AUTOMATIC FLATTENING OF THREE-DIMENSIONAL WIRING HARNESSES FOR MANUFACTURING

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Abstract

Increases in aircraft wiring volume and complexity call for manufacturing design improvements to reduce cost and lead-time. By using Knowledge Based Engineering the repetitive, time-consuming process of flattening a 3D digital wiring harness can be largely automated, while ensuring compliance to physical constraints and manufacturing guidelines.

1 Introduction

There is a significant increase in volume and complexity of electrical wiring in today's aircraft programs. This is illustrated by comparing the total wire length of the Airbus A380 (530 km [1]) with the Airbus A340 (300 km [2]) and the Boeing 747-400 (274 km [3]).

The increase in volume is caused by the introduction of new electrical systems and the replacement of pneumatic and hydraulic systems by electric systems [4].

According to Sussman's complexity classification [5], the aircraft wiring system is *structurally* complex. This is because of its many different components with their inter-relationships and dependency on other aircraft systems. The level of wiring system complexity is expected to increase further, because of the stricter regulatory requirements on reliability and redundancy from one hand, and the growing customers demand on flexibility of the electrical system configuration from the other.

The complexity of wiring system development led to a 1-year delay of the Airbus A380 [1, 2] program.

The aircraft electrical wiring system design and manufacturing process starts with the definition of requirements. This is followed by the concurrent definition of the electric wiring system architecture and the modeling process of the wiring system in the aircraft 3D digital mock-up. The outcome of these two design activities consists of a set of electrical and geometrical definitions, which must be transformed into manufacturing instructions and drawings. Then, harnesses are manufactured and finally installed in the aircraft.

Fig. 1. A wiring harness on a formboard. Source: Fokker Elmo B.V.

Wiring harnesses are produced on flat tables, by means of a 1:1 scale production drawing, typically addressed as *formboard* (see Fig. 1). A formboard is a flat representation of the wiring harness 3D digital mock-up. The flat harness assembled on the production table will have to be bent into its 3D shape during installation in the aircraft (see Fig. 2).

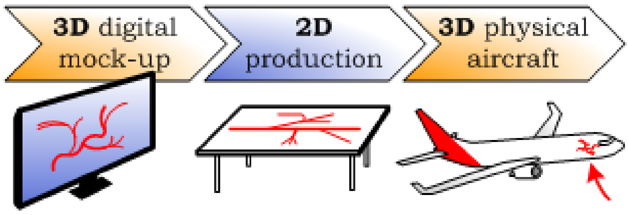

Fig. 2. The wiring harness is designed in 3D, produced on a flat table and installed in 3D.

The creation of a formboard drawing is a repetitive and time-consuming process. This is mainly due to the fact that several manual quality checks and model adjustments are required to ensure the flat production wiring harness can be fitted in the airplane. In particular, it is important that the stiffness constraints of the various harnesses are met, otherwise:

- The harness cannot be fitted in the airframe, as it may be too difficult to bend the wire bundles.
- Wires and pins may be damaged during installation or operation.

The process to transform a 3D wiring harness design into a formboard drawing consists of the following main steps (see Fig. 3):

1. Check on quality and completeness of the 3D digital design (*analysis*).
2. Transformation of the 3D model to a flat plane (*flattening*).
3. Rearrangement of the flat model to fit the given dimensions of a table frame (*fitting*).
4. Addition of production instructions (*dress-up*).

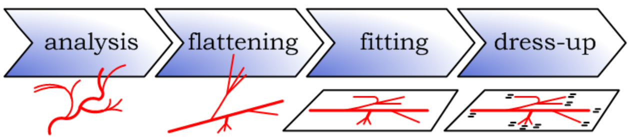

Fig. 3. The formboard design process

Current flattening methods (process step 2) do not take constraints of the physical harness, such as bending stiffness, sufficiently into account. This can cause considerable rework and a high risk of installation issues.

The flattening process could be improved by eliminating manual, repetitive development steps through automation. Knowledge Based Engineering (KBE) is the technology adopted in this research work to largely automate this process.

The objective of this paper is to present a method to automatically transform any 3D wiring harness digital mock-up into a 2D formboard, while taking physical product properties into account, by using KBE techniques.

Section 2 provides more details on the current flattening method and the associated issues. Background information on KBE is given in section 3. In section 4 the development of the flattening tool is explained and results are given in section 5. Section 6 provides conclusions and discusses future work.

