Intelligent system to improve the switch-on and switch-off procedures in industrial plants

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In order to improve the safety and reduce plant shut down/up time during scheduled maintenance tasks, Aceralia and the University of Oviedo are developing and testing a novel application to help in the process, ensuring that the right equipment is correctly and safely switched off/on as quickly as possible. The system also provides with updated information regarding the current state of maintenance tasks and equipment and performs automatic analyses of events during plant shut down periods.

The system is currently being developed and tested in the Hot Strip Mill of Aceralia at Avilés, as this is perhaps the most complex facility of the company and the one where such switching off/on procedures consume more time.

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■ INTRODUCTION

Plant shutdowns for performing maintenance tasks are periodically scheduled in the Hot Strip Mill facilities of Aceralia Group Arcelor, in Avilés, Spain. Such maintenance tasks necessarily require to previously switch off the affected machines in order to guarantee the safety of the maintenance staff during the work, and to switch them on after tasks are completed.

The objective of scheduled shutdowns is to concentrate in time a group of maintenance tasks to be concurrently carried out, reducing as much as possible the period of inactivity of the line necessary to perform those tasks. Shutdowns are usually scheduled once a week and normally last from 8 to 16 hours, apart from two special annual shutdowns that last longer.

Switch off procedures in a scheduled shutdown last on average for one hour and forty minutes. The switching on procedures usually take another hour and ten minutes. This implies to increase about two hours the time needed for maintenance tasks, which reduces the operating time of the installation. Thus any reduction in the time spent in switch off/on procedures would be beneficial since it would decrease the line inactivity time, increasing the production of the facility and the profit of the company.

Both external subcontracted companies and internal staff from Aceralia take part in the scheduled shutdown. We will distinguish several staff roles throughout this article:

- Shift Chief, he is in charge of the facilities during a work shift, he decides the start of the scheduled shutdown when all the necessary conditions are fulfilled.
- Electrical supervisor, he supervises the switching off/on requests and their realization.
- Operators, the staff from Aceralia who carry out the switching off/on procedures.
- Petitioners (also referred as requesters), they are staff from Aceralia or subcontracted companies who have to carry out some type of work on a given machine. As a consequence, they previously request to power off that machine. This sometimes involves switching off several power-switches linked to that machine. Once the task has been performed, they will inform the operator, who will switch on every previously switched off power-switch related to that work, if a set of conditions are satisfied. Currently, the petitioner must know exactly how many switches must be switched off to perform his task at a given machine, which drives to occasional mistakes in the procedures.

Système intelligent pour améliorer les procédures de mise hors tension et sous tension des installations industrielles

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Pour améliorer la sécurité et réduire les temps d'arrêt de l'installation liés aux travaux de maintenance, Aceralia développe et évalue, dans son train de laminage de bandes à chaud d'Avilés, une nouvelle application qui permet de réaliser correctement et en sécurité la mise hors tension de l'équipement sélectionné. Cette application crée aussi des procédures optimisées pour réaliser la mise hors tension et sous tension afin de minimiser le temps nécessaire pour réaliser lesdites tâches, selon des priorités et des critères définis au préalable. De la même manière, il délivre une information actualisée sur l'état des équipements et des travaux de maintenance en cours. Finalement, il réalise des analyses automatiques des incidents survenus durant les arrêts, des écarts par rapport au programme et d'autres analyses statistiques.

Le nouveau système permet de réduire de 30% le temps de mise hors et sous tension des installations, ce qui correspond à 3h par mois.

Fig. 1 - Switch off/on cards. traditional format (top) and current format used after SICRET setup (bottom); information is coded in a bar code to be used in the shut down/up process.

Fig. 1 - Cartes de mise sous et hors tension. Format traditionnel (haut) et nouveau format SICRET (bas) ; l'information est en code barre pour le process de mise sous et hors tension.

