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A method for the cost optimization of industrial electrical routings

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ABSTRACT

The cost reduction is one of the most spread strategy adopted by companies for guaranteeing profits in a competitive market. This paper presents an approach for the cost optimization of industrial electrical routings. The proposed optimization process consists of two levels: the arrangement of the cables within the cable trays and the 3D routing of the cable trays for connecting the modules of a product. The arrangement of the power and signal cables and the selection of the cable trays are carried out considering specific configuration rules. A genetic algorithm, coupled with the Hightower's algorithm, is used to solve the routing optimization problem. The proposed cost functions consider the raw materials and manufacturing/assembly operations. The optimization process has been used for optimizing a portion of the electric cable harness of a 43 MWe power plant with a size of 44 × 20 meters, and a total of 40,60 kilometers of cables. The optimization process let to a cost saving of about 15% compared to the design carried out with the traditional approach.

KEYWORDS
Cost optimization; electric cable harness; cable routing; oil & gas

Abbreviations: *CTs*: cable trays; *CUi*: hourly rate for the installation phase [€/hour]; $CUrmt_k$: hourly rate for the *k-th* cost center used for transforming a semi-finished component [€/hour]; *Cut*: hourly rate for the test phase [€/hour]; CU_{tray}: unitary cost of a cable tray [€]; *DOE*: design of experiment; *GA*: genetic algorithm [€]; *Ic*: installation cost [€]; *If*: installation factor [-]; *PAc*: cost for the preliminary analysis [€]; *PAcp*: percentage used for calculating the cost of the preliminary analysis [%]; *RMc*: cost of the raw material and relative transformation operations [€]; $RMcc_i$: cost of the *i-th* commercial component [€]; *RMoc*: percentage of the overhead costs related to the management of the raw material [%]; $RMsc\_scraps_j$: cost of the scraps for the *j-th* semi-finished component [€]; $RMsc_j$: cost of the *j-th* semi-finished component [€]; *RMtc*: cost for transforming semi-finished components [€]; T_{cl}: commercial length of a straight cable tray [meter]; $Ti_{i,j}$: standard installation time for the *i-th* or *j-th* component [hour]; T_l: linear distance between two points of the wiring system that need to be connected [meter]; $Trmt_k$: time for the *k-th* operation for transforming a semi-finished component [hour]; Tt_k: standard test time for the *k-th* skid of the electrical system [hour].

1. Introduction

The cost reduction is one of the most spread strategy adopted by companies for guaranteeing profits in a competitive market. The most important player who can reduce costs is the designer since he/she is responsible of about 80% of the manufacturing and assembly cost. Cost optimization is a general method that can be applied to different kind of products to reduce cost without changing the product functionalities. The paper focuses on industrial electrical routings generally used for complex products (e.g. power plants, refineries, etc.).

The routing optimization is an important step toward the cost optimization of an electric cable harness. In such a field, the literature contains several research studies presenting solutions for this aim. A group of approaches, such as *Ittner et al.* [1] and *Pillai et al.* [12], deal with the cable routing problem for the cost minimization, by the use of a heuristic approach. Another group of works, such as *Kloske et al.* [6] *and Ma et al.* [9], present streamlined approaches (e.g. genetic algorithms) for the routing optimization for bulk cable harness. The first kind of approaches consider the cost but cannot be easily used for industrial electrical routings made by thousand cables. The second one does not consider the cost. Similarly, *Wedzik et al.* [14] presents a method for the simultaneous optimization of network layouts and cable cross-sections for wind farms, based on MILP (Mixed Integer Linear Programming) algorithms with the aim to reduce the investment costs. By using this method, it is possible to consider many constraints (cable dimensions, number of feeders, etc.) for getting high precision results without increasing the computational time. In the same way, *Zhu*

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et al. [16] provide a Knowledge-Based optimization technique for the automatic routing of aircraft wire harness, taking into account the total cost. Wei [15] describes a cost model for wire harnesses that includes product and manufacturing costs with the aim to find the best tradeoff between product variant complexity and material costs. This method, based on MATLAB simulations, is suitable for automotive applications. *Kobayashi et al.* [7] present another optimization method for the automotive sector. They use a Genetic Algorithm (GA) to optimize the assembly process of an automobile wire harness.

Despite the many approaches, the abovementioned methods are not based on CAD systems, forcing the designers to use specific tools in addition to the commonly used design tools.

Many of the software tools used by the electrical engineers are able to optimize the layout and the routing of a wire harness reducing cable length and avoiding interference. These tools (e.g. Catia Electrical® by Dassault System®, NX Electrical® by Siemens®) are having a rapid development due to the growth of the electrical cars sector where the wire harnessing plays a fundamental role. However, these software tools provide only path optimization functions to reduce the path length. Such tools, even if in literature numerous methodologies for cost estimation have been proposed [11], do not consider the cost of electrical components and installation phases. It is important to underline, especially in case of big and complex structures, that the shortest path is not always synonymous of cost saving because the installation cost could be much higher than the material cost.

