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Identification of Weld Beads in Assemblies of B-Rep Models

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ABSTRACT

Current CAD systems have dedicated functionalities to model weld beads, but it is often cumbersome to use these systems. This study presents a method to analyze the geometry of assemblies of B-Rep models to automatically identify possible welds among the parts using prediction rules. Adjacent faces are detected, and Boolean operators on planar loops are used to identify bead paths. Beads are then split in homogeneous portions based on the topology of the connected parts. The main goals of this study are to increase the speed of the welding definition process and to benefit applications such as the cost estimation of steelwork products. Cost estimates are based on the shape, the length and the dimension of each weld bead. Some industrial examples are presented to show the benefits in terms of time savings and accuracy to the estimation process.

Keywords: weld beads identification, feature recognition, virtual prototyping of welds.

1. INTRODUCTION

The Virtual Prototyping (VP) process of mechanical products is based on solid representations in 3D CAD systems [24]. These representations communicate concepts for new products, are necessary for virtual analyses such as structural simulations and are used to produce production documentation. The main advantages of VP applications are achieved during the product design phase, when several validation analyses can be performed on virtual models without spending time to realize physical mock-ups.

A significant portion of mechanical production involves welding beams and bent metal sheets to form metalworking assemblies. These assemblies include chassis of tractors and earthmoving machines and building structures such as roofs and stairs (Fig. 1). The representation of the parts and how they are assembled often relies on parametric feature-based systems. These systems are consolidated tools used to model 3D geometry. However, it is not a simple process to input weld beads into these systems.

Mid-size commercial CAD packages include functionalities to input welds and represent them through solid volumes or annotations in 3D representations of products. The user usually selects a pair of faces, and the system proposes alternative weld bead shapes to join the faces. The beads are created as associative features for drawings and are taken into account in computations of mass properties of products.

However, many design departments do not model weld beads because of the time required to manually identify beads and select their required options. Therefore, welding operations are only added manually to 2D drafting documentation. This causes important inefficiencies in design and VP processes. First, time is wasted by the manual procedure. Moreover, 3D and draft files lose alignment when product models are revised. Second, the bead definitions cannot be used in further virtual prototyping activities such as structural analysis of the welded joints or cost estimation of the manufacturing process [1,12–14]. These activities require a 3D representation of the beads and their links with the connected parts.

The aim of this study is to present a method to facilitate and accelerate the process of weld bead definition starting from the 3D assembly model of the product. This approach targets assemblies composed of beams and sheet metal parts joined to form chassis, frames and covers. In these cases, all of the contact parts are welded together to increase the stiffness of the group. For other types of products, the parts to be welded must be opportunely selected. Currently, a slightly similar approach that provides different output can be found in FEM systems. The

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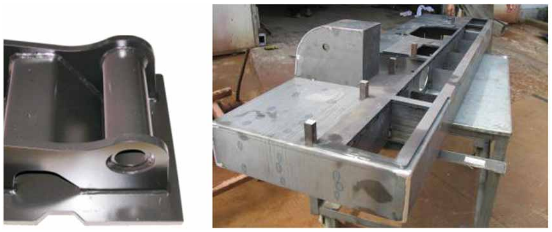

Fig. 1: Examples of parts made of welded metal sheets and beams.

distances of the mesh nodes of parts that are in contact are used to add weld connections and simulate weld joints.

Fig. 2 depicts the proposed virtual prototyping scheme for mechanical products making use of welding processes. This approach aims to close the gap between geometry modeling systems and virtual prototyping systems. Geometric recognition rules are introduced to traverse the product geometry and to identify possible weld beads. Prediction rules are based on the characteristics of the welding process and the actual possibility of geometrically accommodating a bead. The result is given in terms of 3D curves representing the mean axes of the recognized beads and parameters regarding their type, shape and dimension.

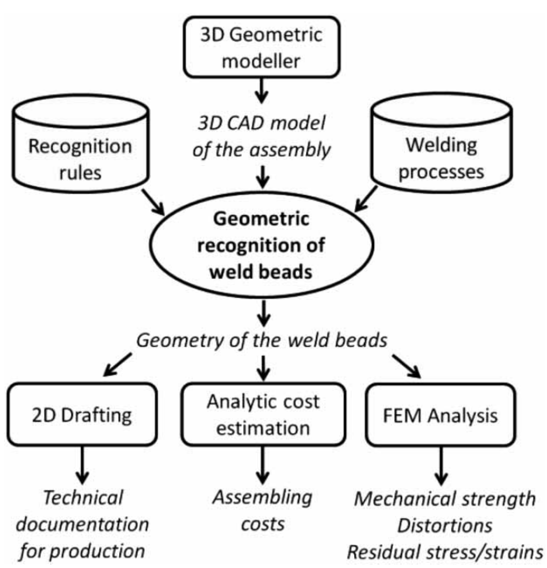

Fig. 2: Examples of parts made of welded metal sheets and beams.

The obtained bead definitions form the input to activities such as drafting, cost estimation of the production process, and analysis of product mechanical behavior using FEM tools. This approach is limited to the welding technologies based on filler material such as arc welding or MIG welding, in the presence or the absence of a flux. In these cases, the possibility of forming welding beads is given by the following geometric conditions (Fig. 3):

- *Corner welding*: The surfaces of the two parts form a corner that is filled with material.
- *Butt welding*: The bead is formed between two aligned parts. Fillets must be prepared on the two parts.
- *Double corner welding*: The parts touch on a corner, and two beads can be formed.

