{r_p^2} dt \tag{3}$$

If the roping factor is different, the expressions (1) to (3) must contain the parameter rf (for reasons of space these expressions are not presented). Regarding the energy consumption of the door operation, in every opening and closing of the doors the consumed energy is assumed to be $E_d = 0.29Ws$ (see paragraph 2).
Given now that there is an extensive scientific work about elevator kinematics [Peters 1995] and that the described circulation study (see par. 3) provides information about number of stops, trips, loads in trips and travelled distances, it is possible to apply the expression (3) in every trip for every elevator of the system and to multiply all the door openings and closings with E_d. In that way, not only the performance of the elevator system can be estimated for certain traffic conditions, but also its energy consumption.
Within the context of the present approach, the multi-attribute optimization of elevator system design is proposed, focusing simultaneously on the optimization of system's performance and on the minimization of the energy consumption. In other words, for a given building architecture, purpose and population, and for an estimated transportation demand, the values of the system's design variables must be selected appropriately, so that the system's performance vectors are the best possible, while the consumed energy for reaching that level of performance is the minimum. For that, the interval (INT), the handling capacity (HC) and the energy consumption for the estimated heaviest

5-min traffic peak of the given building are correlated for the formulation of the following objective function:

$$F_{opt} = \frac{(INT)\cdot\left(\sum E_k + \sum E_d\right)}{(HC)} \quad \left(\frac{W \cdot s^2}{person}\right) \tag{4}$$

where $\sum E_k + \sum E_d$ is the energy consumption for the sum of the trips and door openings/closings of all elevators of the system, performed in the heaviest 5-min peak traffic period. The value of F_{opt} must become the minimum possible and this can be obtained with the application of Genetic Algorithms method for obtaining optimal design variable values. It is expected that Genetic Algorithms will perform efficiently as an optimization tool because the present case is characterized by: a. a large number of design variables, some of them are of a qualitative nature, b. an excessive number of constraints that come mainly from standardizations and established limitations posed by the accumulated design experience on the field and c. design parameters that usually present non-continuous value ranges and are rather restricted in sets of discrete values that mostly come from existing standards. This fact poses some difficulties in using conventional mathematical tools for obtaining optimal values.

5. Conclusions

In the present paper a new approach for the optimization of traction elevators' parametric design is presented. Within this context, a novel method is proposed where the development of the function structure of an electromechanical system is used for the detailed, yet qualitative representation of energy flows and conversions that take place between system's subfunctions. Then, a subtractive procedure is applied to the function structure and leads to a chain of subfunctions that represent the basic function of the system and consume without inefficiencies the energy that is absolutely necessary for its performance. For the elevator, the basic function that is performed is the vertical translation of loads and the corresponding subfunctions depend only on the motion pattern selected. On the other hand, the subfunctions that are characterized by energy losses are indicated for their autonomous efficiency-improvement capability, as their efficiency factor is not related to the basic function performing pattern. The parameters registered in the inputs and outputs of the remaining basic function provide the design variables that affect the energy consumption problem. These are correlated with the design variables that are related to the elevator system's service performance and are used in circulation studies. Then, with the use of appropriate formulas and vectors, and after the implementation of Genetic Algorithm method, it is possible, for a given building and transportation demand pattern, to retrieve the values of the design parameters that lead to the optimum overall efficiency of the elevator system, in terms of energy usage and service performance.

The proposed method can be a useful tool for the optimum selection of elevator equipment that not only serves the estimated transportation demand efficiently, but also uses the minimum possible energy. Many combinations of design parameters' values could be evaluated and the results could be useful not only to building designers, but also to engineers of elevator industries as new, out of product range, combinations of equipment and characteristics may occur. Finally, the proposed systematic process can evolve to a generic technique for the configuration and parametric design of energy saving electromechanical systems. It may start from the introduced method of variation of function structure, continue with the demonstration of energy flow and transformation and end up with the determination of the design variables that refer to the energy consumed for the performing of the basic function.

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