The scientific literature presents several algorithms for drawing wires routings. They allow to find out a path to connect two points with the aim of minimizing length or computational time/cost. They can be broadly classified in two main classes: maze running and line search. Within the first class, the most used are the Lee's [8] and Hadlock's algorithms [3]. Thanks to the use of these methods, especially with the Lee's algorithm, it can be possible to find out a path (if it exists) that is always the shortest. However, these methods require great quantity of computational memory and computational time. The other class, the line search algorithms, are based on the creation of a set of line segments (Manhattan path) between two points. In presence of obstacles, several lines need to be drawn. They do not find the optimal path but they drastically decrease the computational time and space complexity. Indeed, thanks to the use of line segments instead of nodes grid, the required memory is significantly reduced [13]. Mikami-Tabuchi [10] and Hightower [4] are the most used line search algorithms. They are very similar but the Hightower's, instead of creating all line segments perpendicular to a trial line, takes into consideration only those ones that can be extended beyond the obstacle that blocked the preceding trial line. Despite these algorithms are not so recent, they are commonly used for solving routing problems [2].

This paper presents an approach for the cost optimization of industrial electrical routings. The optimization process consists of two levels: the arrangement of cables within cable trays (CTs) and the 3D routing of cables based on the Hightower's algorithm. The arrangement of power and signal cables and the selection of cable trays are carried out considering specific configuration rules (e.g. power cable cannot be overlapped, cable trays can move only along perpendicular directions etc.). The cost functions consider the preliminary analysis of the project, raw material (cable trays, cables, support systems, multiple cable transfer etc.), manufacturing operations (e.g. cutting, crimping, screwing etc.), installation phases (e.g. support and multiple cable transfer mounting, cables arrangement etc.) and tests.

The optimization process has been used for optimizing portions of the electric cable harness of a gas turbine power plant with a size of 44×20 meters, and a total of 40,60 kilometers of cables. The following sections describe the methodological approach used for the cost analysis and optimization. Section 3 shows a case study focused on the optimization of a 400-m electrical harness which interests different types of cables (power, transformer, and instrumental cables). The optimization process, for the portion of the electrical system analyzed in Section 3, let to a cost saving of about 15% of the total cost compared to the not optimized solution. The proposed methodology has been iterated on other portions of the electrical system, achieving an average overall cost reduction of about 10%.

2. Method

The presented optimization process helps electrical engineers to determine the best arrangement of cables within cable trays and to find the optimal routes that minimize the cost of a cable harness.

A cable harness consists of several cable trays, used to support and to steer insulated electric cables. They are required in those installations where wiring changes are possible at the construction site. Cable trays are classified by material, type, cable levels and orientation. While ladder trays are used for power cables (over 1.5 kW) due to the thermal dissipation need, slotted trays are suitable for instrumental cables. A tray could be straight, elbow, with a T-transition or cross. A commercial tray has a standard length of 3 m, even if it can be cut during the assembling for respecting the electric layout.

Next sections describe the proposed methodological approach for the cost evaluation and the optimization workflow. The cost section presents the algorithms for calculating the direct and indirect costs related to each cabling component. The other section shows how to find the optimal arrangement of cable trays for a wiring list and how to optimize the electrical routing of each cable tray system.

2.1. Cost calculation

The cost of a cable tray wiring system mainly consists of the raw material (*RMc*) and relative installation (*PAc*, *Ic* and *Tc*) costs (Eq. 1). The latter is relative to the preliminary assembly operation, cable tray system installation and final test (abbreviations of the terms used within the equations are available in the related section).

$$Cost = RMc + PAc + Ic + Tc \quad (1)$$

The typical elements of such a kind of wiring system are trays, cables, supports, multiple cable transit (MCT) and miscellaneous materials (screws, bolts, washers, cable ties, etc.). These components are commercial (used as provided) or semi-finished parts (adjustment operations required before the installation) defined by the designer by using an electrical CAD system. Hence, the raw material cost calculation (Eq. 2) is a BoM-based costing approach, since the BoM contains the information characterizing the product (dimensions, materials and specific features).

$$RMc = \left(\sum_j RMcc_i + \sum_j (RMsc_j + RMsc\_scraps_j + RMtc) \right) \cdot \left(1 + \frac{RMoc}{100}\right) \quad (2)$$

The unitary cost of each item ($RMcc_i$, $RMsc_j$) is retrieved from specific databases of commercial and electrical components (e.g. https://octopart.com/). The semi-finished components require additional operations before their use. Their costs, retrieved from the previous databases, are relative to a unit of product (cost each piece) or to a unit of a product characteristic (e.g. length for the cables). For semi-finished components, the raw material cost should consider also the relative scraps ($RMsc\_scraps_j$). The latter cost item, which for a straight tray is calculated as follows (Eq. 3), refers to the problem of nesting components.

$$RMsc\_scraps_j = \frac{Remainder\left(\frac{T_l}{T_{cl}}\right)}{Quotient\left(\frac{T_l}{T_{cl}}\right)} \cdot CU_{tray} \quad (3)$$