Other technologies, such as resistance welding of sheet metal, do not form beads and are not included in this study.

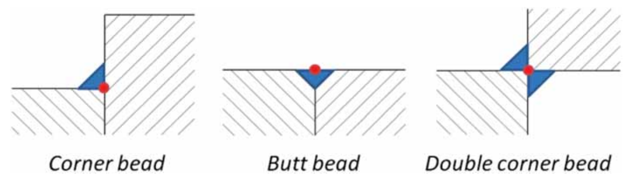

Fig. 3: The geometrical conditions of beads considered by the proposed approach.

This paper describes the proposed method and how its algorithms were implemented. First, a review of the state of the art in virtual prototyping of welding is reported. The proposed approach is described in section 2. The experimental work, which was conducted in collaboration with partner companies, is discussed in section 3. The result of the test activities include the accuracy of the welding recognition process, the quality of the manufacturing cost estimation and the time required to obtain these outputs.

1.1. Virtual Prototyping of Welding in the Design Loop

In current industrial practice, physical mock-ups are used to test the validity of new products. Data for manufacturing times and costs are often measured in trials on the shop floor or by computer simulations. However, CAD models cannot be seamlessly introduced into simulation systems without bead definitions. A robust virtual prototyping of machines should include welding representations and their validation.

FEM analysis is an important method for virtually understanding the effects of the welding process on assemblies. The structural consequences of welded joints are implemented in several software systems. Ma et al. [10] reported on FEM-based welding software packages, such as JWRIAN, QuickWelder and SYSWELD. To facilitate the assessment of the whole assembly, the introduction of all weld beads makes the calculation process comprehensive and not fragmented according to individual joints.

Another field where welding VP can be highly beneficial is Design for Cost (DfC). These methodologies have been studied and formalized since 1985 by Ehrlenspiel [4]. The DfC problem can be defined as the development of methods and tools allowing the designer to calculate costs in the early design phase by managing knowledge of production processes and, hence, associated costs [8]. Accurate cost estimates are crucial to the financial success of manufacturing firms.

The classification of DfC methods as intuitive, analogical, parametric and analytical was introduced by Duverlie et al. [3]. Niazi et al. [15], Roy [19], Rush et al. [20] and Cheung et al. [2] reviewed the state of the art in product cost estimation including qualitative and quantitative techniques. Some of these techniques can be recognized as knowledge-based methods on the basis of the formalization of tacit manufacturing knowledge [21]. Other techniques are variants based on parametric approaches [17] or on case-based reasoning [23]. Many Computer Aided Process Planning systems provide cost analysis, but they cannot be used in the design phase because they require manufacturing information that is not usually available in the early stages of a design process.

In the specific field of welding cost estimation, studies and prototype software systems to manage the welding process from the design phase are discussed in the literature. Chayoukhi et al. [1] proposed and implemented COSTWELD, a cost estimation system focused on welding evaluation. Moropoulos et al. [12,13] implemented CAPABLE software for aggregate process planning. Its CAPABLE/Welding module was developed to support the design and process assessment of complex fabrications including welding. The CAPABLE/Welding module divides the product model into components, i.e., machined mechanical parts, and fabrications such as mechanical parts that contain weld features defining the shape and dimensions of the weld joints. After a CAD plug-in gives the product assembly tree to the CAPABLE/Welding system, the Welding module evaluates the feasibility, the production cost and the lead-time, and recommends the best welding process on the basis of known factory data and a simulated annealing algorithm.

However, this software lacks the capability of automatically recognizing component welds, and the weld dimensions must be defined manually. A tool for cost estimation of weld operations in mechanical assemblages has the same limitations according to Masmoudi et al. [14]. Those authors combined two cost estimation methods, analytic and parametric, and took into account all aspects that are involved in the welding process. However, data are manually input, and results are too onerous to be obtained for assemblies that have 10 components.

In conclusion, the accuracy of the prediction system is a fundamental aspect, but the data input phase is equally critical for the user. It is necessary to introduce automation to facilitate welded assembly VP assessment (costs, structural resistance, rendering) and to limit risks associated with redesign loops and waste of time and money.

2. APPROACH

In this study, a method based on CAD models of assemblies is used to analyze products and automatically identify possible welds among the parts. Then, the obtained solution can be manually refined in a short period of time.

This approach requires that the geometry of a product is represented as in a traditional 3D CAD system for solid modeling in the field of mechanics (Fig. 4). The product model assembly is formed by a tree of documents representing components or sub-assemblies. An assembly document contains references to other child documents and their relative orientations with respect to the assembly document. A child can be either a part or an assembly.

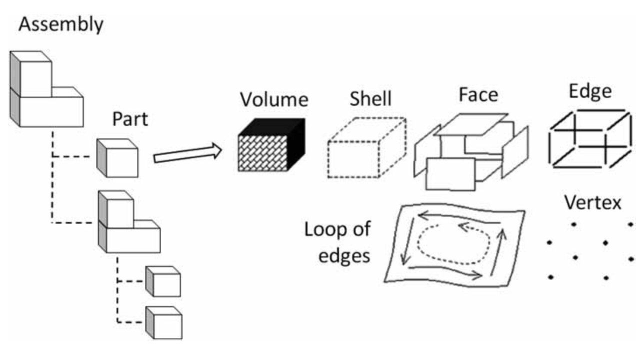

Fig. 4: Representation of the solid geometry of the product is the basis of the proposed approach.