According to internal safety regulations, the switch off/on requests have to be carried out by means of special three-bodied normalized switch off/on cards *(fig. 1)*. An individual card must be filled in for every power-switch that must be handled during the process. Left body of the card (red) is used to request the switching off and will be left at the breaker. The central body (green) is given to the petitioner to confirm that the machine has been switched off. It will be given back to the operator upon work completion as an authorization to switch it on. Both parts basically contain the same information, identifying the machine and the petitioner. The third card body (right), is used for other tasks irrelevant in the context of this article.

Shutdowns are scheduled in a meeting where all the involved staff decide the maintenance tasks that must be carried out in the facilities, their priority and the order in which they will be executed, as several resources such as cleaning or cranes may need to be shared in several tasks. After that, the scheduled shutdown will be developed according to the following process:

- After knowing which maintenance tasks must be performed, petitioners manually fill in a card for each power-switch of the facilities to be handled. A period from twelve to twenty four hours is reserved for that purpose.
- Just before the scheduled shutdown starts, petitioners must bring their cards down to the operator's office. The electrical supervisor will authorize the switching off/on cards if everything is correct in the request, giving them to any of the operators who will be responsible for switching off the corresponding power-switches.
- After receiving a group of cards, the operator must classify them according to their priority and to the power-switches localization in the plant, in order to decide the route to follow across the facilities to perform the switching off tasks. This is a critical point because it has a noticeable influence on the time consumed by the process.
- Internal safety regulations demand that the petitioners must accompany the operator to witness the switch off tasks. Thus, after deciding the route to follow, the operator and the petitioners together must walk along the facilities.
- Once they arrive at a power-switch to be turned down, the operator will physically switch it off if it has not been done yet. The petitioner will certify the correctness of the process. The red part of the proper card is then placed in a box near the power-switch, indicating that a task is being carried out

in the associated machine and thus the switch cannot be turned on. The rest of the three-bodied card is given to the petitioner for later operations. As it is possible that several maintenance tasks involving several petitioners need to be carried out in the same machine, several cards could be simultaneously present in the same power-switch box at a given moment.

- After turning off the necessary power-switches, the involved petitioners are allowed to work on that machine.
- Once a petitioner finishes his tasks in a machine, he walks to the operator's office to inform him of the conclusion of the task, giving back to the operator the two green bodies of the cards he filled in for that machine. Both together must go later to remove the red body of the card left at the machine, ensuring that the right card is removed.
- When the electrical supervisor authorizes the power switching on (he can authorize several partial power switching on processes during the same scheduled shutdown), a group of the collected central card bodies are given to the operator, who will again classify the cards according to their priority and breaker location and then go to the power-switches accompanied by the corresponding petitioners.
- Once arrived at a given power-switch, the operator will check if red cards still remain at the corresponding box. If no one is left, power-switch on can be done.

At the end of the scheduled shutdown, all the used cards are stored for further analysis. No computer tools have been used to support the scheduled shutdown process. This lack of a technological support and the manual process used for the information management during switch off/on tasks, facilitates the existence of human errors that could affect the safety of people during the process. Also, time spent in switch off/on procedures is not optimized as scheduling of actions is done by each operator. Another drawback of the current system is the impossibility to automatically compile the information that is generated during the scheduled shutdown, which hinders later statistical analysis of the process.

As an attempt to solve these difficulties, Aceralia introduced the project SICRET (Sistema Informatizado de Corte y Reposición de Energía en el Tren Semicontinuo). Main goals are to ensure human safety during the process and to reduce the scheduled shutdown duration. Several hardware and software solutions are being developed to support switch off/on tasks and allow storage and further analysis of the process.

■ ARTICLE ORGANIZATION

The following section shows the architectural design of the system, giving a broad overview. Next, a description of the general operation of the system will be outlined, highlighting the differences with regard to the previous modus operandi, explained in the introduction. The paper continues with a detailed description of a critical module from the point of view of reducing the time employed in the scheduled shutdowns: the route optimization module. Finally, conclusions are drawn from the work described.