The overall scrap cost of a wiring system is calculated by iterating Eq. 3 for each cable tray. It is worth to highlight that the cost of the raw material has to be increased for an overhead factor for considering a mark-up for management-related activities (*RMoc*). The cost of semi-finished parts need also to consider its transformation (*RMtc,* Eq. 4). For instance, where a cable path requires cutting a commercial tray, the sawing and beveling operations determine supplementary costs. The sawing cost is a multiplication between the hourly rate (it considers the overhead costs) of a worker ($CUrmt_k$) and the time required for this operation (function of the cutting area, material of the tray and cutting speed) ($Trmt_k$). In addition, the cables require preparing operations related to the arrangement of their ends. The time for this operation depends by cable dimension, type (e.g. power, instrumentation, lighting, etc.) and kind of fitting at its ends.

$$RMtc = \sum_k (Trmt_k \cdot CUrmt_k) \quad (4)$$

The installation-related costs refer to a list of operations required for the complete realization of a cable tray wiring system, once completed the design stage. The operations considered by the cost models are the preliminary analysis, installation and test.

The preliminary analysis of a wiring system is required for planning the installation phase. It aims to establish a work plan (e.g. organization of the workers, commercial components procurements, etc.) and find/solve technical issues of the wiring system. This cost item (*Pac,* Eq. 5), which is directly proportional to the complexity of the wiring system, is a percentage (*PAcp*) of the overall cost.

$$PAc = (RMc + Ic + Tc) \cdot \frac{PAcp}{100} \quad (5)$$

The installation of the supports, trays, cables and miscellaneous materials is the core phase for realizing a wiring system. The installation cost (Eq. 6) of each component consists in multiplying the installation time ($Ti_{i,j}$) by the hourly rate of the cost center (*CUi*) and a corrective factor (*If*). The installation time is a value relative to standard installation conditions (e.g. one worker, not in elevation, etc.). These values are retrieved from a database of standard times, developed by measuring the installation phase of cable tray wiring systems. This database consists of a list of tables, one for each kind of component (supports, trays, cables and miscellaneous materials). The installation time refers to a specific component category, generally defined according to its dimension, weight and type. For a tray, the categories are determined by a combination of their width (i.e. 400 mm, 600 mm, 800 mm, etc.) and type (cross, planar bend, outside bend, inside bend, planar tee, vertical tee, etc.). The corrective factor is a parameter for adjusting the standard time with the actual installation conditions. For a tray, the factors are position (elevation or not elevation) and installation (floor, wall or ceiling). While the first factor considers difficulties for installing cable trays using ladder trucks or cranes, the second one considers issues related to arduous work, need of more workers and additional clamping for securing the component.

$$Ic = \sum_{i,j} (Ti_{i,j} \cdot CUi) \cdot If \tag{6}$$

The test of the electrical system aims to verify that the overall installation was perfectly done (Eq. 7). The approach is similar to the installation cost but the standard test time (Tt_k) is defined for each equipment unit (e.g. control panel, electric motor, etc.) of the electrical system.

$$Tc = \sum_{z} (Tt_k \cdot CUt). \tag{7}$$

2.2. Optimization workflow

Fig. 1 describes the design methodology for the cost optimization of electrical cable trays. The input data is the list of electrical cables and the layout of the plant. An electrical cable list includes information such as the equipment units to be connected, the level of power and emission per each wire, the cable size, and the specific weight. The plant layout is the 2D and 3D representation of the building structure with the equipment units of the electrical installation to be connected. The design approach (Fig. 1), based on the common way used to design electrical harnesses, foresees a multi-level cost optimization. During the design of a cable harness, the electrical engineer firstly defines the cables routing made by several bundles of cables. The bundle selection depends by the power level, the equipment to be connected and the type of the electrical system to which a cable belongs. The level of power classifies the electrical cables in groups (power transmissions, instrumental connections, etc.). A cable list collects wires by type with the same starting point inside the same electrical system. A group of cables, as defined, can be bundled in the same cable tray system. A cable tray system can be constituted by a single tray or more. The electrical engineer must define each component to assemble a cable tray unit. Therefore, the first level of optimization (Fig. 1) allows searching the optimal sizing of a cable tray system in terms of cost, as described in the following section. The second level of optimization regards the reduction of the cost related to the cable routing. The definition of the cable tray routes is a task of the electrical engineer who must define the ways to connect each equipment with the related electrical cabinet. From a geometric point of view, the path of a cable tray should be drafted close to each unit to be connected. For each electrical connection, a cable tray can change its section because the cable tray is split in two or more ways so that the number of wires decreases. Therefore, the optimization of a cable tray concerns each section of the path.