A part document contains solid bodies represented by their boundary faces and edges. The solid volume representation is given by the traditional B-Rep scheme. The product is expected to be a hierarchical assembly of solid bodies bound by faces. Each face is delimited by inner and outer loops, formed by edges that are shared with adjacent faces.

Modeling features are therefore neglected. The geometry is not linked to a particular modeling strategy and can be read from standard solid formats (STEP, Acis, Parasolid). This choice is justified by the intrinsic difference between design and manufacturing features [11]. Indeed, most feature recognition applications target the machining domain [7] and are not beneficial in the context of welding bead recognition.

2.1. Steps in the Bead Recognition Process

Hint-based geometric reasoning is the basis for many feature recognition approaches in the literature [7]. The *hint* is a rule that expresses the trace of a searched pattern in the solid geometry.

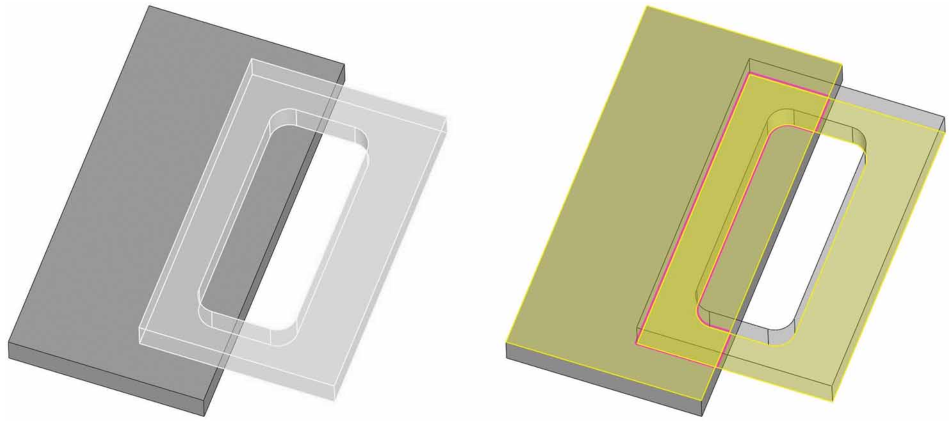

Fig. 5: Example of two plates to be welded. On the right, the pair of faces in contact are highlighted in yellow, and the possible weld beads are shown in purple.

Two hints are introduced to identify possible beads and characterize whether the part geometry is sheet metal.

Hint1: *Weld beads are generated by edges of pairs of faces in contact. In particular, they are given by boundaries of the two-dimensional domain resulting from the intersection of the loops of the two faces of the pair (Fig. 5).*

Hint2: *Sheet metal parts are formed by trimming and bending a foil of constant thickness. Therefore, sheet metal parts are characterized by the presence of recurrent pairs of parallel faces at a constant distance, i.e., the thickness of the foil.*

The characterization of a part as sheet metal can make distinctions among the obtained beads and attach additional attributes such as thickness.

Given these two assumptions, the algorithm is based on the following steps:

1. *Selection of components* where beads are to be searched. Given an input assembly at any level of the product, a list of solid parts is produced from the product tree structure. Parts not to be welded are excluded at this stage.
2. *Analysis of the parts* to recognize sheet metal components from the presence of recurrent pairs of cylindrical and planar faces with opposite normals and positioned at a reciprocal fixed distance, i.e., the thickness of the sheet metal.
3. *Search for contact face pairs*. Pairs formed by the possible combinations of the selected parts are tested to identify contact faces, i.e., planar or cylindrical faces with opposite normals and null distance.
4. *Boolean intersection of the loops of the face pairs*. For each pair of contact faces, the planar domains of the parametric spaces are considered. The Boolean intersection of these planar regions [16] is computed to use the borders of the resulting areas as weld bead sources. Borders are subdivided on the basis of ownership by one or the other connected part, allowing the distinction between corner and butt beads.
5. *Bead extraction and properties computation*. Beads are then split in homogeneous portions based on the classification of the faces of the identified sheet metal parts. The geometrical analysis of the connected parts also allows a bead to be characterized in terms of thickness, type, length and accessibility.

Each step is described below in more detail.

2.1.1. *Selection of components to be welded*

An assembly consists of parts to be welded or joined by other means, such as screws. Assembly models of products may contain subassemblies to be welded together. Any assembly model in the product structure can provide input for the recognition process.

First, the user chooses an assembly for analysis. Then, the iteration proceeds to the child subassemblies. Two options are available:

- Only parts belonging to the same level are searched. A component of a subassembly can only be welded to another component of the same subassembly.
- The hierarchy of the assembly is flattened. All components at the various levels are considered.

A list of models to be excluded from the process can be supplied. An effective means of exclusion can be the part material. This process can ignore plastic or rubber parts as well as other nonwelded components. The final output of this step is a list of components wherein weld beads are searched.