2 Flattening: current practices and issues

The objective of the flattening process is to create a 2D representation of a wiring harness providing the means to manufacture on a flat table a product that will fit in the 3D airplane (see Fig. 2). To this purpose, any 2D wiring harness model must respect the corresponding requirements:

- Component orientation, i.e. respecting the facing side with respect to the 3D model.
- Allowable bending, i.e. respecting bundle stiffness limits.

In the past, before the availability of 3D digital mock-ups, formboard drawings were created by first manufacturing a wiring harness prototype directly in the 3D physical mock-up of the airplane. The prototype harness was then physically flattened (by force) on a table and a drawing of the contours or a photo were made as a blueprint for series production. As the prototype could fit in the airplane, harnesses built with these drawings would also fit.

The need for expensive 3D physical mock-ups in today's concurrent aircraft design process has been reduced by the introduction of digital

3D models. Nowadays, aircraft wiring harnesses are generally designed in a 3D digital mock-up using a CAD system. CATIA V5 [6], for example, provides an electrical toolbox, which includes a method for flattening wiring harness 3D models. However, this flattening method is based on a projection algorithm, hence the orientation of bundles with respect to each other depends on the selected flattening plane. The effect of using a certain flattening plane is illustrated in Fig. 4. Suppose that the harness projected in the X-Y plane (right) represents the closest match to the 3D model. If the Y-Z or X-Z planes would have been used, the bundle and component orientations differ more from the 3D model than what is strictly necessary to obtain a flat result. Depending on the flexibility of the wiring bundles, an orientation different with respect to the 3D model can lead to installation problems as is illustrated further in this section.

Independently of the used flattening algorithm, only straight segments result from a flattening operation. However, this is not always physically allowed. Bundle sections with high curvature should be manufactured directly in bent form, in order to make sure their installation is possible. The methods currently implemented in commercial CAD systems, are not able to automatically detect and respect these high curvature sections during the flattening process.

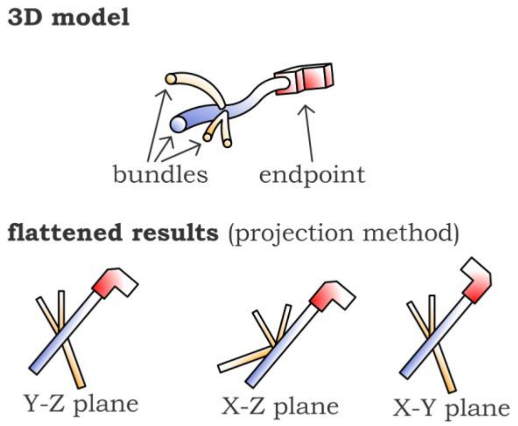

Fig. 4. Schematic representation of a 3D wiring harness and resulting flat representations, depending on the projection plane.

By not accounting for component orientation and flexibility, problems can occur during installation. For example, a bundle will need to be bent beyond its allowable limits, or could result in insufficient length to reach a destination connector, as illustrated in Fig. 5 and Fig. 6.

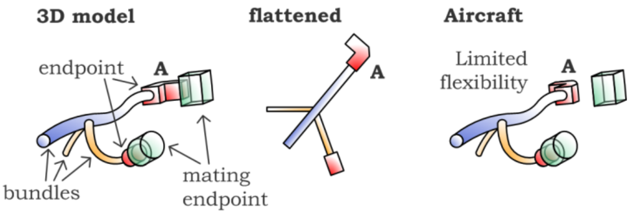

Fig. 5. Schematic representation of a 3D wiring harness, the resulting flat representation and the harness during installation. Due to limited bundle flexibility endpoint A may not be able to reach its mating endpoint.

In order to avoid these issues, time-consuming checks and rework is currently necessary. This provides an opportunity for improvement using KBE.

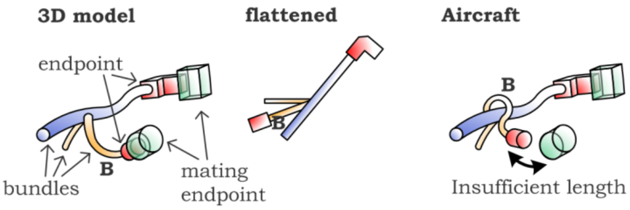

Fig. 6. Schematic representation of a 3D wiring harness, the resulting flat representation and the harness during installation. The incorrect orientation of bundle B leads to the situation where there is insufficient length to reach the destination connector.