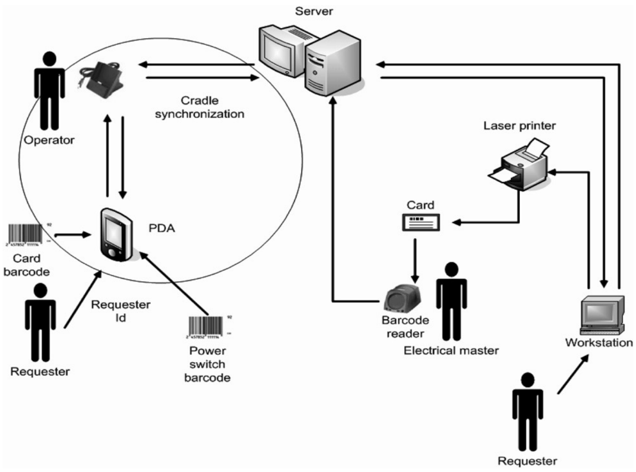

Fig. 2 - System operational diagram.

Fig. 2 - Diagramme opérationnel du système.

■ SYSTEM DESIGN

The system is based on a distributed architecture that is built around a central server accessible via the Web from any workstation in the Intranet of Aceralia *(fig. 2)*. This server allows to query information about scheduled shutdowns, to generate the switch off/on cards, to display the state of the facilities at a given moment, etc. For such purposes, a standard web navigator from any workstation is used. The operating system for the server is Microsoft Windows 2000 server.

The new system is based on a different format for the switch off/on cards *(fig. 1)*. Like the previous model, they include information related to the switching request (petitioner, machine, etc.). The difference is that they now include a bar code that individually and unequivocally identifies each request, including the identification of the corresponding power-switch. Every power-switch in the facilities has been code-labelled with an identification that allows the system to individually address it.

Petitioners need not manually fill in the switch off/on cards. It can be done from any workstation of the intranet. They can also request packages of cards, i.e., the system can generate all the necessary cards to perform a specific task at a given machine. In this way they do not need to know all the power-switches that must be handled to perform such a task in that machine.

The use of bar codes for identifying requests and power-switches plays the main role of the actual management policy proposed in the project SICRET.

By means of reading the bar codes in the card and in the physical power-switch, it is possible to ensure in every switch off/on operation that it is being properly carried out and in the right equipment.

Switching off/on cards authorization by the electrical supervisor is also different. After partially checking the correctness of the request, the card is passed in front of a fixed bar code reader. A software application will then check several details about the request such as, for instance, if it has been requested before. This authorization using a bar code reader is also useful to make the system aware of the authorized switch off/on, a necessary operation for subsequent tasks.

The operators are given a PDA equipped with a bar code reader. It will be used during the switching off/on processes to match the bar codes of the cards with the bar codes of the power-switches. Additional information about the process will also be collected using this device.

Data will be synchronized between the server and the PDAs using serial connection cradles.

■ OPERATIONAL DESCRIPTION OF THE SYSTEM

Using the system defined in the project SICRET, some operative changes are introduced in the work dynamics *(fig. 2)*, regarding the switching off procedures in particular:

