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A DESIGN TO COST METHOD FOR ELECTRIC CABLE HARNESS

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Abstract

The Design to Cost method is a well-known methodology for developing cost-competitive products. In the context where the Industry 4.0 initiative is pushing the research on innovative systems for data exchange and analysis, the electric aspect of a product is becoming more and more important. The scientific and industrial literature contains several methods and tools for the cost estimation of electric cable harness, but they essentially calculate the cost by simply considering the Bill of Material and computing the cost of the raw material. The installation cost is not considered. The paper presents a Design to Cost method for electric cable harness, based on the analytic cost analysis of the raw material and routing process. The inputs of such a method are the electric Bill of Material and the 3D path of the cable harness. The cost consists of three items: purchasing, installation and cutting. The method, once implemented within a prototype software tool, has been applied for the cost optimization of the electric cable harness of an on-shore module for power generation. The average accuracy, measured comparing the results with experimental data, was 10.5%.

Keywords: Design costing, Design to X, Industrial design, Electric cable harness

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1 INTRODUCTION

One of the most important driver for the development of competitive products is the cost. Considering that almost 80% of the final cost of a product is determined during the design stage, designers are forced in considering this aspect. The combination of the market globalization and the product customization has been pressing designers for the development of optimization methods to be used during the early design phases, to reduce cost and increase performance. In this context, the issue concerns the right trade-off between cost and performance.

This aim is supported by the Design for X paradigm, and Design to Cost (DtC) is part of it. Even if DtC methods have been conceived in the late 80s, they are becoming widely used only during the last years. The development of ease to use software tools, integrated with CAD systems, allowed designers to apply this method during the design phase. DtC methods and tools are currently widely used for mechanical products realized with chip removal processes or for steel structures.

The promising results, achieved by the companies using such methods and tools, are pushing the research toward new contexts of application of the Design to Cost. In particular, electric and electronics engineers are looking for DtC methods for supporting the design of wire harness or cable routings. A Design to Cost process passes through the analytical evaluation of the manufacturing process of a product or even its lifecycle (in case of a DtC extended to the product lifecycle cost).

The scientific literature contains several analytic methods and software tools for the manufacturing cost estimation of mechatronic products (Cicconi et al., 2010). However, in case of bulk cable harness (e.g. power plants, refineries) designers cannot use such methods for a quick and easy evaluation of the cost during the design. Moreover, such tools essentially calculate the cost by simply considering the Bill of Material and computing the cost of the raw material. The installation cost and the material scraps are not considered. Thus, designers need to be supported by analytic but easy and quick methods for the cost analysis.

In this framework, the paper goes beyond the state of the art presenting a cost estimation method for bulk electric cable harness. Based on an analytical approach, the method consists of a set of data and rules for computing the cost for realizing electric cable harness. It considers the cost of the raw material (cables, cable trays, supports, multi-cables transit), preparing operations (e.g. cables and cable trays cutting), preliminary analysis (e.g. planning of the installation), assembling operations (e.g. supports fixing, cables laying) and test. The method starts considering the cable harness BoM (Bill of Material) and the CAD model of the cable trays. The first input allows the calculation of the raw material, while the second one mainly provides data for assessing the assembling operation. The result consists of a cost value, properly split in sub-items for better informing the designers about the cost-related criticalities.

2 LITERATURE REVIEW

Preliminary researches regarding Design to Cost (DtC) methodologies started since 1985 (Germani et al., 2011). They aimed to study and develop techniques to facilitate the estimation of costs during the early phase of the design process taking into account costs of raw materials, manufacturing and assembly (Ehrlenspiel et al., 2007). In literature, different approaches for cost estimation have been proposed. They can be broadly classified as: knowledge-based, parametric, variance and bottoms-up.