3 Knowledge Based Engineering

The definition of KBE adopted in this paper is provided by La Rocca [7]: KBE is a technology based on dedicated software tools called KBE systems, that are able to capture and reuse product and process engineering knowledge. The main objectives are reduction of development time and costs by automating repetitive, non-creative design tasks and support multi-disciplinary design optimization. KBE cornerstones are rule-based design, object-oriented modeling and parametric CAD [7].

La Rocca [7] introduces the concept of High-Level Primitives (HLP) to construct KBE applications. As opposed to CAD (low-level) primitives, i.e., points, lines, solids etc., a HLP is a functional element or parametric building block, incorporating and reusing relevant knowledge. A HLP can be instantiated and assembled in different configurations, as is illustrated for an aircraft in Fig. 7. More details can be found in [7] and [8].

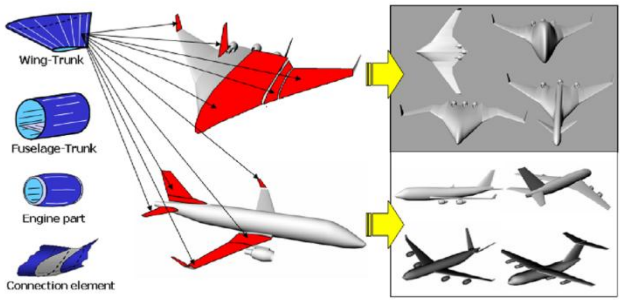

Fig. 7. Generation of different aircraft configurations and variants using the HLP modeling approach [8]

The KBE system used to develop the applications described in this paper is Genworks GDL [9]. GDL is a functional, declarative object-oriented language linked to a geometry kernel library. More information on GDL and KBE systems in general can be found in ref. [10] and [11].

KBE applications are best developed using a systematic Knowledge Engineering (KE) process, as elaborated in [12-14]. Main steps of this process are knowledge acquisition, implementation in a KBE system, verification and deployment.

Examples of KBE applications to support aircraft wiring system design and 3D routing can be found in [15-17]. However, the manufacturing design process of wiring harnesses has not received so much attention in the scientific community.

The wiring harness flattening process is an interesting case for the application of KBE as the process consists of many non-creative, repetitive steps, is largely rule-based and poses geometry manipulation challenges, such is the analyses and transformation of CAD models. A KE process has been applied to the entire formboard development process in a cooperative study with wiring harness manufacturing experts from industry [12]. The flattening method presented in the next section is the result of several development iterations.

4 Development of the KBE flattening tool

The objectives of the flattening tool are to reduce the time required to design a formboard and increase the quality in terms of consistency and completeness. The following two options have been considered:

1. Use the flattening methods provided by current CAD systems and develop a KBE application to automate all the required manual checks and adjustments.
2. Use KBE to develop an alternative flattening method that eliminates the unnecessary checks and adjustments and automates the required ones.

Option 2 would require the development of a new approach to wiring harness flattening. Option 1 would maintain the use of an approach already familiar to wiring manufacturing engineers, which is, however, the main cause of problems. Eventually, option 2 was selected, because the availability of industrial wiring harness manufacturing and installation experts was the most favorable condition to initiate the development of an alternative method. The description of the developed flattening method is presented in three parts: section 4.1 describes the model definition and application set-up; section 4.2 describes the analysis approaches; section 4.3 describes the 3D to 2D transformation.

4.1 Wiring harness model definition

The KBE application for wiring harness flattening is set up using the HLP concept. Given the fact that any wiring harness actually consists of the following basic components, four HLPs have been defined, which can be assembled in the KBE application to model any sort of wire harness:

- Bundles (bundled wires)
- Endpoints (assembly of connectors and backshells)
- Coverings (e.g. sleeves and braiding)
- Attached components (e.g. clamps)

To connect the different components, a virtual component is introduced, namely the connection point, for which one extra HLP has been defined. The wiring harness components and two instantiations of wiring harnesses modeled using the HLPs build-up approach are illustrated in Fig. 8.