- After the preliminary scheduled shutdown meeting, petitioners will use the workstations to generate the corresponding switching off/on cards. According to the new format, they will contain a bar code in each body.
- Just before the scheduled shutdown starts, petitioners must bring their cards down to the operator's office. The authorization process will be carried out in the new system using the fixed bar code reader, thus registering the authorized requests in the server.
- The operator can decide at any moment to start with a sequence of switch off tasks (the system advises him about this matter). Then he will download to the PDA the information about the switch off requests that have been authorized but still have not been carried out. An optimal route to carry out the switch off actions in the facilities, calculated by the system, will also be registered in the mobile device. The calculation of that optimal route, treated in detail in a later section, will be guided by different criteria (time spent, priorities, etc.).
- Once the requests are stored in the PDA, it is possible for the operator and the corresponding petitioners to follow the optimal route to perform the powering off.
- When they arrive at a power-switch to be turned off, the PDA assists them in carrying out the process, thus improving the safety of the task. After reading the bar codes of both the card and the power-switch, a match check is automatically performed in the PDA. If the codes match, the operator reads the identification of the petitioner using again the bar code reader of the PDA (petitioners have been provided with personal bar coded identification cards). If everything is correct, the PDA prompts a message to the operator indicating that he can perform the switch off. Diverse information will then be stored in the PDA: identification of the petitioner that witnesses the task, date, time etc.
- As in the former procedure, the operator will place the red body of the card in the power-switch box and will return to the petitioner the rest of bodies. He will proceed to switch off the power-switch if it has not been done already.
- The PDA also helps the operator during the switch off action showing him a textual help about the correct sequence of the steps to be followed.
- When the operator finishes the switching off sequence according to the route downloaded to the PDA, he will upload the information stored in the PDA to the central system using the serial connection. Although wireless communication was considered in the context of the project because it could provide a valuable real-time synchronization, this possibility has been discarded due to the high electromagnetic interference present in the facilities.

The switching on process is similar. As a set of central body cards has been returned to the electrical master indicating the finished tasks, optimal routes to perform switching on procedures are calculated by the system according to the defined schedule (the system can also advise the operator about the most appropriate timing). PDA is used to store information about the switch on tasks details and the optimal route to follow. Bar code reader is also used to help during the power up process to match switch on requests (central part of cards) and power-switch bar code identifications. Diverse information about the process is also collected. All the information is uploaded to the server at the end of the process using the serial communication.

The system also provides several utilities to help with the management of the scheduled shutdown. One of the most useful utilities is a display module that allows visualizing the state of the facilities at any moment. It shows all the power-switches in the facilities using different colours to codify their state: powered-up, powered-down, failure, etc. It is also possible to check the time a specific power-switch has been switched off/on, the petitioner involved in such actions, etc.

The system has also the capability to provide several statistics about present and past scheduled shutdowns.

■ ROUTE OPTIMIZATION MODULE.

Route optimization is one of the critical components of the system. It is responsible for suggesting optimal routes across the facilities to carry out a sequence of power down/up actions. Thus, reducing the time spent in such procedures during a scheduled shutdown mainly depends on the efficiency of this module.

In order to carry out the switching off/on procedures, the operator and several petitioners must physically move to the corresponding power-switches. The order in which they do so is important from several points of view. Firstly, the distance to cover will depend on the chosen sequence of actions, such distance being directly related to the time employed in the process, but other relevant factors must be taken into account:

- Each switch off/on request has its own priority, assigned in the scheduled shutdown preliminary meeting. This priority must be respected as far as possible. Thus the requests with higher priorities should be processed first.

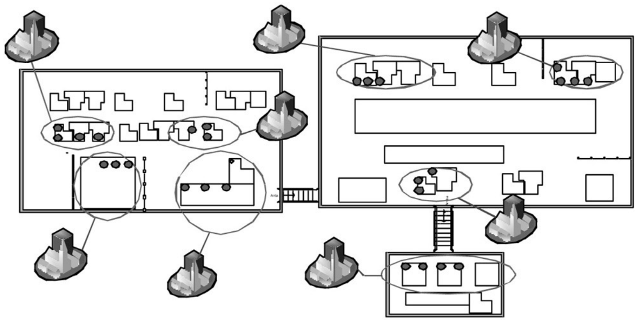

Fig. 3 - HSM facilities map, power-switches are grouped into clusters, each cluster is identified with a city in the TSP.

Fig. 3 - Carte du TAB, les interrupteurs sont rassemblés en grappes, chaque grappe correspond à une ville dans le TSP.