The optimization workflow includes two optimization loops, as described before. The electrical engineer can use the proposed approach to reduce the effort during the design phase. Three tools have been developed to support the design methodology. The first tool is the *CT SIZING OPTIMIZATION*, which is a DOE-based workflow implemented with the Isight® platform for optimizing the components of each cable tray path in terms of cost. The result of the first optimization workflow is the list of all cable trays to be drafted with the details of each cable tray element to be bought for the installation of the electrical system. Therefore, after the first step, all the cable tray sections are sized for what concerns the basic structure. The definition of each cable tray route concerns the second phase of the analysis. A tool called *CT ROUTING OPTIMIZATION* has been developed for searching the optimal path for each cable tray system. This tool is an optimization flow developed with the Isight® platform and uses GA methods to find the shortest paths at the minimum cost. A third tool has been developed as a routine to solve the Hightower's algorithm for the definition of the path to be optimized with the GA approach. The final output is the layout of all cable trays with geometrical paths, detailed BOMs, and cost.

2.2.1. Cable arrangement optimization

The described approach starts optimizing the cable trays to find the optimal cables arrangement within the relative cable tray (Fig. 1) in terms of cost, as described in the previous section. The output of this phase is a list of cable trays with relative dimensions. This phase allows to minimize the cost of such a cable tray while ensuring the correct arrangement of all the cables. This result represents the input for the second optimization level, where the cable trays list is used to estimate the total cost and to compare every possible route.

The input of the cable trays optimization is the list of cable groups and the related separators. The type and size of electrical wires to be grouped in a cable tray are defined before by an electrical engineer.

The Fig. 2. describes the approach used in the *CT SIZING OPTIMIZATION* tool to support the optimization of the cross-section dimensions (height and width) of a cable tray unit. The input is not only the list of the cable groups to be assembled but also other information such as material (GPR, AISI 304, AISI 316, etc.), installation

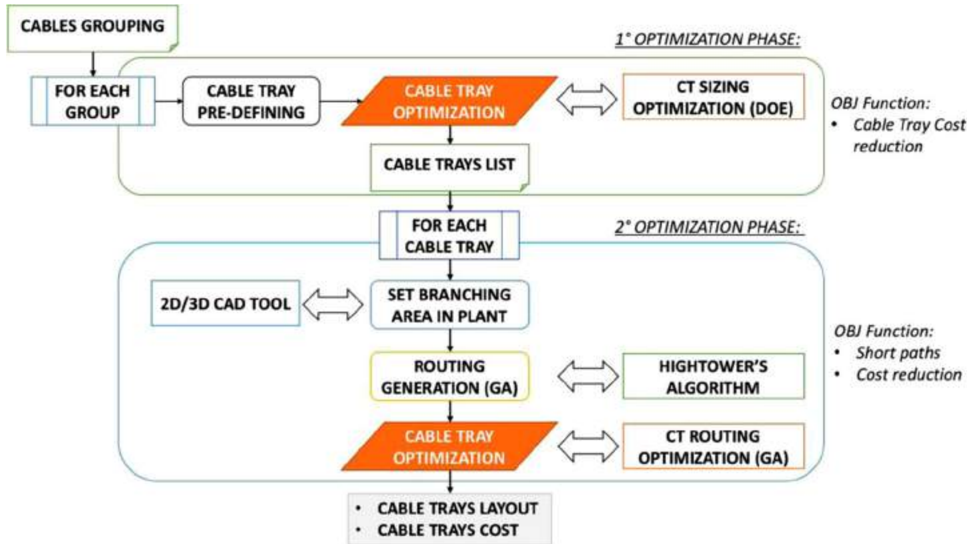

Figure 1. The proposed design methodology for the cost optimization of electrical cable trays.

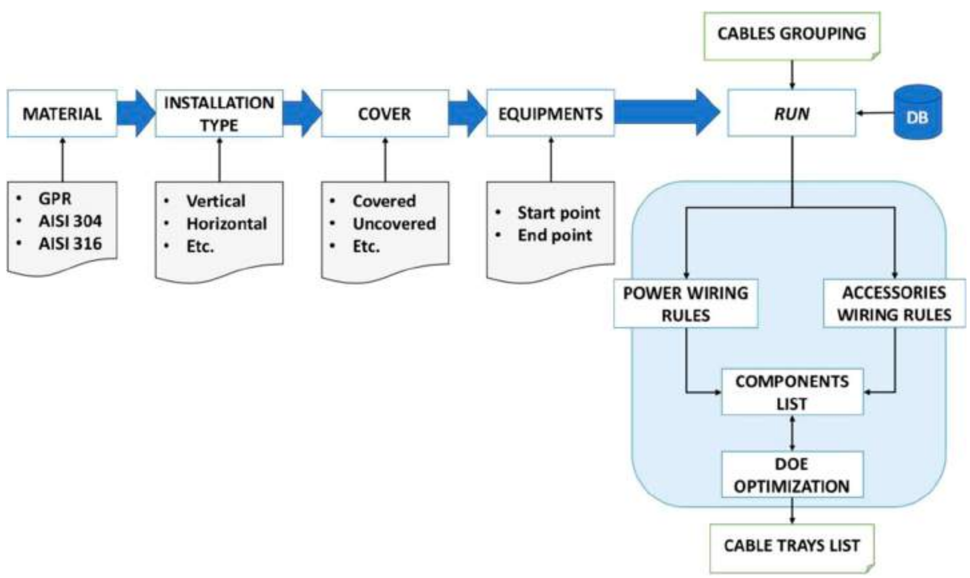

Figure 2. The workflow related to the *CT SIZING OPTIMIATION* tool.

type (vertical, horizontal, etc.), covered or uncovered tray, etc. The design variables elaborated in the phase of CT SIZING OPTIMIZATION are height and width of each cable tray. The range and step of variation of each geometrical dimension are related to commercial catalogs. While the CT dimensions are variables, the material parameter is a fixed value defined at the beginning of the design project.