2.1.2. Analysis of sheet metal parts

Sheet metal parts are primarily employed in welded assemblies and are formed by bending a trimmed foil of constant thickness. The geometrical peculiarity of these parts is the possibility of distinguishing between a front and a back surface. An example is shown in Fig. 6.

The welding recognition process includes the ability to distinguish between beads that are connected to the front side versus the back side of a sheet. This distinction provides a means to classify and exclude unwanted beads.

The identification of sheet metal parts is based on the analysis of the component face set. At first, plane faces are selected to identify pairs of faces with opposite normals and constant separation. The same search is carried out on cylindrical pairs of faces. If more than three pairs are found, then the part is recognized as sheet metal; otherwise, it is discarded from further analysis.

The front face set is identified by starting from the plane face with the maximum area. The set is populated with faces that are connected through smooth edges, i.e., edges forming a solid angle of 180 degrees [9]. The back set is formed in an analogous way by starting from the face that is opposite the maximum area face. The front is identified as containing the larger number of convex cylindrical faces, and the front set is recognized as the external side of the part. If necessary, the front and back sets are exchanged.

The faces that are not identified in front or back sets are marked as "thickness" (Fig. 6). These are border faces belonging to trimmed contours.

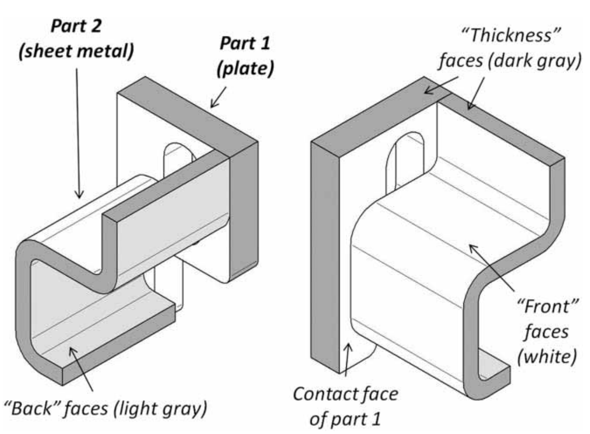

Fig. 6: A pair of test parts in contact: a trimmed plate (Part 1) and a bent sheet metal (Part 2).

2.1.3. Search for pairs of faces in contact

A pair of faces in contact is formed by two faces belonging to distinct components and sharing the same geometrical definition but opposite orientation of their two normals.

Each component is defined in its own reference system. When arranged in an assembly, components are positioned through 4x4 matrices that express their orientation relative to the parent assembly. To determine the relative orientation of faces of distinct components in a consistent reference system, the global orientation matrix of each part is computed. The global orientation is obtained iteratively by pre-multiplying the orientation of a part by the orientation of the parent assembly until the global reference system is reached.

The geometrical definitions of the components are then expressed and compared in the global reference system. Geometrical definition refers to the analytical representation of the underlying face. This face can be a plane, a cylinder or a tabulated surface, which is a surface obtained from the linear extrusion of a generic profile.

The following conditions identify valid pairs of faces:

- *Pair of planar faces*: a point on one face must lie on the other face; the surface normals must be opposite.
- *Pair of cylindrical faces*: the axes must have the same or opposite direction; a point of one axis must lie on the other axis; the two cylinder radii must be equal and the surface normals opposite.
- *Pair of tabulated faces*: extrusion must have the same or opposite direction; the two profiles must be coincident.

Given the list of n selected components, the number of possible combinations is $n^*(n-1)/2$. The number of contact face pairs for each component pair can be 0, 1 or more than one. The list of contact face pairs concludes the third step of this approach.

2.1.4. Boolean intersection of the loops of the face pairs

The process of extracting weld beads is iterated for each face pair identified in the previous step. Each of the two faces of a pair has boundary loops of edges that are processed to identify weld beads.

The parameters space of the first face of the pair is used as a common 2D working space. The 2D representation of the edges of the loops in this parameter space is straightforward. However, the edges of the second face are expressed in the coordinate system of the first part, and then the transformed edges of the loops of the second face are projected in the parameter space of the first part.

In the parameter domain, the loops of the two faces describe two overlapping connected domains. If no overlap occurs, no beads can be identified and the face pair is skipped.

In the literature, approaches based on simplician chains are used to compute planar Boolean domains