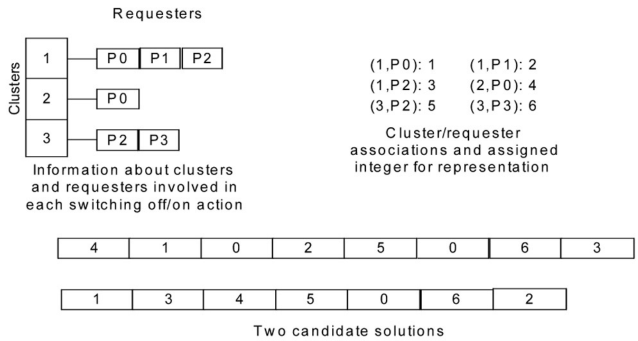

Fig. 4 - Individual representation.

Fig. 4 - Représentation individuelle.

- A high number of petitioners walking with the operator in a shut down/up expedition (defined as the displacement that starts and finishes in the operator's office) could be a nuisance making displacements across the facilities more difficult.
- It is considered positive that the petitioners and the operator need to do the lowest possible number of expeditions.

Thus the problem of defining optimal routes is not trivial. It is in fact a multi-objective optimization problem with diverse and conflicting factors to be taken into account.

The approach followed to solve the route optimization problem is based on the well-known classical travelling salesman problem (TSP).

The TSP looks for a route with minimum cost between certain cities (1). Starting in one of the cities, a valid solution must pass by each one of them and return to the starting point. Although easy to state, TSP is a classical NP-hard problem with a complexity that increases exponentially with the number of cities. As an example, there are a few possible routes when four cities are considered, and several million possibilities if the cities considered are twelve.

Several techniques have been used to achieve optimal or nearly optimal solutions to the TSP: linear programming (2), branch and bound (3), or more advanced methods, derived from artificial intelligence, such as neural networks (4), tabu search (5) or genetic algorithms (6). Among them, we have chosen to apply genetic algorithms to solve our particular version of the problem, as they have shown to be an efficient optimization method, frequently used to solve the TSP.

Genetic algorithms are inspired in the natural selection process of the evolution theory. From a population or initial group of candidate solutions (individuals), usually set randomly, the objective is to achieve through iterations (also called generations), an optimal solution, according to a predefined evaluation function. In each iteration, new solutions are generated from the pool of existing ones, applying what is known as genetic operators. Such operators are also inspired by natural reproductive processes, such as crossover and mutation.

A relevant operation in a genetic algorithm is the selection process, which is once again inspired by the evolution theory, specifically, by the principle of the survival of the fittest. The selection process will be responsible for determining which individuals will take part in reproductive processes, so influencing their spread across successive generations. Selection processes usually present a random behaviour, although a bias is set in the sense of the fittest individuals.

A fitness function plays a relevant role in the evolution of the algorithm. It is responsible for giving to each individual a measure of the grade of optimality. This measure will guide all the evolution of the algorithm.

The algorithm used in this project is based on the steady state approach. In each iteration, a reproductive process is performed. The new created individuals are directly inserted into the existing population, replacing an equal number of selected individuals.

In the following paragraphs, we will show how we have used the genetic algorithm approach to solve the route optimization under the classical framework of the TSP problem.

Solution representation

Power-switches considered close enough with respect to each other will be grouped into a cluster. These clusters will play the role of cities in our problem *(fig. 3)*. In this way we will not work at the power-switch level (there are hundreds in the facilities), but at a cluster level, thus significantly reducing the complexity of the problem.

The representation used in our work is based on an array of integers. Each integer will represent a cluster-petitioner pair. This implies that each number represents a set of petitioner tasks over a group of power-switches that are close to each other.

The zero is a special number used to reference the operator's office.

Therefore, each of the solutions will be a vector of integer numbers, containing the cluster-petitioner pairs and an undefined number of zeros (two implicit at least, representing the starting and ending points). Whenever a zero is found it indicates that there is a return to the operator's office *(fig. 4)*.