The knowledge-based method (also known as intuitive cost estimation technique) is built on past experiences. Engineers apply subjective considerations based on accumulated knowledge and expertise in order to have a quick cost estimation. However, even if it is an easy to operate method, suitable even when details are unavailable, it lacks of accuracy. Ficko et al. (2005) presented an example of the knowledge-based method. They developed an intelligent system for predicting the total cost for the manufacturing of sheet metal products by stamping. Their tool is based on the concept of CBR - case base reasoning. It extracts geometrical features from past designs CAD models and calculates the similarities with the new product's features. The most similar cases are exploited for the cost prediction by genetic programming method. Shehab and Abdalla (2001) developed a decision support system (DSS) dealing with cost modelling of both a machined component and injection molded component. They created a cost model, based on the analysis of the past molded product life cycles, that integrates the relationship between cost factors, product development activities and product geometry.

The parametric method is based on the identification of the parameters that determine the cost and on the expression of cost as a function of these parameters. It could be applied when the parameters, occasionally known as cost drivers, can be straightforwardly identified and when enough data on the relations between variables and cost are available. Various commercially available software tools are based on this technique. Cavalieri et al. (2004) created a parametric model to estimate the unitary manufacturing costs of a brake disk using the weight of the raw disk, unit cost of raw material and the number of cores as parameters in their model. Boothroyd and Reynolds (1989) chose a parametric costing approach to develop a cost model for rotational components machined from bar in a CNC turret lathe. To estimate the cost, they used the volume of typical turned parts as parameter.

The variance method (also known as analogical method) exploits historical cost data of existing designs, similar to the investigated one, to estimate the costs. It is applicable only if similar designs exist and it requires a reliable comparison with analogous products. Some adjustments may be adopted to obtain an exhaustive and accurate cost prediction. A regression analysis could be useful for the identification of the relationship between the past products costs and the values of certain selected variables. Lewis (2000) used existing designs to provide cost estimates for similar new designs. He developed a tool that performs the historical research on company database and then generates the cost estimate. Chen and Chen (2002) proposed a BPNN - Back Propagation Neural Network model for cost estimation of a strip-steel coiler. The neural network can be instructed to store the past knowledge to infer answers to questions.

The bottom-up or analytical method is based on the decomposition of a system/product into its fundamental units, processes and activities that represent consumed resources during the manufacturing cycle. The cost is the sum of all these elements. To exploit this kind of method, specific software tools or databases, containing a large amount of data and knowledge about costs, are fundamental. This method provides an accurate cost estimation. Jung (2002) proposed a feature-based cost model to estimate the manufacturing cost of machined parts. In that work, the machining cost is proportional to machining time (setup, operation and nonoperation time). The Jung's model is suitable to be used only in the final stages of design process because of the type of information required. Bernet et al. (2002) developed a cost model in order to assess the potential of commingled yarns for cost-effective manufacturing. It estimates the total product cost by summing material costs, manufacturing costs and overheads as well. It requires detailed information to be properly applied.

The scientific literature contains also studies about the cost estimation of electric cable routing. For example, Davis (1995) estimated the installation cost of a standard cabling system in a building. Wei (2012) developed a cost model, which includes product and manufacturing costs of vehicle wiring harnesses. The ASPE - American Society of Professional Estimators (2014) evaluated the cost of a clean room and data-center equipment electrical work. Lumbreras and Ramos (2013) applied decomposition strategy to perform a cost analysis for the electrical layout of an offshore wind farm. However, scientific literature lacks of original works about a methodology for the cost estimation of bulk cable harness.

On the market, commercial software tools are already available for the routing and for the cost estimation of pipe, supporting the engineers in the early phase of the plant design process. Some of these software tools are, for example, SmartPlant® Isometrics (by Intergprah®) or Pipe-Pro® (by Professional Estimating Systems®) that allow to sketch the pipe path and to estimate the materials cost.

