Title:
An Analytical Cost Estimation Approach for Generic Sheet Metal 3D Models

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Introduction and related works:
Global competition forces industrial companies to monitor production costs already during the early design process [11]. Design to Cost (DtC) and cost estimation are becoming key design activities to pursue the most convenient production strategy and thus to guarantee producibility and economic sustainability for new products [7].

In the context of sheet metal stamped components, largely used in several industrial sectors (e.g. automotive, household appliances), the estimation of production costs is mostly based on the formalization and reuse of the company past experiences. Literature studies about this topic are grounded on knowledge-based methods [9], cased-based reasoning approaches [3], or even artificial intelligence and neural networks [10]. Generally, all these methods are not sufficiently accurate and reliable, require the availability of huge amounts of data to be opportunely classified, and strictly depend from the application context (i.e. the knowledge gathered in a company is usually not reusable in other companies). An analytical cost estimation approach seems to be the most interesting solution to solve the abovementioned issues. This method consists in determining the economic value of a product by considering the manufacturing process for transforming the raw in the final product. This approach allows designers to easily find economical criticalities of a product and evaluate how its features (i.e.: material, dimension and shape) impact on the manufacturing cost.

An analytical cost estimation approach requires the definition of technological parameters (e.g. die dimension and typology, stamping sequence, press parameters), as well as the identification of relevant product features (e.g. blank shape and dimensions, embossing, louvers, tolerances). Feature recognition algorithms aim to recognize aggregate of entities from standard 3D models to support the process and assembly planning [2]. In the context of sheet metal components, one of the most complex and interesting topic regards the surface flattening and the recognition of features from freeform surface CAD models [1][8]. Literature studies, focused on the generation of 2D flat patterns from triangulated 3D surfaces, mainly include: (i) physically based methods [12], (ii) methods based on energy model [5][6], and (iii) methods using mass-spring model [4].

This paper wants to integrate the above-mentioned state of the art by defining a systematic workflow for calculating the production cost of sheet metal stamped components. The proposed analytical cost estimation approach is based on the information extracted from the 3D CAD model with feature recognition techniques. This approach allows the recognition of relevant geometrical parameters needed for the successive calculation of technological parameters, and, finally, for the estimation of costs related to raw materials, stamping process, accessory processes, setup and tooling. The cost estimation method potentially represents a useful tool to quantitatively compare design alternatives and guide the decision-making process toward a reduction of production costs.

Method:
The proposed cost estimation approach consists of two steps. Firstly, it analyses the 3D CAD model to extract product related features (i.e. tolerances, roughness, dimensions, undercuts) and the sheet metal blank. Secondly, it allows assessing the stamping process related parameters and cost.

Sheet metal blank calculation
The main geometric driver for stamping a sheet metal part is represented by the blank piece, namely the portion of the flatten sheet, which is the starting point of the folding or stamping process.

In cost estimation tasks, the blank geometry is obtained by using a reverse engineering approach, starting from the 3D shape of the final product. Depending on the manufacturing process, a sheet metal 3D model may consist or not of only developable faces, i.e. planes, cylinders, cones. A face is considered developable if it is linear at least along one direction. Non-developable faces are manufactured allowing a certain degree of deformation, which will produce local changes in the sheet metal thickness because of stretching or accumulation of material.

Hereunder the steps required for the geometry analysis process:

- Subdivision of the model faces in three groups, namely the *front skin*, the *back skin* and the *border faces*. Such separation is based on the smoothness properties of the connection between faces belonging to the same skin. Moreover, faces of the front skin are mapped to corresponding faces of the back skin, by means of pairs of opposite faces, which are separated by a constant distance, i.e. the thickness of the part.
- Flattening of the front, or back, skin faces to a plane. This step requires the combination of several algorithms, including analytical formulas for cylinders or cones, planar projection, projection in the parameters spaces or progressive mesh facets flattening as in [6]. A spring-based relaxation process follows to ensure the minimization of the deformation energy.
- Definition of a flattening graph from the adjacency information of the skin faces. Only the major cluster of connected developable faces composes a sub-graph.
- Alignment of the flattened faces, following the topology of the original model, and joining to build the final shape of the blank. A further relaxation is required to stretch the flatten faces and match their borders.

The main geometric parameters provided by the blank are:

- *Sizes*: width and length of the blank bounding box;
- *Thickness*: distance between the front skin and the back-skin faces. For representation simplicity, usually, the blank thickness is assumed as the same of the 3D model;
- *Perimeters*: length of the outer and inner contours. These parameters directly influence the time or force required to cut the blank borders from the raw material (e.g.: coil, rectangular sheet metal, etc.);
- *Stamping area*: area of the front skin. This parameter directly influences the stamping force;
- *Step distance*: distance between two adjacent parts in the stamping process (see next paragraphs).