Note that the covering HLP can be instantiated as various types of covering. This can be seen in Fig. 8 where different colorings identify different types of covering. Some types or combinations of covering can affect the flexibility of a bundle section.

In practice, each HLP is defined as a *class* using the GDL object oriented language. Each class has a number of attributes. Once values are assigned to these attributes, specific instances of the HLPs can be generated to model the given harness. The values for the 3D geometric representation attributes of the HLP instances are obtained from the wiring harness input CAD model. These include, for example, the bundle centerline and the dimensions of the endpoint component. The 2D representation is another attribute of each HLP, section 4.3 explains how it is generated. The HLPs have other attributes as well, such as material properties, part number codes, etc. The HLPs contain also analysis and transformation capabilities (e.g. bending analysis, see section 4.2). There are various dependencies between the HLPs, as the attribute of a given HLP can refer to the attribute value of another HLP. Two examples: The stiffness of the bundle HLP depends on the material type of the covering HLP. The orientation of an endpoint HLP depends on the orientation of the connection point HLP used to connect the given endpoint and bundle. The dependencies between HLP instances are managed via the wiring harness class.

4.2 Geometry analysis

The 3D wiring harness model generated in the CAD system must be analyzed to guarantee compliance to manufacturing and installation requirements. The KBE tool reads in the wire harness model exported from the CAD system and systematically analyzes the model searching for the following violations:

1. 3D shapes at bundle connections that cannot be flattened
2. Exceeded flexibility limits.

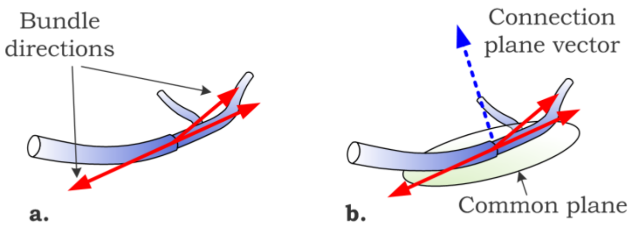

Fig. 9. At a bundle connection point, direction vectors are determined (a) and the closest common plane is computed (b).

A wiring harness can be flattened in correspondence of a connection point, only when a common plane exists, which yields a sufficiently small deviation from the direction vectors of the splitting bundles.

The common plane is found by determining the bundle direction vectors at the connection point (Fig. 9a) and calculating the

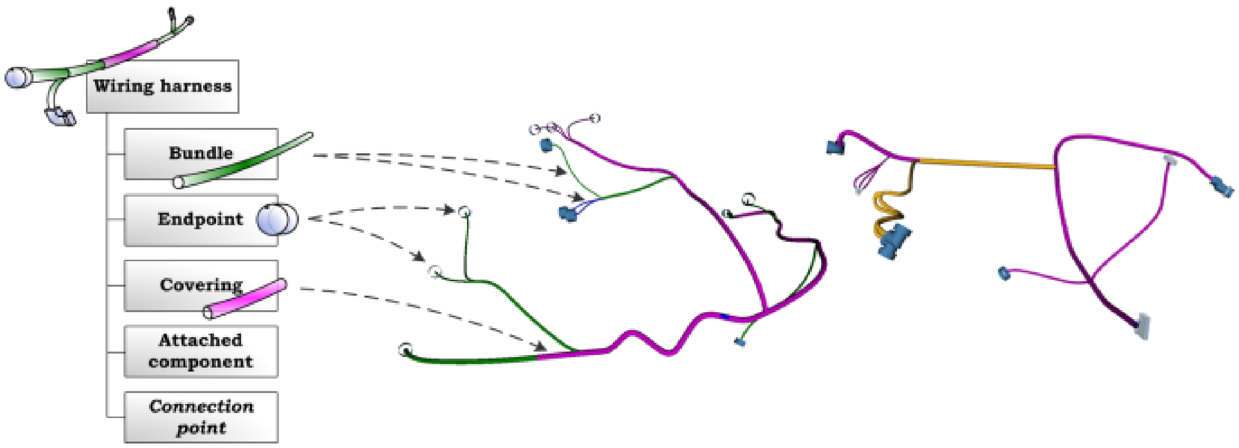

Fig. 8. Left: Breakdown of wiring harness components. Center and right: Two 3D wiring harness models composed of instances of the wiring harness HLPs

closest common plane of these vectors (Fig. 9b).