Moreover, for the cable harness design, the most well-known software are SmartPlant® Electrical (by Intergprah®), Eplan Electric® (by Eplan®) and VeSys® (by Mentor Graphics®). Even if there are important similarities between piping and wire harnessing, the latter does not contain functions to forecast the costs of the electric systems. For this reason, designers who operate with these tools need to adopt manual methods to evaluate costs of components and installation process, employing a long time for the costs estimation phase (especially for bulk cable harness). The software commercially available for the electrical cost estimation are tools based on the bottom-up method that have been developed to be used in the building sector such as TurboBid, McCormick, Viewpoint MEP etc. They require the definition of the electrical components (Bill of Material) and all the needed operation for the installation. The creation of the list is a manual process because they lack of an interface capable to communicate with the common CAD/CAE system. Through the interaction with a pre-build and customizable database, they are available to figure out how much materials, equipment and labor will cost.

In this context, the paper aims to develop a method for the analytic cost estimation of bulk electric cable harness. By analyzing the electrical BoM and the CAD model, with the support of formalized rules and algorithms, the method calculates all the cost items for an electric cable harness.

3 MATERIALS AND METHOD

This section presents the method for the electric cable harness cost estimation. The approach is particularly focused on bulk electric cable harness made by components such as cable trays (ladder, slotted, straight, elbow, etc.), cables, supports, panels and MCT (multi cable transit) boxes. The chapter firstly gives an overview on the electric cable harness and relative components. Secondly, the authors present the method for the cost calculation and related rules.

3.1 Electric cable harness

The electric cable harness considered in this paper consists of a combination of cable trays, cables, supports and MCTs (multi cable transits). Figure 1 shows such components.

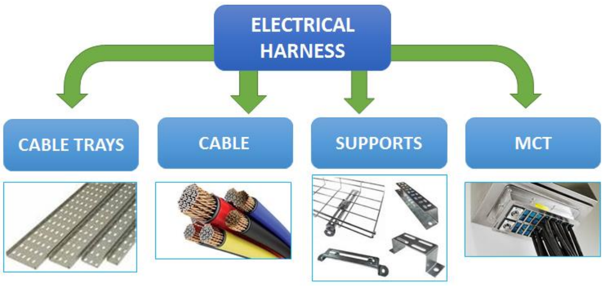

Figure 1. The main components of a cable tray wiring system

The cable tray is the most representative functional unit of a cabling system. Its function is to support insulated electric cables in applications such as commercial and industrial steel constructions, buildings, communications, power plants etc. A cable tray is used in all installations where wiring changes are possible. Generally, cable trays are classified by material, type, cable levels and orientation. Typical materials used for trays are carbon steel, stainless steel, or GRP (glass-reinforced plastic). 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. Commercial elbows are 90° and 45°, and possible accessories are cable barriers, clamping and splice plates. A commercial tray has a standard length of 3 m. The tray can be cut during the assembling for respecting the electric layout.
Figure 2 shows the O-O (Object-Oriented) representation of an electrical cable tray. A cable tray is an object defined by four main properties, which are material, type, width and components list.

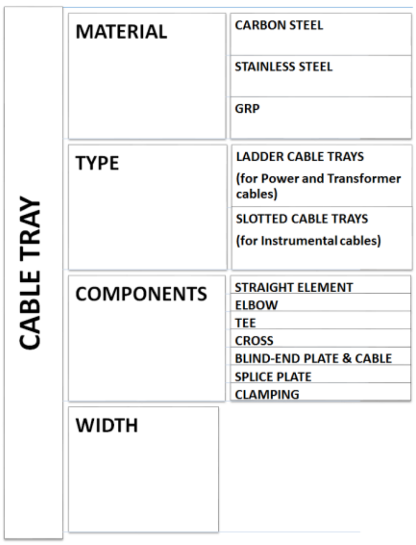

Figure 2. The object-oriented model of a cable tray

The components list is a collection of all possible items that can be used in a cable tray assembly. Each type of component is described by a different list of properties. For example, an elbow item is represented by the angle property (90°, 45° or adjustable) and by the type of orientation (horizontal or vertical). The attributes of a cable tray such as type and material are common to all child components of the O-O structure. Figure 2 is not a full representation of the whole properties of a cable tray object, but a schematic representation. The structure implemented within the prototypal tool includes additional fields such as the tray length for straight items.