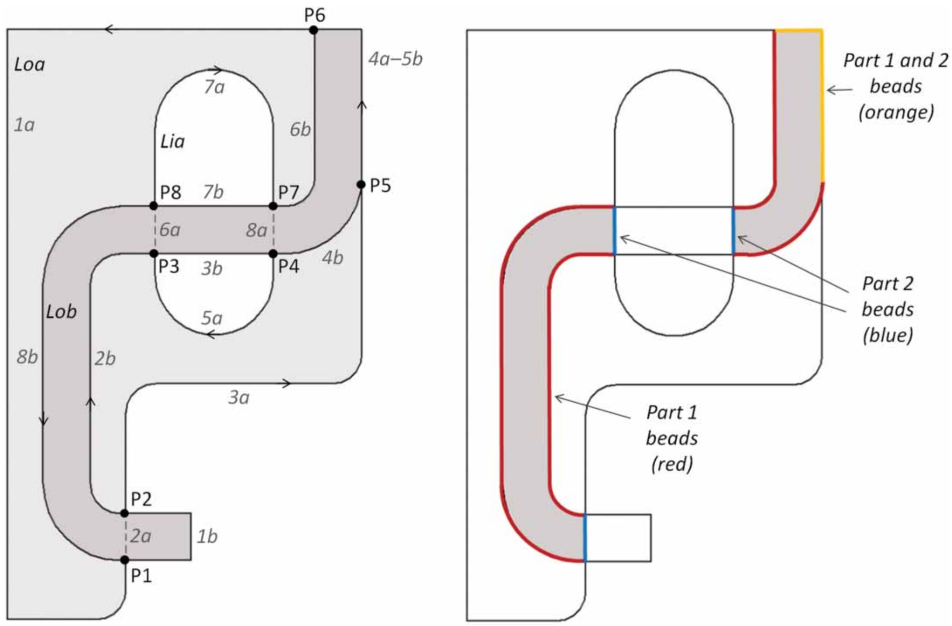

Fig. 7: Extraction of the welding beads for the example presented in Fig. 6: the algorithm for the Boolean intersection of the planar domain of the contact faces.

[5,18]. An extension of this traditional approach was recently developed by Peng et al. [16].

In this study, the proposed algorithm follows similar reasoning and is based on the following steps:

- First, the loops of the two parts are expressed as polylines, i.e., an ordered set of points. The polylines are computed within an assigned tolerance value. The loops are projected on the parameter space of the face of the first part. In Fig. 7, *Loa* and *Lia* are the outer and inner loops of Part 1, respectively, while *Lob* is the outer loop of the sheet metal Part 2;
- The loops of the first face are intersected with the loops of the second face. The resulting points (*P1, P2,..., P8*) divide each loop into portions;
- The loop portions are given an attribute of *ownership* to a loop of the first face (*1a, 2a, ..., 8a*) or the second face (*1b, 2b, ..., 8b*);
- The loop portions are further classified as *inner*, *outer* or *border*. The first loop type refers to portions that lie inside the domain of the other face (*2a, 6a, 8a, 2b, 4b, 6b, 8b*). *Outer* loop portions refer to the opposite situation (*1a, 3a, 5a, 7a, 1b, 3b, 7b*). *Border* loop portions are those that overlap ($4a, 5b$). This classification is evaluated by taking an inner point of the loop portion, such as the midpoint, and evaluating whether it is inside or outside the desired planar domain;
- The loop portions delimiting the Boolean intersection of the face domains are of the *inner* or *border* type. These loop portions determine the outline of the weld beads.

The result of the intersection of the planar domains is reported on the right of Fig. 7. The boundary curves of the intersection domains represent the whole set of possible welding beads that are expected to connect the two faces.

2.1.5. *Bead extraction and property computation*

In this final stage, these loops are segmented in portions that are then labeled with attributes. Three attributes are computed: the *contact condition*, the *sheet metal side*, and the *bead thickness*.

The first attribute, the *contact condition* of the two parts, results in three types, as depicted in Fig. 3: *corner*, *double corner* and *butt*.

The *ownership attribute* allows the contact condition to be recognized as follows:

- *Corner:* The bead is defined as a portion of a loop polyline whose points belong to the edges of only one part. For example, *2a, 2b, 6a, 8b, 8a, 4b, 6b* are corner beads.
- *Double corner:* The bead is defined as a portion of a polyline whose points belong to edges of two connected parts. The edges of one part are oriented opposite the edges of the other part. This condition generates two opposite corner beads that share the same edge.
- *Butt:* The bead is defined as a portion of a polyline whose points belong to edges of both connected parts. The edges of one part are oriented parallel to the edges of the other part and in the same directionality, e.g., the $4a$-$5b$ loop portion.

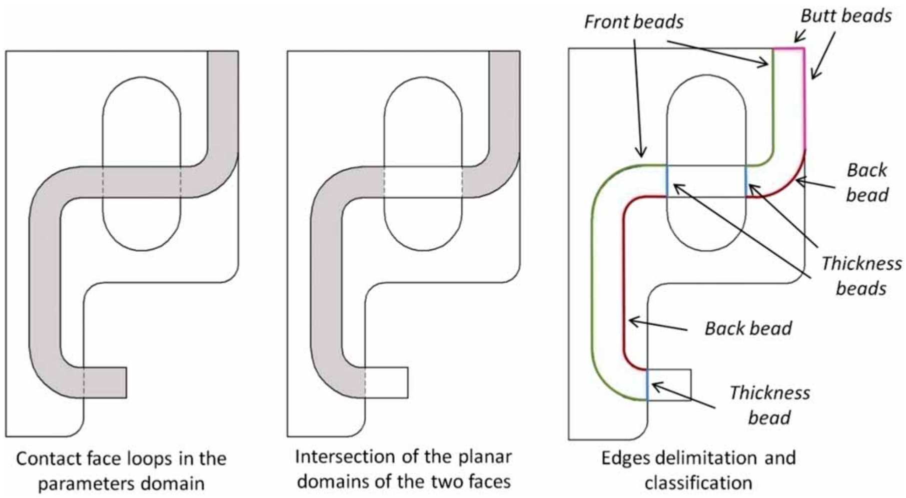

Fig. 8: Subdivision of extracted beads on the basis of the topology of the sheet metal part.