Using the main bundle direction vector as a reference, cross-products with the other bundle direction vectors are computed. The final connection plane vector is the vector yielding the smallest deviation with respect to all the cross-product vectors. The deviation is the angle between the plane set by the connection plane vector and the bundle direction vector.

When the deviations exceed a set tolerance, the connection is automatically identified as a 3D break-out and the designer is informed that the given harness cannot be manufactured in 2D.

The bundle curvature distribution is analyzed for violations of minimum bend radius limits (Fig. 10a). To this purpose the value of specific bundle attributes (e.g., the diameter value of the given bundle instantiation) is compared with the allowables derived from experiments performed by the tool customer and recorded in proprietary reports.

Based on the results of this curvature analysis, the KBE tool identifies the bundle segments that can be straightened and those whose bend radius must be respected (Fig. 10b). A further test determines whether the sections that cannot be straightened are allowed to be flattened.

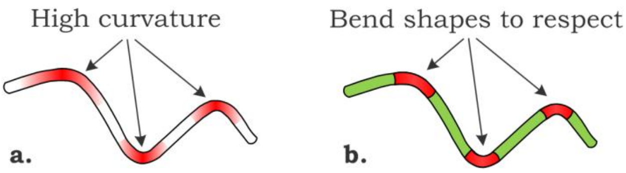

Fig. 10. The curvature of wiring harness bundles is analyzed (a) and sections with bend radii violating bending rules are identified (b).

If the wiring harness does not comply to the constraints, the KBE tool informs the user that flattening is not allowed. When this is the case there are two options: redesign the 3D model in order to ensure it can be flattened or use costly 3D tooling (physical mock-ups). In case no violations are present the model can be flattened, according to the procedure described in the following section.

4.3 Transformation from 3D to 2D

When the KBE tool has verified that no violations are present in the wiring harness model, the transformation from 3D to 2D can take place. The value of the 2D representation attributes of the various HLP instantiations are determined from the analysis of the 3D representation discussed in section 4.2. In order to obtain a flat wiring harness, the tool will have to perform the following tasks:

- Connection points must be flattened
- Bundles must be flattened
- Bundles must be adapted to rotate all connected components onto a single plane

Since endpoint components are rigid, no 2D parameters have to be computed. Their orientation in the plane depends on the connection point linking them to a bundle. Rules specific to an endpoint instance geometry set the plane(s) the endpoint is allowed to be positioned in. For example, the presence of an angled backshell will lead to an allowed plane vector corresponding to the cross vector between the backshell centerline vectors. Some components do not require a specific flattening plane (e.g. a circular connector). This is illustrated in Fig. 11.

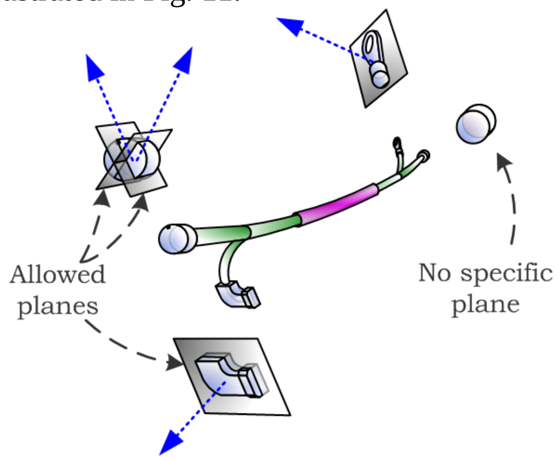

Fig. 11. For each endpoint component, the allowed flattening plane(s) are determined based on component specific rules.

The 2D parameters of connection points connecting multiple bundles (break-out) are