3.2 Cost calculation process

The proposed method (Figure 3) is based on two different inputs. They are the layout of the electrical routes, which is generally a 3D CAD model, and the electric BoM, which contains additional information such as material, cable data, etc. During the design phase, the electrical engineer defines the path for each cable route using 3D CAD/CAE tools. Each route is a path tree where the electrical panel is the root and the connecting units are the leaves. Commercial CAD/CAE tools support the engineer in the modeling of electrical routes for cable trays. Libraries, already implemented in CAD/CAE tools, allow bulk materials selection from a database. The 3D CAD model does not contain all the data required for realizing the cable harness. For overcome this issue, designers define the product and manufacturing information within the electric BoM.

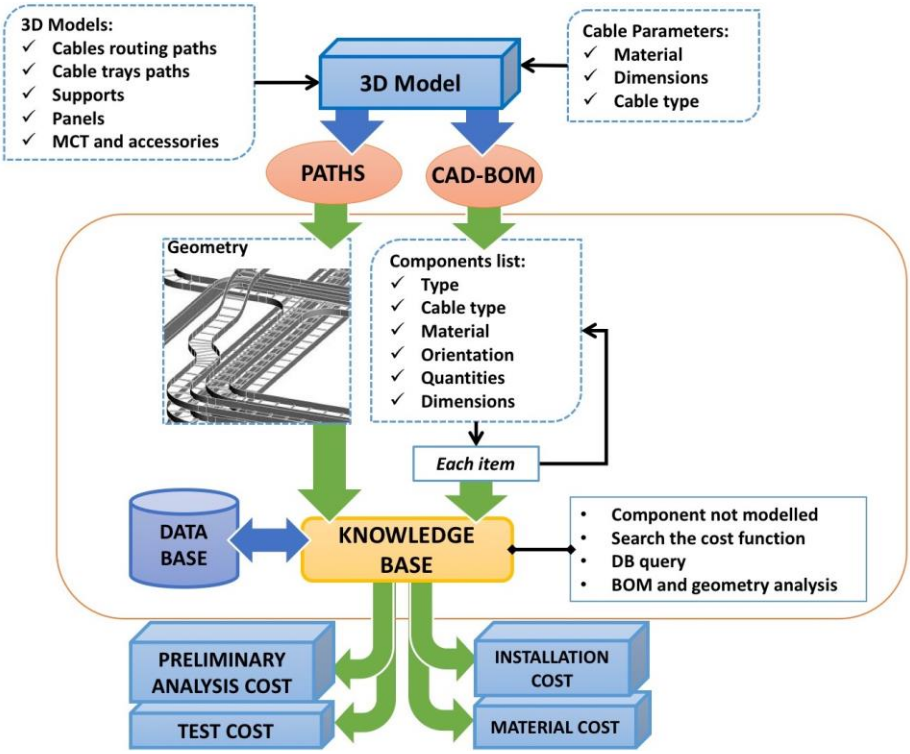

Figure 3. The methodological approach

The block "knowledge base", highlighted in Figure 3, represents a set of rules and algorithms for the cost calculation. Figure 4 shows the implemented approach for the cost estimation of each component. The first step for calculating the cost consists in analyzing the input data and adding those components not modelled by the designer. This is required for getting the complete description of a cable tray system. For instance, the cable tray can be one single body, which needs to be split in many items. The output of this first step is the Bill of Material. The second step consists in searching the cost function from a database of rules, which was implemented before at the time of the research. The third step consists in retrieving the calculation parameters from the database, which are the specific cost of the commercial items, the time for each operation (cutting, installation, etc.) etc. The fourth step is the computing phase, where each cost item is resolved for each component. In particular, Figure 4 highlights the typical cost items for a straight cable tray.