The rules for the cable bundling are different for power wires and accessory ones due to the different levels of emission. Therefore, the *CT SIZING OPTIMIZATION* implements knowledge-based rules for clustering wires within a cable tray and calculating the filling values. Indeed, power cables cannot be overlapped in order to facilitate the heat dispersion and to avoid overheating. In case of different instrumental cables, an internal separator is essential for reducing electromagnetic interferences. In this manner, a linear arrangement is defined for the power cables while a volumetric arrangement for the instrumental cables, as shown in Fig. 3.

Once the starting/ending points and the cable configurations is a defined input, the optimization of the cables trays is driven by the proposed tool. As mentioned before, this tool has been developed using Isight® software but the rules and the algorithm to define a set of cable trays are performed integrating an Excel-based tool. This second tool, which is an Excel file with macros, includes rules and the database with all the commercial

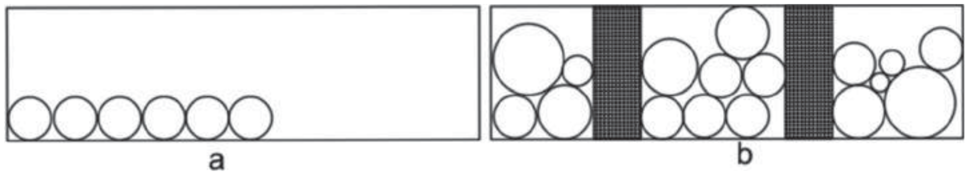

Figure 3. Possible cables arrangements: (a) linear arrangement for power cables, (b) volumetric arrangement for instrumental cables.

and employable cable trays. The implemented rules calculate the quantity of trays necessary to serve the selected equipments. Moreover, this database also includes the cable trays cost information to compare the different solutions elaborated during the optimization process. Since the connection between the Excel-based tool and Isight®, it is possible to change autonomously the cable trays number and dimensions according to the database, for searching the optimal configuration of the cable tray arrangement. In particular, the optimization is based on a DOE approach because the number of trays combinations is finite. In fact, the number of combinations is limited by the available commercial solutions. Through an iterative process and using the formalized rules and algorithms, the optimization software collects information about the cables arrangement and costs for each cable tray configuration following an initial DOE table. In this way, it is possible to evaluate several combinations to find that one with the lowest cable trays unitary cost.

2.2.2. Route optimization

Regarding the method described in Fig. 1., after the definition and sizing of the sections of each cable tray to be arranged, the designer must draft the path of each wiring harness using the proposed tool. Generally, the electrical cabling consists of several wires connecting different equipment units. Therefore, it is a common practice grouping similar wires (by type and level of emission) in the same cable tray if they have the same starting point. For this reason, the path of a cable tray should optimize the connections with the all equipment to be cabled. Indeed, several branching points are necessary to split a cable tray into two or three ways to connect different units. The proposed approach aims to define an area for each branching point of a cable tray. As example, the Fig. 4. shows some branching areas defined for three equipment units to be connected with a cable tray. The same figure also shows an obstacle area within the 2D plant layout. The electrical engineer has the task to draft these graphical objects, such as branching and obstacle areas, into the 2D/3D CAD models of the plant. This approach makes sense because helps the routing algorithm to draft valid paths. Moreover, branching points are necessary in a cable tray route and

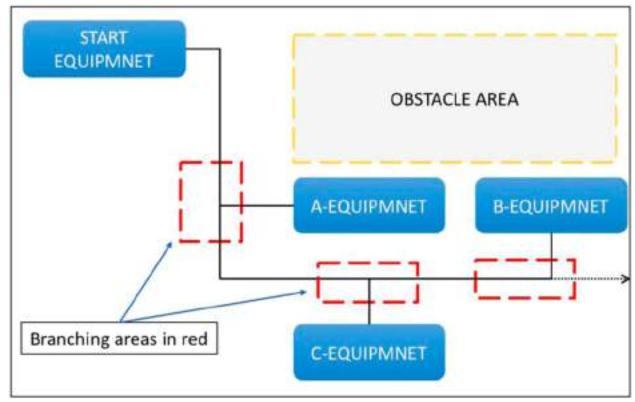

Figure 4. Identification of the branching areas.

their position could be a design constraint in several cases. Thus, the designer can define a range where the coordinates of a branching point change. The proposed approach makes this variation guided by GA methods, in order to find the optimal configuration.