The second attribute applies when at least one of the two connected parts has been identified as sheet metal and the bead is a corner type. In this case, the bead can be further marked as *front, back* or *thickness*. A corner bead lies on an edge that connects one side face to one of the faces of the contact pair. The type of the side connected face determines the bead type. Fig. 8 highlights these portions in different colors.

Finally a third numerical attribute can be estimated for a bead, which is its thickness. Unless it is derived from considerations on the basis of stress level, the transverse dimension of a bead is typically related to the thickness of the two connected parts. The following rule is employed:

$$t_{bead} = k \cdot min(t_1, t_2) \tag{1}$$

where t_{bead} is the bead thickness, t_1 and t_2 are the thicknesses of the two parts and k a constant value, which is usually equal to 0.7. If the first or the second part has been recognized as sheet metal, then t_1 or t_2 or both are known, and the bead thickness can be computed. Otherwise, a default thickness value is used.

3. SYSTEM IMPLEMENTATION AND TEST CASES

The approach proposed in this study was implemented in a software tool, LeanCOST® (by Hyperlean Srl, Ancona, Italy), for estimating manufacturing costs. The system was conceived for use by designers during the embodiment phase to evaluate the manufacturing cost of the product under development. The estimation process starts with a 3D CAD model of a component or assembly and proceeds with cost estimation wizards based on manufacturing feature recognizers (for sheet metal, carpentry, and chip forming operations) [6]. A specific module for welding bead recognition was developed and integrated in LeanCOST® for evaluation and to assess the method described in this paper. The remainder of the LeanCOST® architecture provided functionalities for reading CAD models, visualization, user interaction, data management and other manufacturing cost computations.

Fig. 9 depicts the interface of the prototype module used to test the weld bead recognition algorithm. On the left-hand side of the interface, the recognized beads are listed with attributes such as the length, the geometrical condition and the sheet metal side. On the right-hand side, there are some functionalities and options to refine the search for weld beads.

It is possible to include or exclude beads generated from inner loops. This option can automatically eliminate bead definitions created from edges of holes or slots. For example, beads identified by portions 6*a* and 8*a* (see Figs. 7 and 9) may be neglected in actual design applications.

In addition, the distinction between *front*, *back* and *thickness* beads helps to avoid considering double of the required length in some models including sheet metal parts. In fact, a piece of sheet metal may be welded only one side because its other side is not accessible or its load does not require a weld. Therefore, this software includes a dedicated functionality to select beads on the basis of the sheet metal side. Finally, it is possible to discard short beads below a threshold length.

3.1. Description of the Validation Program

Actual test cases were evaluated for the following reasons:

- to assess the reliability of the algorithm and the heuristic rules. In particular, contour loops of contact areas among components

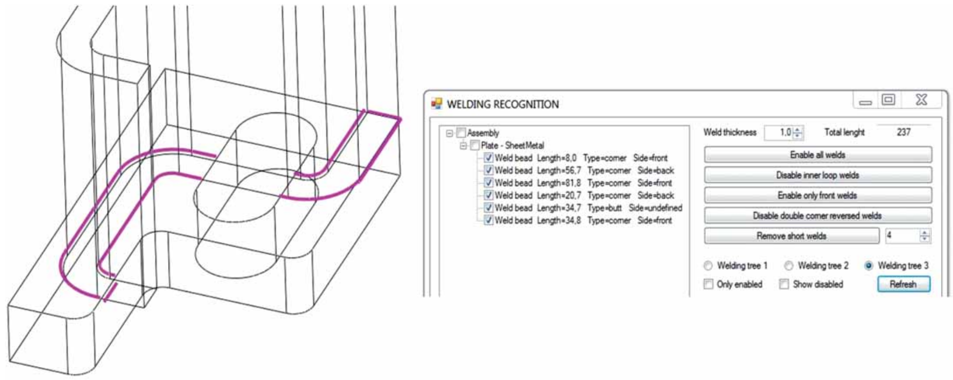

Fig. 9: Implementation of the weld bead recognition algorithm. This figure illustrates the example used in the previous section and the software functionalities.