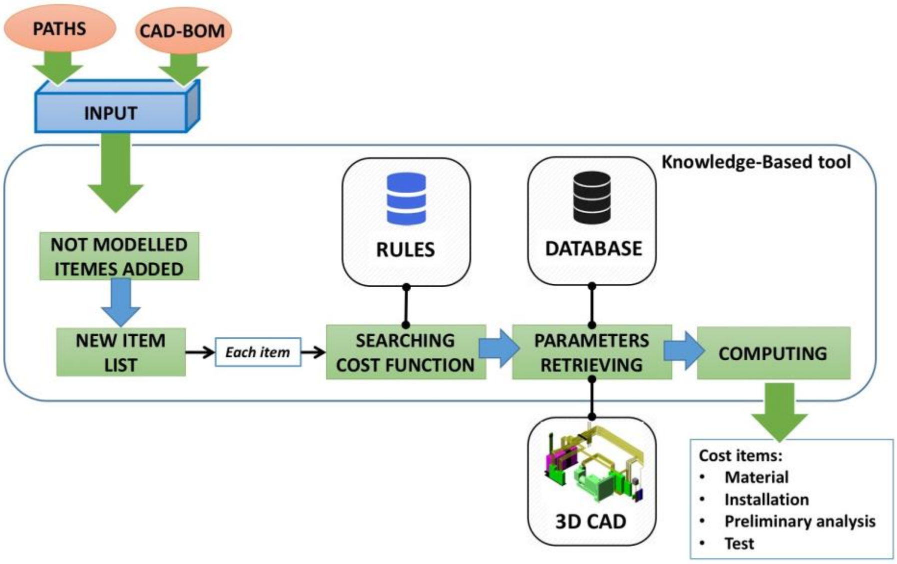

Figure 4. The detailed approach for the costing of each component item

3.3 Manufacturing cost calculation rules

The cost of a cable tray wiring system mainly consists of the raw material (RMc) and relative installation (PAc, Ic and Tc) costs.

$$Cost = RMc + PAc + Ic + Tc \tag{1}$$

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 through an electrical CAD tool. Hence, the raw material cost calculation is a BoM-based costing approach, since the BoM contains the information characterising the product (dimensions, materials and specific features).

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

The unitary cost of each item (commercial: RMcci and semi-finished: RMscj) is retrieved from specific databases of commercial and electrical components (e.g. https://octopart.com/). 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_scrapsj). It is worth to highlight that the cost of the raw material has to be increased for an overhead factor that consider a mark-up for management-related activities (RMoc).

The cost of semi-finished parts need also to consider its transformation (RMtc). For instance, where a cable path require cutting a commercial tray, the sawing and bevelling operations determine supplementary costs. The sawing cost is a multiplication between the hourly rate (it considers the overhead costs) of a worker (CUrmtk) and the time required for this operation (function of the cutting area, material of the tray and cutting speed) (Trmtk). 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.

$$RMtc = \sum_k (Trmt_k \cdot CUrmt_k) \tag{3}$$

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 (PAc), installation (Ic) and test (Tc).

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), which is directly proportional to the complexity of the wiring system, is a percentage (PAcp) of the overall cost.

$$PAc = (RMc + Ic + Tc) \cdot \frac{PAcp}{100} \tag{4}$$

The installation of the supports, trays, cables and miscellaneous materials is the core phase for building a wiring system. The installation cost of each component consists in multiplying the installation time (Ti,j) by the hourly rate of the cost centre (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.). Such 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. 400mm, 600mm, 800mm, etc.) and type (cross, planar bend, outside bend, inside bend, planar tee, vertical tee, etc.). The corrective factor is a value 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 to secure the component.