The problem of generating the route of a cable tray is simplified by considering many simple paths defined by each branching point drafted into the 2D layout. As discussed before, the position of each branching point can change within an area defined by the user. A genetic algorithm changes the position of each branching point in order to optimize the cost of the electrical installation. A tool called CT ROUTING OPTIMIZATION has been developed within the Isight® platform for supporting the automatic generation of a path for an electric cable tray. The Hightower's algorithm has been implemented using a VBA script to calculate each path. Since the approach considers a path as a list of sub-paths, the Hightower's algorithm was used to draft each single route from two midpoints. The design variables elaborated during the optimization process are the geometrical coordinates of each branching point.

The Hightower's algorithm [3] (Fig. 5) was used to perform the route generation of each sub-path (from two midpoints) because it provides a line search approach. This algorithm is a vector router that sends two lines in orthogonal directions both from the starting point (S) and from target point (T) until an obstacle is reached. From there, this method repeats the process until the segment originated from S intersects the segment originated

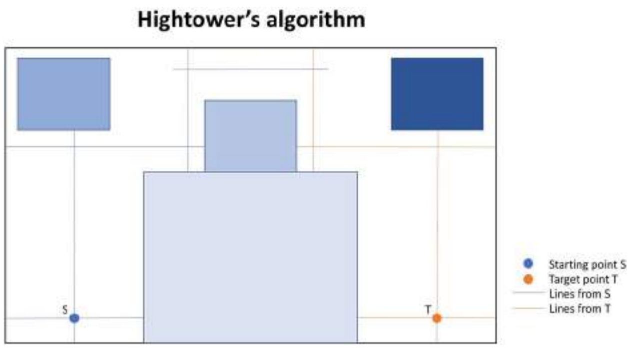

Figure 5. Hightower's algorithm.

from T (Fig. 5). It is very suitable when there are few obstacles but relatively long distances to be covered and it has been chosen for its rapidity in finding the solution, even if it does not guarantee the finding of the shortest path. However, this drawback can be bypassed thanks to the automation of the optimization problem. In this way, it can be possible to analyze a large quantity of solutions in an automated manner (using a GA method), reducing designers' effort and calculation time. The second optimization level is crucial because an inadequate formulation could lead to a path that requires very high installation costs.

3. Case study

This section presents a case study for evaluating the proposed methodology. It concerns the cost optimization of the electrical cabling of an on-shore module for power generation in oil & gas sector. The proposed test case is focused on the optimization of a 400-m electrical harness which interests different types of electrical cables (power, transformer, and instrumental cables). This analysis has been carried out with the collaboration of a multinational company which is one of the world leaders in the production of turbomachinery solutions for oil & gas applications.

An on-shore module is a reticular structure made by around a thousand of welded steel beams, which integrates core equipment with all relevant auxiliary systems (gas turbines, compressors, fans, piping, electrical system etc.) for electric generation. It weighs more than 1,500 tons (2,300 tons considering all the items) and it is 44 meters long, 20 meters wide and 24 meters high. The proposed test case focuses on a portion of a module which is one of six 43-MWe modules of a 258-MWe power plant.

The origin point of the electrical system, from which all the cables depart, is represented by the local electric room (LER), namely the cabin containing all the power and control panels. The end points are represented, instead, by the various items to be connected. The electrical wiring consists of 24.8 km of power cables and 15.8 km for instrumental cables. The cable routing cost of the module under investigation, considering material, installation, preliminary analysis and test, is about 4% of the total cost.

According to the proposed method, the inputs for the cost optimization are the electrical BoM (Tab. 1) and the layout of the plant.

The first step of the methodology is the definition of the starting and target points. To simplify the discussion of the case study, only the connections between LER (yellow box in Fig. 6. and Fig. 7) and four plugged-in items (red boxes in Fig. 6 and Fig. 7 are analyzed).

Then, the installation preferences must be set. In this case, engineers choose aerial installation as cable-laying

Table 1. Electric BoM of the routing chosen by the designer in a traditional way and by the use of the proposed method (within parentheses).

Electric BoM of the traditional design and of the **(optimized one)**			
Cable trays		Cables	
Width [mm]	Length [m]	Type	Length [m]
600	165 (**138**)	Power	38 (**27**)
450	74 (**65,3**)	Instrumental	524 (**437**)
300	68,7 (**56,2**)	Transformer	1432 (**1270**)
150	43,6 (**38,8**)		

Miscellaneous - power cable trays				
Cable tray width [mm]	90° Elbow [part]	45° Elbow [part]	T transition [part]	Cross transition [part]
600	12 (**10**)	12 (**6**)	8 (**7**)	0 (**0**)
450	0 (**2**)	0 (**1**)	2 (**1**)	1 (**0**)
150	7 (**4**)	0 (**2**)	2 (**2**)	0 (**0**)

Miscellaneous - instrumental cable trays				
Cable tray width [mm]	90° Elbow [part]	45° Elbow [part]	T transition [part]	Cross transition [part]
600	0 (**0**)	1 (**1**)	3 (**2**)	1 (**1**)
300	3 (**2**)	5 (**3**)	1 (**0**)	1 (**0**)
150	2 (**2**)	2 (**2**)	1 (**1**)	0 (**0**)