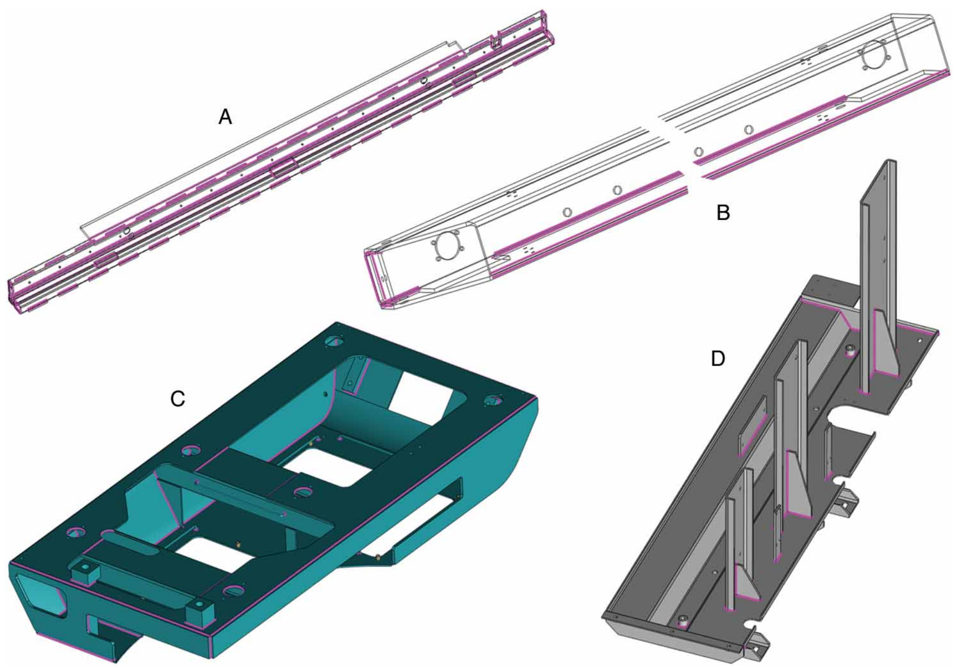

Fig. 10: Examples of analyzed test cases with recognized weld beads: groups of a woodworking machine (A) and earthmoving machines (B, C, D).

were evaluated as correct sources of welding beads. Hence, bead characteristics were checked against design specifications (type, contact condition, dimension, length, ...);

- to measure the time saved during realization of a comprehensive virtual product prototype, including 3D modeling, weld bead definition, early manufacturing cost estimation and 2D drafting execution;
- to evaluate the reliability of the manufacturing cost estimation algorithms.

The experimental program focused on woodworking and earthmoving machines. These products are characterized by welded groups consisting of tens to hundreds of sheet metal parts and beams joined together by welding (Fig. 10). These products fit the scope of the present approach because they are characterized by dozens of meters of weld beads and their manufacturing cost determination is very time consuming.

A dozen designers were involved in a three month evaluation. They were divided into two groups with the same number of people in each group. The first group proceeded with the traditional design approach. They manually defined weld beads using standard functionalities provided by the 3D CAD system. The cost estimation was performed manually by computing the total length of the weld beads, the execution time and the relative cost with the help of a spreadsheet. Such data were recorded as reference results.

The second group of designers experimented with the LeanCOST® software integrating the weld beads module. The VP phase was performed thanks to the extraction of weld beads and their attributes. In the validation activity all the beads recognized by the system were taken in to account. The welding cost was then estimated using the algorithm presented above, where the input comes directly from the recognized weld bead data.

In the real usage, the user may obviously edit the obtained results to come to the same output as in the manual approach. This is accomplished in little time since the major work has been accomplished by the software. This step includes the input of additional data prescribed by the normative, such as the welding surface shape. Even if the time for this phase is not part of the validation, it has been also annotated.

3.2. Results and Discussion

The testing phase was performed on approximately 50 product subassemblies with different numbers of components and geometrical arrangements. Two examples (labeled A and B in Fig. 10) were selected as significant examples of the strengths and limitations of this approach (Tab. 1).

Assembly A consisted of 14 types of components, 2 hollow beams and 12 sheet metal parts. This assembly included multiples of these components and a total of 70 parts. It was characterized by a total of approximately 65 meters of welding. The other example, B, is a smaller assembly that consists of 3 types of sheet metal parts and approximately 10 meters of welding.

Tab. 1 reports data as they come from the automatism and does not include manual corrections of the recognized beads. However, after the results were recorded, the designer proceeded to switch on and off beads or to correct the default computed thickness in the system on the basis of structural considerations. The time for this phase, that is obtaining the same result as in the manual approach, has been reported in the table by a separate row.

The time saved during the virtual prototyping phase was obtained mostly from the automatic versus the manual selection of welded edges. In the traditional approach, the user identifies weld beads by isolating welded components and hiding components that obstruct views of welds. This manual activity is time consuming and entails the risk of omitting weld beads in complex assemblies of many component parts.

Moreover, in the automatic approach, weld bead thicknesses are derived from welded component thicknesses. This simplification saves time because it is not necessary to know and enter the thickness of the joined parts in the software.

Faster production cost estimates are another time-saving advantage of the new software. A spreadsheet was used to make a side-by-side comparison between manually entering weld beads in traditional software and using LeanCOST® software, which gave the same result in much less time. Ultimately, automation significantly reduced the duration of the cost estimation activity.

A second important result was the difference between weld bead lengths that were recognized automatically and measured weld bead lengths that were input manually on the basis of designed experience. The two test cases highlighted opposite results.

		TEST CASE A		***TEST CASE B***	
		Spread sheet	*LeanCOST® & Welding module*	*Spread sheet*	*LeanCOST® & Welding module*
Time saved during the design phase	*3D Virtual prototyping [min]*	15	5 *(-67%)*	2.5	1 *(-60%)*
	Manufacturing cost estimation [min]	28	8 *(-71%)*	15	4 *(-73%)*
	Time to correct erroneous data [min]		2		0.5
Reliability of the welding recognition algorithms	*Total weld bead length [mm]*	64900	65711 *(+1%)*	9881	18082 *(+83%)*
	Bead thickness error [%]	-	*17%*	-	*12%*
Reliability of the welding cost estimation algorithms	*Welding cost [€]*	148	171.3 *(+15.7%)*	26.8	47.3 *(+76.5%)*
	Total cost [€]	1300	1376 *(+5.8%)*	181	195.5 *(+8%)*

Tab. 1: Results from the validation program for two significant test cases.