$$Ic = \sum_{i,j} \left(Ti_{i,j} \cdot CUi \right) \cdot If \tag{5}$$

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

$$Tc = \sum_{z} (Tt_k \cdot CUt) \tag{6}$$

4 CASE STUDY AND RESULTS DISCUSSION

This section presents a case study for testing the proposed methodology. It concerns the cost estimation of the electrical cabling of an on-shore module for power generation. The proposed test case is focused on an electrical harness long 380m, made by different types of electrical cables (power, transformer and instrumental cables). This analysis has been carried out with the collaboration of a multinational company that is one of the world leaders in the production of turbo-machinery solutions.

The module is a reticular structure made by 1123 welded steel beams, which integrates core equipments with all relevant auxiliary systems (turbines, compressors, fans, piping, electrical system etc.) for electric generation. It weighs more than 1500 tons (2300 tons considering all the items) and is 44 meters long, 20 meters wide and 24 meters high. It is a part of six “mega structures” that contains a turbo-generator train for a total of 6 gas turbines and electrical generators. Each module can feature 43 MWe.

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 is about 4% of the total cost.

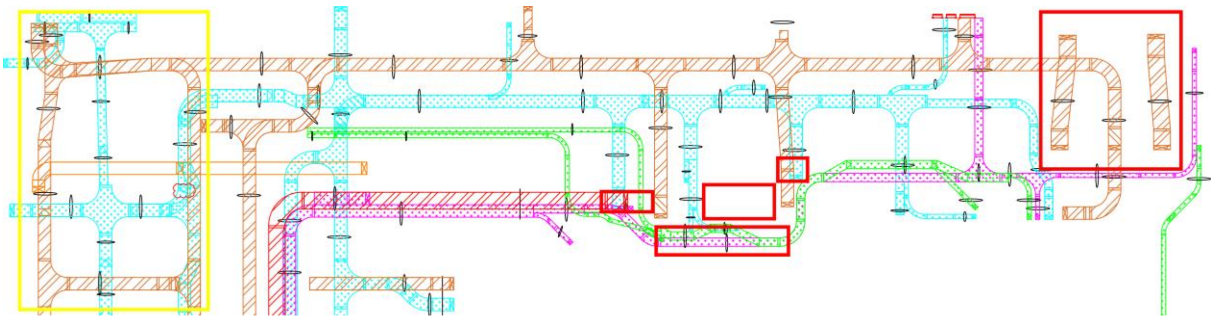

Figure 5. Top view of the cable trays analyzed in the presented case study

4.1 Case study

This subsection shows how using the proposed method and related tool for estimating the cost of the electrical connection between the LER and five items. The connected items are the turbine enclosure, the fuel gas valves, the turbine outlet duct and the power transformers (two items). The case study refers to five different cable trays, containing power, instrumental and transformer cables. Figure 5 shows the top view of the cable trays considered in this case study. The red boxes identify the plugged-in items, whereas the yellow one the starting point from the LER.

According to the proposed method, the input for the cost calculation are the layout of the electrical paths and the electric BoM. In the case study, these input have been provided by a 3D CAD model created through the SmartPlant® suite. The prototypal tool, developed for implementing the proposed approach, takes these data as input for generating the complete list of bulk materials for costing the electrical cablings. To simplify the discussion of the case study, the cost evaluation is limited only to cables, cable trays and miscellaneous materials (elbows, cross transitions and T transitions). Table 1 contains the BoM provided by the prototypal tool.

Starting from the BoM, the tool computed the overall cost and related items for each component. This was possible thanks to the integration with a database containing all the rules, algorithms, parameters and cost functions necessary for the calculation. Four different items of cost have been considered: material, installation, preliminary analysis and test.

Table 1. Electric BoM of the presented case study.