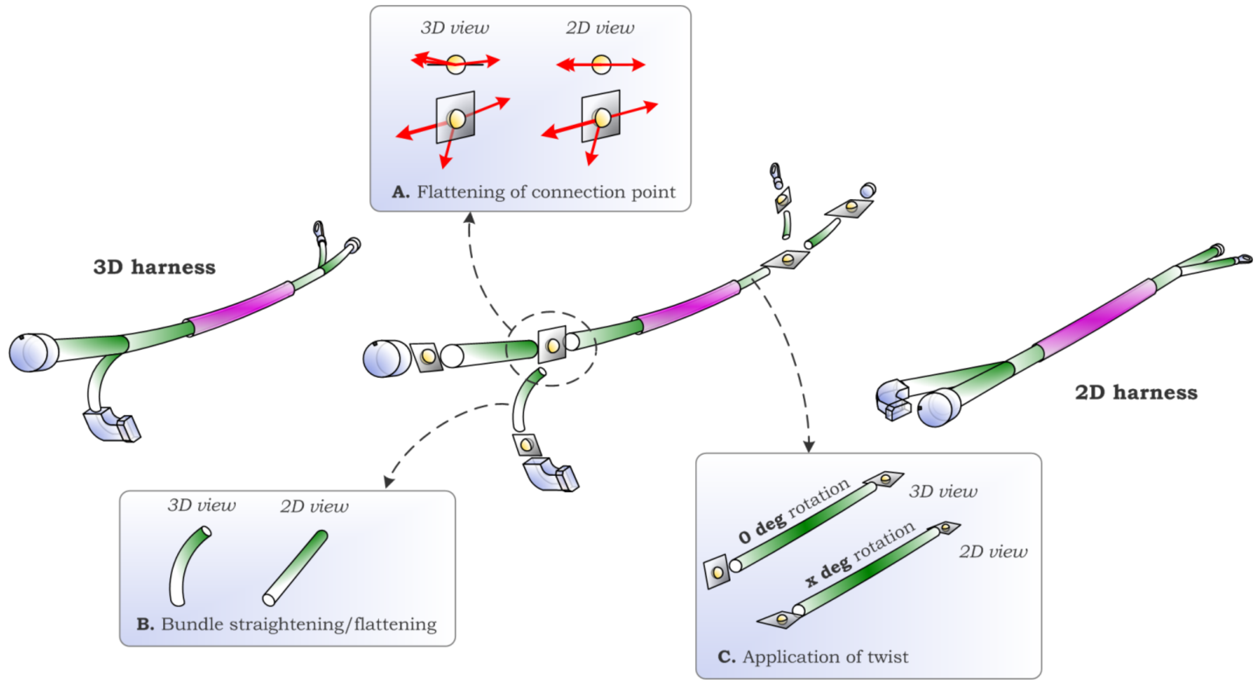

Fig. 12. Schematic illustration of the procedure to generate a 2D wiring harness representation. Each connection point HLP is flattened (A), each bundle HLP is flattened (B) and a twist angle is applied to each bundle (C).

determined by rotating the bundle vectors to their common plane using the smallest possible angle (Fig. 10a).

When allowed, a flat bundle representation is straightened (Fig. 10b). When a bend must be respected, the plane of the bend is determined and the bend is reconstructed based on the in-plane curvature.

In order to transform the wiring harness model completely to 2D, a rotation is applied to align two connection planes (Fig. 10c). The used rotation angle is found as follows: The start plane vector is translated along the bundle centerline without introducing a rotation by applying rotation minimizing frames (RMF) (refer to [18] for details). The angle difference between the translated start vector and the end vector is the rotation angle.

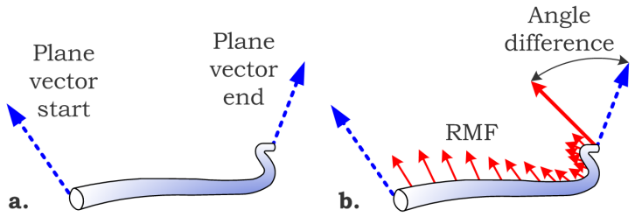

Fig. 13. The plane vectors at each end of a bundle are computed (a) and the effective angle difference between both planes is computed (b).

The result is a flat wiring harness model, independent of a projection plane, as shown in the right part of Fig. 10.

5 Results

This section shows some results from running the KBE tool for wiring harness flattening. First some results from the geometric analyses are presented and finally flat representations are shown.

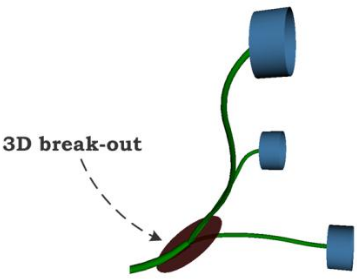

Fig. 14. 3D break-out example

Fig. 14 shows a connection point where some bundles deviate too much from the common plane. This is therefore a 3D break-out and cannot be manufactured on a flat table. The designer is informed by presenting the break-out as a red disc in the 3D model.