The geometry analysis process allows to also recognize local deformation features, defined as clusters of non-developable faces surrounded by developable faces. An algorithm has been developed to propagate among such clusters and identify features representing local deformations, such as louvres, dimples, ribs or darts.

Cost estimation approach
An analytical cost estimation approach aims to calculate the following manufacturing cost items:

- *Raw material*: cost of the raw material used to realize the product or its components. It considers scraps, such as internal cutouts, irregular external shape (*BlankMaterialCost*) and potential revenues from them (*ScrapValue*). Coil, band, rectangular or shaped sheet metal are typical shapes of raw material.
    - Raw*MaterialCost = BlankMaterialCost – ScrapValue*;
    - *BlankMaterialCost=BlankWidth * BlankLength * BlanckThickness * Density * UnitaryCost*
    - *ScrapValue = (BlankWidth * BlankLength * BlanckThickness – ComponentVolume) * Density * UnitaryCost * ScrapRecoveryPercent / 100*
    - *ComponentVolume = Stamping area * BlanckThickness*

- *Stamping process*: cost for transforming a blank in the final product. This is the cost related to the direct stamping phase of the press, which accounts two terms: (i) *MachineCost* (energy consumption, consumable, overhead and depreciation and (ii) *OperatorCost.* The cost of each stamped part depends by the number of cavities of the die.
  - *StampingProcessCost = (MachineCost + OperatorCost) / CavitiesQuantity*
  - *MachineCost = Time * MachineUnitaryCost*
  - *OperatorCost = Time * OperatorUnitaryCost / 60 * OperatorCommitment / 100*
  - *Time = 1 / StampingRate*
- *Accessory processes*: cost for the collateral operations, coil load/unload (*LoadingTime*) and die maintenance (*MaintenanceTime*).
  - *AccessoryCost = (LoadingTime + MaintenanceTime) * MachineUnitaryCost*
  - *LoadingTime = UnitaryLoadTime * StockNumber / BatchQuantity*
  - *MaintenanceTime = MaintenanceUnitaryTime * StationsNumber * BatchQuantity / DieLife*
- *Setup*: cost for preparing the press before starting the production (e.g. die load/unload, coil and blanks first load);
- *Tooling*: cost of the die. This cost item is beyond the scope of this work (this is a capital expenditure).

The stamping process differs a lot according to the production volume, blank shape, piece dimensions and other piece related parameters (e.g. presence of undercuts, surface finish). Moreover, the way the blanks move within the die, determines two different stamping approaches: progressive or transfer. In addition, the raw material changes considerably with the part shape. According to the blank shape, piece dimensions and presence of undercuts, four different types or raw materials could be considered: (i) a band (rectangular blank manually moved by the operator within the press), (ii) a coil (continuous stamping process), (iii) a rectangular blank (discrete stamping process), and (iv) a shaped blank (blank with a perimeter shaped with other cutting processes, such as laser).

The stamping process cost calculation approach essentially consists in combining:

- Product related information (e.g. shape, dimensions, tolerances, surface finish);
- Feature recognition algorithms for extracting, production features from the 3D virtual model;
- Cost models and routings with the knowledge required for converting product features in process information and cost;
- Database of process related information (e.g. presses and related parameters, coils, sheet metals, materials and related parameters)

The workflow for the process calculation, described in Fig. 1, begins from the product and production related information. The first step aims to identify the sheet metal blank from the 3D virtual model of the component. This step is necessary for defining the relevant features that, otherwise, are difficult to manually extract from a 3D CAD model. The workflow proceeds with the definition of the production technology and raw material, which are fundamental for calculating the stamping sequence and the related cost. The process is also influenced by the press used for stamping the blank. The selection is performed considering the stamping force, die and related characteristics (e.g.: dimensions, stroke, clearance, weight). The stamping rate is then conservatively calculated considering the maximum stamping rate of the press, the stamping rate that generates a deformation rate less than the threshold admitted by the material, the dimensions of the die, its level of wear and any difficulties in its lubrication. The effective stamping rate, the number of cavities and the hourly rate of the press (e.g. labour, energy, depreciation, consumable and maintenance) determine the stamping cost for each piece. The workflow for calculating the cost of the raw material, accessory processes, setup and tooling will be described in the full paper.