Electric BoM				
Cable trays			Cables	
Width [mm]	Length [m]		Type	Length [m]
600	157		Power	30
450	80		Instrumental	560
300	64,7		Transformer	1560
150	45,6			
Miscellaneous - power cable trays				
Cable tray width [mm]	90° Elbow [part]	45° Elbow [part]	T transition [part]	Cross transition [part]
600	14	42	0	0
450	0	0	1	1
150	5	0	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	4	0
300	3	5	1	0
150	5	0	1	0

4.2 Results discussion

Figure 6 shows the main results of the analysis. The results are presented only as percentage values due to the data confidentiality. According to the Figure 6, the biggest cost item is related to the cables and its breakdown shows that the predominant item (83%) is for transformer wires. It is due to two reasons: they are significantly longer than the power and instrumental cables (Table 1) and they have also a higher unitary cost (+1147% than the power cables and +258% than the instrumental cables). Moreover, Figure 6 shows how the material and installation cost items impact on the total amount. Material cost is bigger than installation one (45% vs 35%) and it is particularly true for the cables trays (11% vs 7%) and for the miscellaneous (6% vs 3%).

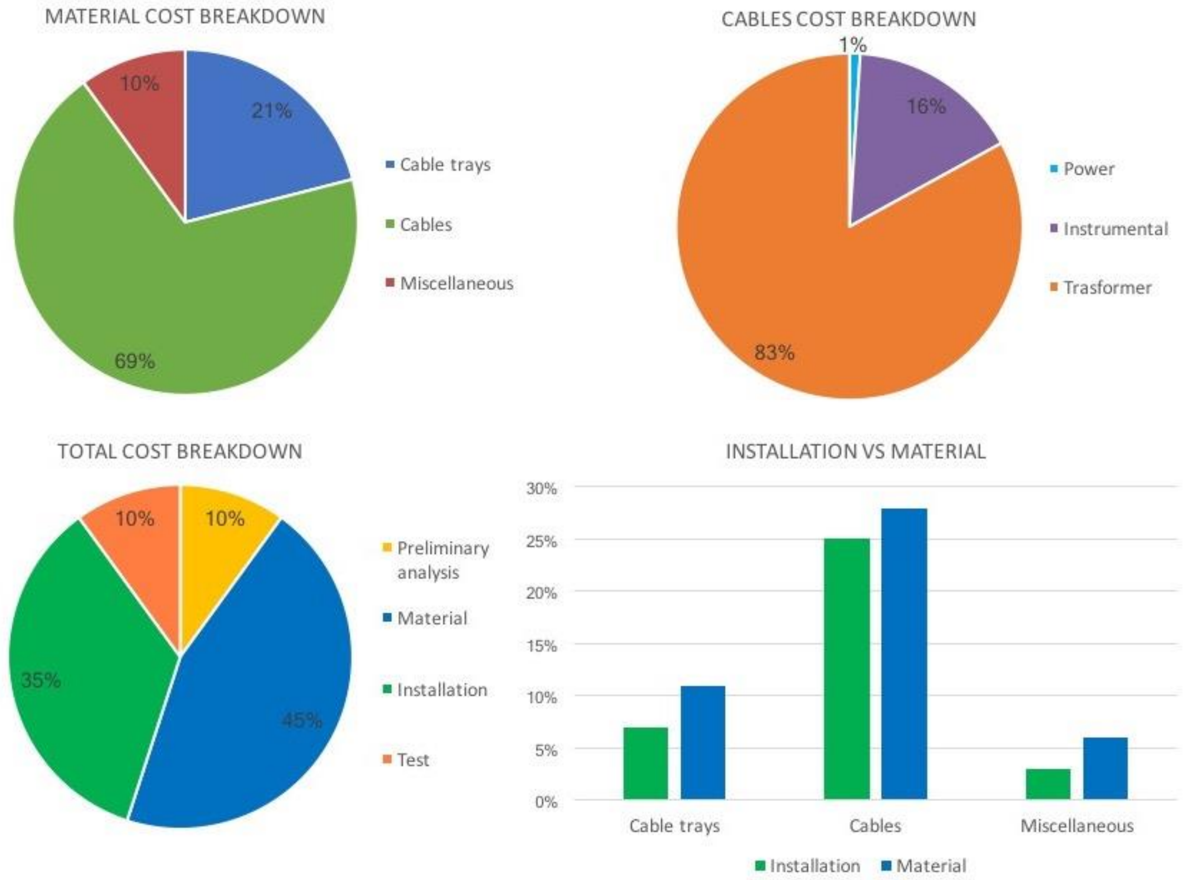

Figure 6. Cost breakdown analysis for the original wiring system

The application of the method, in this case, highlighted that the total cost was higher than the target cost. Therefore, a redesign of the electrical layout was necessary. Thanks to the information provided by the breakdown costs analysis, the designers rapidly re-designed the electric cable harness by firstly focusing on the most important cost-drivers. Indeed, the re-design started by defining a new path for the