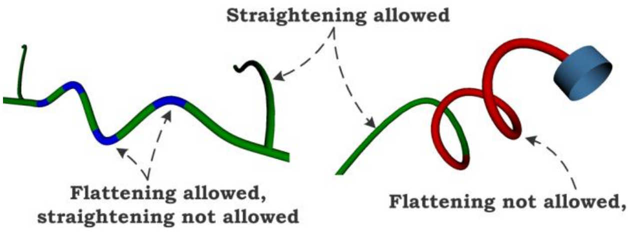

Fig. 15. Bending analysis results examples

Fig. 15 illustrates results from performing bending analyses. Sections that can be straightened are shown in green. When a section cannot be straightened but can be flattened it is a bend that must be respected and it is shown in blue. The red sections indicate that the bundle cannot be flattened at all.

The method presented in section 4.3 has been applied to the wiring harness models shown in Fig. 8. The resulting flat configurations of these harnesses are shown in Fig. 16 and Fig. 17. Note for example the bends that have been respected in Fig. 16.

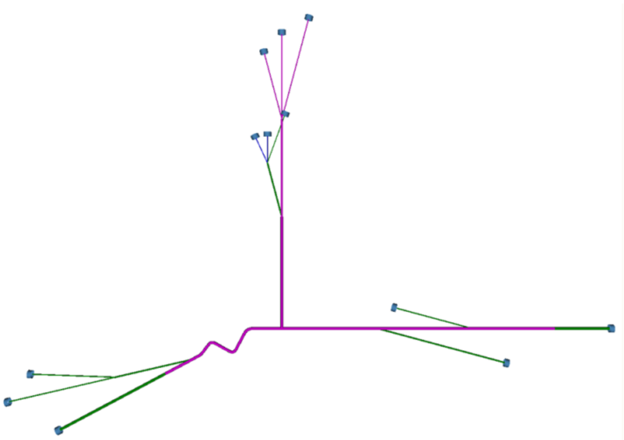

Fig. 16. Example 1: 2D representation of the wiring harness shown in the center of Fig. 8.

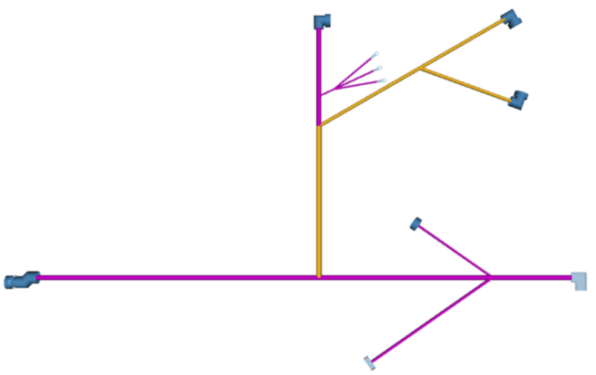

Fig. 17. Example 2: 2D representation of the wiring harness shown in the right part of Fig. 8**.**

The time required to perform the analyses and generate the 2D representation is just a few seconds (using a 2.40GHz Intel Core 2 Duo processor, 4.0 GB of RAM)

These example harnesses are based on real industrial cases, but it must be noted that in practice there is a large variety in complexity. More as well as less complex harnesses exist in practice.

6 Conclusions and future work

A method for flattening a 3D digital wiring harness automatically, based on its physical properties has been implemented using KBE. The tool is able to accept a 3D model from a CAD system and performs a flattening feasibility analysis first. In case problems are identified, their occurrence at a late stage in the manufacturing process can be avoided. Then, based on the results acquired during the analysis, the tool is able to flatten the wiring harness.

The generated application offers specific functionalities that lack in conventional CAD systems. The proposed tool can considerably reduce the amount of repetitive work, while ensuring compliance to physical constraints and manufacturing guidelines.

The generated 2D models still need some rework to make them fit the actual production formboard and to resolve overlapping bundles (as in Fig. 16). This work is not included here and will be presented in a different publication. The flattening method will be further developed to take into account also closed-loop harnesses. These are particularly complex cases but of increasing occurrence, due to the growing number of separation requirements for wiring harnesses. The next critical step concerns the validation of the method with industrial cases where the KBE tool will be operated directly by wiring harness design and manufacturing specialists.

7 Acknowledgements

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