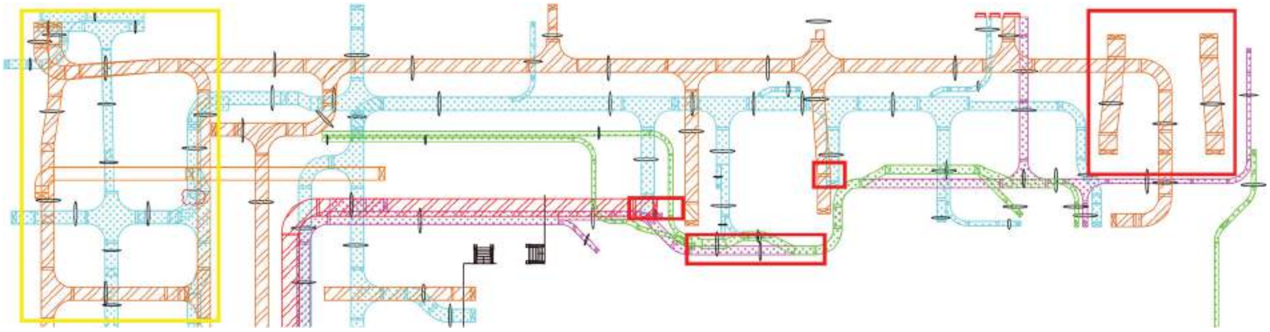

Figure 6. Not optimized routing of the cable trails reached in a traditional way.

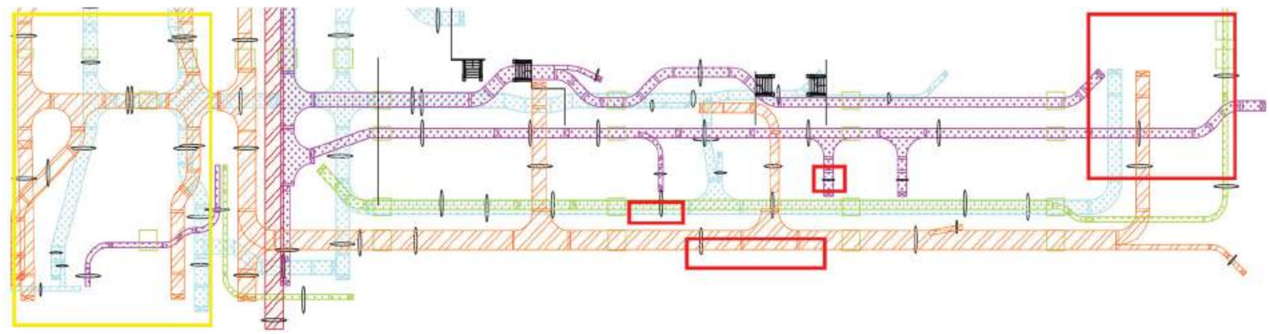

Figure 7. Optimal routing of the cable trails reached by the proposed methodology.

method, covered and fiberglass CTs. Next, for the first optimization level, the cable trays dimensions have been chosen as variables for the DOE. At this point, the best cables arrangement is reached via an optimization software (Isight® by 3DS®) coupled with the Excel-based tool that contains all the necessary algorithms and rules for the cost calculation. The output of this level of analysis is the list containing the number and the dimensions of cable trays that optimize their cost per meter. The output of this optimization level has been set as input for the second one. The designers must establish the branching points and define an area around where the points can be moved. The coordinates of these points have been chosen as variables in the optimization software imposing as constrains the maximum dimensions of the area, tailored for each equipment. The CAD system (in this case AutoCAD® by Autodesk®) has been opportunely customized by using its API (Application Programming Interface), in order to modify the layout and to recognize possible clashes between the cable trays and the obstacles. The genetic algorithm of the optimization software varies the position of the branching points and then, the Hightower's algorithm draws the route of the cable trays. Once finished the sketching, the total cost has been calculated considering the length of the straight parts and the number of curves and T-transition. Through an iterative and automated process, the system calculates many feasible solutions each one with the relative total cost. Such optimization saved, for the considered portion of the electrical system, about 15% of the total cost compared to the not optimized solution. This solution was reached by the designers in an iterative and manual way through a "design-evaluation-redesign" approach. Engineers, after the creation of the CAD model, were asked to identify manually the cost optimal solution iteratively varying the cable routings. This approach is time consuming (due to the high degree of interaction with the designers) and it does not guarantee that the optimum is found.

Fig. 8 shows the costs breakdown of the solution reached by the designers in a traditional way (Fig. 6). Due to the confidentiality of the data, the results are shown only as percentage values. Fig. 8 highlights that the cables represent the main cost item and from its decomposition it turns out that the transformer wires are the prevalent item (79%). In this case, it appears evident that this is due to the significantly greater length (Tab. 1) and higher unitary cost of the transformer wires (+1147% respect to the power cables and + 258% compared to instrumental cables). Moreover, Fig. 8 displays the breakdown of the total cost between preliminary analysis, material, installation and test. The predominant cost item is the material (50%), followed in order by installation (30%), preliminary analysis (10%) and test (10%).