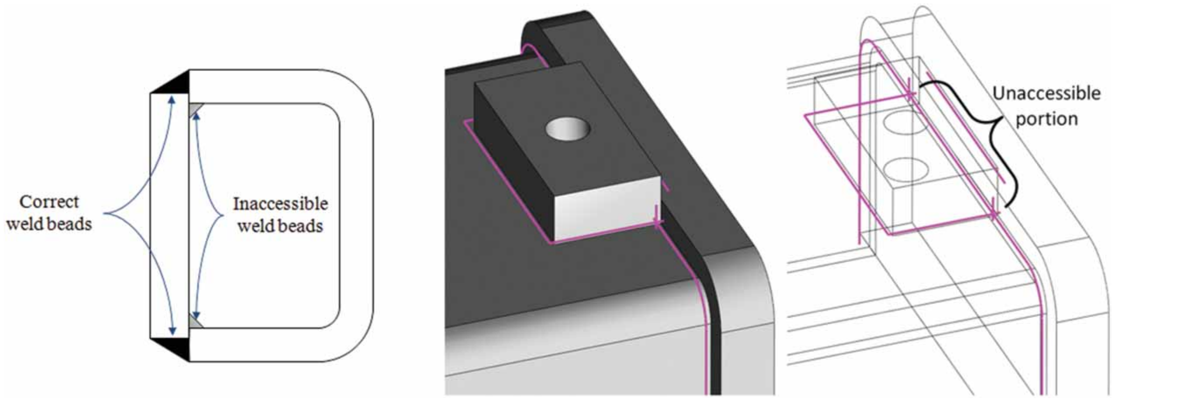

Fig. 11: Two examples of accessibility limitations that cause recognition errors. On the left, geometrical obstructions make it impossible to reach some weld beads. On the right, the bead overlaps other solid parts.

For product A, the difference was negligible because the algorithm accurately reproduced the weld bead lengths provided by the designer. However, there was an unacceptable deviation of 83% between automatic and actual weld bead lengths in test case B.

The source of error in automatic weld bead lengths was identified as an accessibility issue regarding the bead position. Fig. 11 highlights two examples of this problem. In one case, a C-shaped sheet metal part is in contact with a plate. The proposed approach identifies external and internal contact faces. However, the internal faces lead to incorrect identification of weld beads because it is not possible to reach the edge to add a weld. In the other case, the identified bead overlaps another component, and the weld bead length should be delimited to the allowable portions of the components.

Apart from this case, the effectiveness of the algorithm is demonstrated by the results for the deviations between automatic and manual weld bead lengths for test case A and many similar examples. As mentioned before, the results in the Tab. 1 refer to recognition algorithm outcomes that were obtained using default options and without manual adjustments. In the real usage, the system user can easily select and switch on or off each recognized bead to rapidly refine the result.

Errors in weld bead thickness recognition were evaluated by the following equation:

$$Error[\%] = \frac{1}{N} \cdot \sum_{i=1}^{N} \frac{|RT - AT|}{AT} \cdot 100 \qquad (2)$$

where:
N is the number of weld beads
RT (Recognized Thickness) is the thickness of the *i-th* weld bead, recognized automatically by the proposed algorithms;
AT (Actual Thickness) is the actual thickness of the *i-th* weld bead, defined by the designer.

The error in the thickness recognition is mainly due to the application of a very basic rule of dimensioning the bead. The correct values of the thickness are drawn by the designer experience or from some structural analyses on the whole product. Such considerations goes beyond the scope of the proposed approach.

Finally, the cost estimation phase included two highlights: the pure welding cost and the total assembly cost. In the first case, the error strictly depended on recognition of weld beads. In the second case, this dependence on weld beads was mitigated by additional costs for raw materials and manufacturing operations. Errors in the cost of test case B partially depended on erroneous bead recognition.

4. CONCLUSIONS

Welding is widely used to join sheet metal parts and beams to fabricate many industrial products. Current CAD systems contain functionalities to define weld beads and their attributes. However, it is cumbersome to apply these CAD programs to large assemblies because it is necessary to identify every welded contact and manually enter the required bead geometries and attributes in the software. Moreover, identifying and entering this information in the software considerably increases the risk of errors in the detailing phase of the project as well as the virtual prototyping activities.

In this study, a new approach was implemented in a software system to automatically recognize weld beads from edge loops on contact faces of an assembly model. This automated system was evaluated in collaboration with partner companies. Data were gathered and used to compare the new tool with traditional CAD functionalities.

The main outcome of this study was that the new software significantly reduced the effort needed to define a virtual product prototype including weld bead definitions. Moreover, the new approach reduced errors in the manufacturing documentation (drafting with welding annotations) and decreased the number of model revisions that were required.

However, some limitations with this new approach emerged. It is necessary to improve the recognition algorithm in cases where the weld bead cannot be manufactured, as shown in the previous section. The approach should include a test on bead accessibility based on additional geometrical considerations.

Finally, it would be useful to modify the software to provide greater user interactivity, allowing the user to easily input attributes that cannot be derived from geometrical considerations. This modification will improve the usability and effectiveness of the system.

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