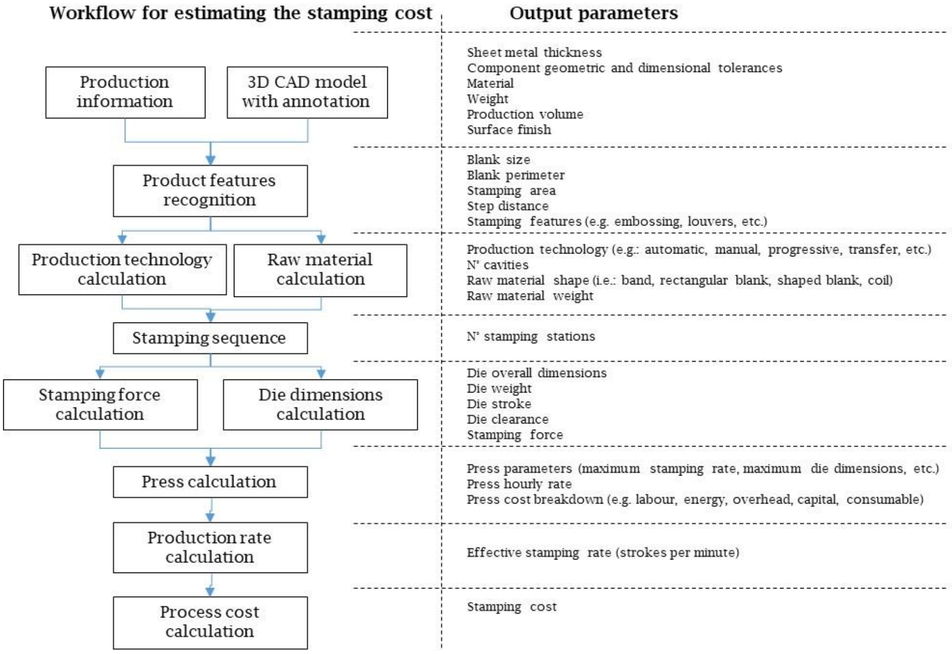


Fig. 1: workflow for estimating the stamping cost.

Case studies and results discussion:

The proposed approach has been adopted for the estimation of several sheet metal parts to test the effectiveness and the reliability of the developed algorithms. The testing phase has been performed in cooperation with different manufacturers of sheet metal parts with the aim to have a robust feedback about the obtained results. Fig. 2 shows the cost breakdown of three sheet metal components with different features and different complexity degrees.

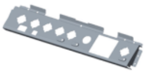
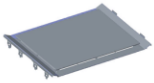
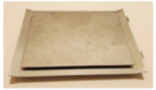
	Component #1		Component #2		Component #3	
	Estimated	Manufactured	Estimated	Manufactured	Estimated	Manufactured
						
Material cost [€]	0.014	0.013	0.403	0.399	2.013	2.001
Revenue from scrap [€]	-0.002	-0.002	-0.041	-0.039	-0.187	-0.193
Stamping (drawing and cutting) cost [€]	0.044	0.042	0.051	0.055	0.593	0.679
Setup cost [€]	0.003	0.002	0.085	0.091	0.050	0.072
Loading cost [€]	0.003	0.003	0.010	0.011	0.029	0.038
Maintenance cost [€]	0.018	0.014	0.034	0.036	0.032	0.044
Total cost	*0.080*	*0.072*	*0.542*	*0.553*	*2.530*	*2.641*

Fig. 2: Costs breakdown of three different sheet metal components (estimated vs. manufactured).

Based on the developed algorithms for 3D model analysis (i.e. feature recognition) and the adopted cost models, the estimated results are in line with the final cost provided by the parts manufacturers (maximum deviation of 10%). In particular, the higher error is observed for *Component #1*, which is the simplest part (only cutting operations). The main difference is related to maintenance cost because the proposed analytical model over-estimated the cost of maintenance operations (the complexity of the part does not require a recurring maintenance of the die). Concerning *Component #2* and *Component #3*, maximum deviations between estimated costs and final manufactured costs are respectively 2% and 4%. In these two cases, the deviation is limited, and the main differences are observed in *Setup cost* for *Component #2* and in *Accessory processes* (i.e. dimensional and aesthetical controls) for *Component #3*. *Raw material* and *Stamping process* costs are in line with the costs breakdown provided by the parts manufacturers and it represents a robust result of the geometrical analysis of the virtual model including the identification of key parameters for sheet metal drawing. However, mathematical models for cost estimation need to be refined to catch differences in products with specific features (e.g. maintenance, set-up, final controls).

Conclusions and future works:

The paper presents an analytical cost estimation approach for sheet metal stamped components. The algorithms for the automatic calculation of the blank and product related features, as well as the knowledge used for calculating the stamping process and cost are the basis of the presented method. This approach represents a solution toward the adoption of Design to Cost methods during early product design. Future work will aim to integrate deep drawing cost estimation rules with those ones presented in this paper.

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