transformers cables since representing the biggest cost-related criticality. The redesigned layout led to 15% of cost saving. Figure 7 shows the new cost breakdown. By considering the criticalities highlighted by the cost estimation method, designers worked on the components responsible for the higher costs.

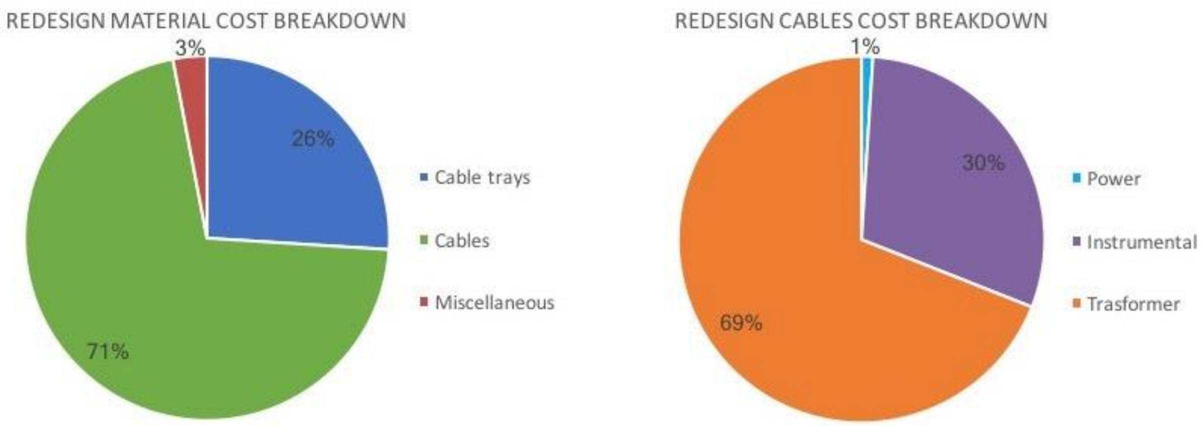

Figure 7. Cost breakdown analysis for the redesigned wiring system

The cost values obtained by using the method and related tool have been compared with the experimental data for evaluating the accuracy. The error was -10.5% (the tool underestimates the total cost). This error is mainly due by two factors: material waste (4%) and installation time (6.5%). The method, indeed, does not consider the scraps for cables (only for trays). In addition, the installation cost is calculated considering that workers work in ideal conditions. However, some random factors (e.g. weather, worker psychophysical conditions etc.) could complicate the installation phase, by increasing the related cost.

5 CONCLUSIONS

The paper presents a cost estimation method for electric cable harness, based on the analytic analysis of raw material and routing paths. The input of such a method are the electric BoM and the 3D path of the cable harness. 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 evaluation of the electric cable harness of an on-shore module for power generation. The average error, measured comparing the results with experimental data, was 10,5%. Future works should reduce the estimation error by implementing cost algorithms that take into account the cables waste and the variability of the installation phase.

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