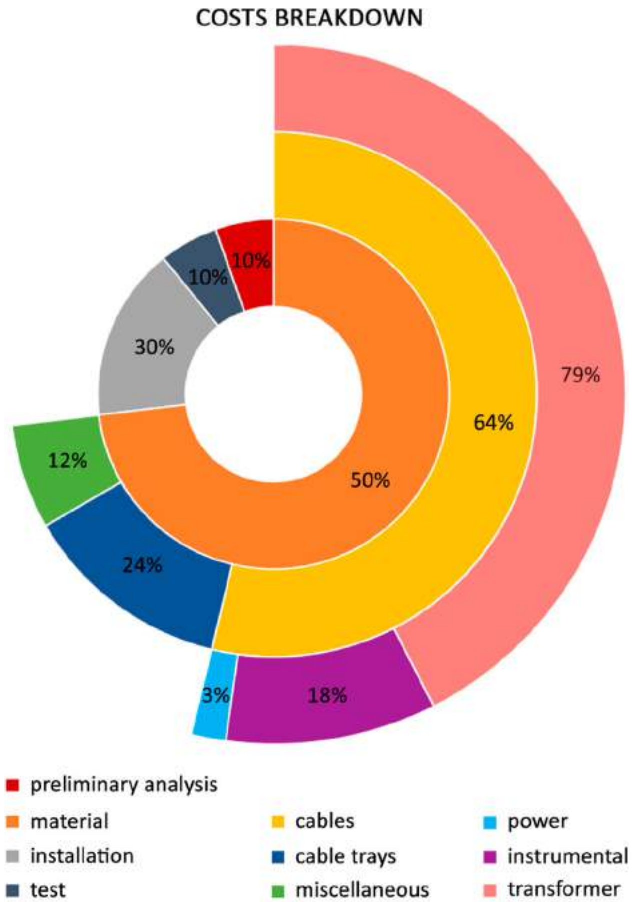

Figure 8. Costs breakdown of the design reached through a traditional approach.

Table 2. Percentage of the cost reduction reached thanks to the proposed methodology.

	Cost reduction [%]
Preliminary analysis	-1%
Material	-15%
Installation	-9%
Test	-1%
Cables	-16%
Cable trays	-12%
Miscellaneous	-8%
Power cables	-4%
Instrumental cables	-10%
Transformer cables	-17%

The cost of the solution achieved thanks to the proposed methodology (Fig. 7) was compared with the one obtained via a traditional design process (Tab. 2). Cost items that are less affected by the application of the presented method are the preliminary analysis (−1%) and test (−1%) phases. In fact, the related costs are proportional to the complexity of the electrical system, which does not vary too much among different cablings routings. Instead, the electrical layout optimization has a significant impact on the cost reduction of materials (−15%) and installation (−9%).

The cables are the main element of the electrical system and therefore, as was intuitive to assume, the greatest cost reduction is achieved on these elements (−16%). However, for the analyzed design, CTs and miscellaneous also reach an important cost reduction (respectively −12% and −8%).

Observing the cost reduction obtained on the various types of cable, it can be confirmed that the weak point of the "traditional" design was the path of the transformation cables (−17%).

The proposed methodology has been iterated on other portions of the electrical system, achieving an average overall cost reduction of about 10%.

The time needed to conduct these analysis, considering both the phases for the workflow initial set-up, optimization and post-processing of the results, it was 5 days. It is important to underline that this kind of approach is very suitable to be completely automated. Therefore, designers can employ the running time in other business activities.

The costs estimation results provided by the proposed method have been compared with experimental data in order to evaluate the accuracy. The tool underestimates the costs by 9.5%. Two factors contribute to generate this underestimation: waste of material and time of installation. Indeed, the estimation of scraps is not an easy task due to the uncertain related to the variability of the manual cutting process. Moreover, the installation time and costs sometimes increase as a result of not ideal working conditions (weather, worker psycho-physical conditions etc.) that make difficult the installation phase.

4. Conclusion and future works

The paper presents a cost optimization method for the design of electrical cable harness, based on the analytic cost analysis of the raw material and cable routing. The inputs of such a method are the cables list and the layout of the plant. The method presented in this paper, even if focused on electrical cabling, can be also extended to other arrangements such as piping. The method, once implemented within a prototypal software tool, has been applied for the cost optimization of the cable routing of an on-shore module for power generation. Thanks to the use of this methodology, considering the portion of the electrical system analyzed in section 4, it was possible to save up to 15% of electrical cable routing cost. The proposed methodology has been iterated on other portions of the electrical system, achieving an average overall cost reduction of about 10%. However, the layout modification is limited only to the position of the branching points and thus it is not possible get an overall change of the layout (only sub-optimal solutions can be achieved). For this reason, future works will address the development of effective and time-efficient algorithms exploring a wider range of solutions. The cost estimation models require a further refinement for reducing the cost estimation error (improvement of the material waste calculation and the variability of the installation phase). Moreover, in order to give a general validation to the proposed approach, it is necessary to test the method on products other than that presented in this paper (e.g. auxiliary facilities of production plants).

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