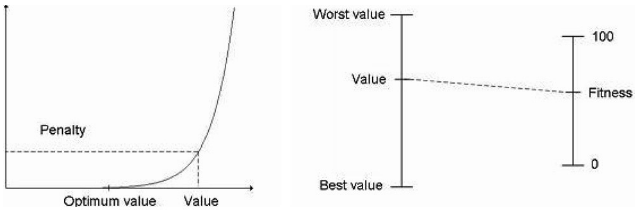

Fig. 5 - Fitness scaling (right), a value is linearly scaled between 0 and 100 on the basis of best and worst known values. Fitness penalization (left), the value is penalized depending on its deviation from the optimal value, this value is next scaled between 0 and 100 using best and worst penalization values.

Fig. 5 - Ecart à la valeur cible (droite), la valeur est attribuée entre 0 et 100 selon la meilleure et la plus mauvaise solution. Pénalité d'écart (gauche), la valeur est pénalisée en fonction de son écart à la valeur optimale, cette valeur est graduée de 0 à 100 avec la meilleure et la plus mauvaise valeur de pénalisation.

Fitness function

The proposed problem is a multi-objective optimization problem where different factors are involved in the fitness function (distance, number of petitioners, priority, etc.). As opposed to more complex approaches, like those based on the Pareto dominance criteria, we will use a linear aggregative function which weighs the different components according to their partial relevance (7):

$$\text{fitness} = \frac{\sum_i w_i \cdot s_i}{\sum_i w_i},$$ where s_i is the grade of fulfilment of subgoal i
w_i is the weight assigned to subgoal i

It is therefore possible to manually influence the search, according to the preferences and the results obtained during the real work, then adapting the algorithm to the (possibly changing) real necessities at the factory.

Under this approach, it is necessary to calculate a value of fitness for each component. The solution adopted was to calculate such values on the basis of the best and worst cases that will receive a score of 100 and 0 respectively. Based on the similarity of the solution with regard to these two extreme values and by means of linear scaling, the fitness value will be obtained *(fig. 5)*. Due to the difficulty encountered at the time of obtaining the mentioned best and worst cases, sometimes a heuristic criterion was used.

This scaling is sometimes preceded by a penalty evaluation. This is the case when a single value is defined as optimum, such as for instance the number of petitioners in each expedition. Increments from that value are previously penalized using exponential functions *(fig.5)*. Linear scaling is done later using minimum and maximum penalty values *(fig. 5)*.

Genetic operators

Classical crossover and mutation operators are used. Crossover operator is inspired by (8), defining each position in the offspring's vector from a "competition" between the positions in the parents' vectors. The operator guarantees the generation of valid solutions, containing all cluster-petitioner pairs just once, making further processing unnecessary.

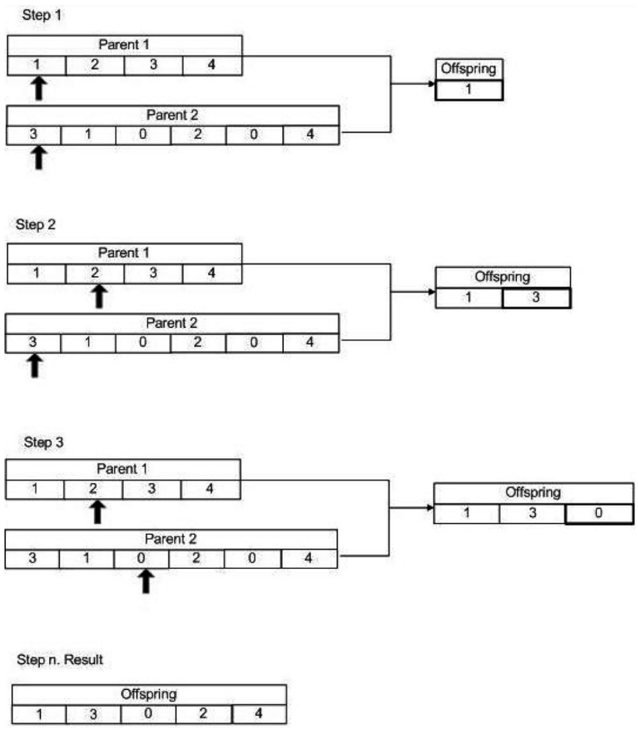

Fig. 6 - Crossover operator.

Fig. 6 - Opérateur hybride.

Starting from the first position of the vectors *(fig. 6)*, the operator sequentially goes through their elements. In each step a competition between the selected positions in both vectors is done, randomly choosing a value from one of them and adding it to the offspring. The operator then advances in both parents until a position with an element not included in the child is reached. Zeroes are always considered as not included in the child. This process is iterated until the child is complete.

Mutation operator is defined as a crossover of the individual with a randomly generated one.

Selection mechanism

Classical tournament selection has been used. It is based on a comparison of the fitness of a group of individuals randomly selected from the population. The best or the worst, depending on the purpose, is then selected as a result.

Results

The algorithm has been applied over a simulated scenario, involving 9 petitioners, 10 clusters and a total number of 19 cluster-petitioner pairs.

This scheduling problem was posed to two human experts, asking them to generate an optimal route, taking into account the partial goals with the following weights: distance (35%), total number of journeys (10%), number of petitioners in each

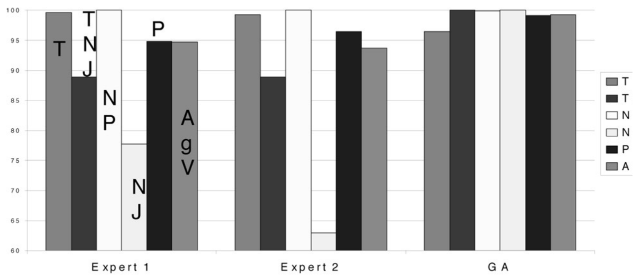

Fig. 7 - Genetic algorithm (GA) results compared with results obtained from human experts. Optimized factors are: time (T), total expeditions (TNJ), number of expeditions for each petitioner (NJ), number of petitioners per expedition (NP), and task priority (P).

Fig. 7 - Résultats de l'algorithme génétique (GA) comparés aux résultats des experts humains. Les facteurs optimisés sont : le temps (T), le nombre total d'expéditions (TNJ), le nombre d'expéditions par intervenant (NJ), le nombre d'intervenants par expéditions (NP) et la priorité de la tâche (P).

journey (10%), number of journeys for each petitioner (10%) and priority (35%). The same problem was solved with the algorithm under the same configuration.

The comparative results are presented in *figure 7*. The values shown correspond to the grade of fulfilment of each objective (100 represents the optimum) and the aggregated value obtained after considering all the factors.

Analyzing these results, it can be concluded that human experts sometimes appear to improve the optimization of some special factor, especially the distance, but they generally do not consider the rest and penalize them. Consequently, the algorithm is better when managing multiple objectives.

■ CONCLUSIONS

A useful system from the point of view of increasing the safety of people involved in scheduled shutdown procedures has been developed. Making a prerequisite the compliance with the actual internal safety regulations of the company, the system provides several hardware and software solutions that impose additional security checks to avoid human errors. It also helps with the development of such tasks, through specific functionalities such as:

- To automatically generate the switching off/on cards.
- To make easier the tasks of the staff and to provide them a support during all the switching off/on process.
- To register data about the scheduled shutdown process.
- To display at any moment the state of the facilities, showing which power-switches are switched off and information about the tasks being performed there.
- To make easier the statistical analysis of the collected data.

Present results show that a reduction up to 30% in the time needed for the switching off/on tasks can be expected with the use of the new system, what will represent more than three hours a month.

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