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Using design geometrical features to develop an analytical cost estimation method for axisymmetric components in open-die forging

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Abstract

Hot forging is an industrial process where a metal piece is formed through a series of dies which permanently change the shape of the part. Open-die forging is a particular type of hot forging in which the used dies are generally flat and the part to be formed has a simple shape. Manufacturing cost estimation is a well-debated topic, especially for traditional manufacturing technologies. However, only few models are available in scientific literature for the open-die forging process. This lack is due to the complexity of the process, characterized by a low level of automation and a high degree of expertise required to develop the process. The paper proposes an analytical model for the cost estimation of axisymmetric components realized using open die-forging. The model uses as input the geometrical features of the part (e.g. dimensions, shape, material and tolerances), and gives as output: (i) the time required for the process development, (ii) the amount of material needed for the part processing and, (iii) the forging machine size/type, from the cutting of the billet to the piece deformation. Two cylindrical discs have been analysed for validating the proposed cost estimation model. The case studies show that the cost models give an accurate result in terms of cost breakdown, allowing the designer a quick calculation of process costs.

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Keywords: hot forging; cost estimation; open-die forging; analytical cost model; design features;

1. Introduction and State of the Art

Forging is a manufacturing process which shapes a billet by applying compressive forces on it. The process temperature, employed during forging operations, classifies the technology in hot-forging and cold-forging [1]. Another typical aspect of this process is the use of hammers or presses to squeeze and deform the material into a high strength part. In the first case, the process configuration is called open-die forging and in the second one the process configuration is called closed-die forging. The open-die forging process of axisymmetric parts can be divided in various phases as shown in Fig. 1. Pieces manufactured by open-die forging process are highly costly due to the typical big dimensions of products and its low level of automation. The design of open-die forged products is a long and iterative process, which begins from product specification and ends with the detailed definition of technical and functional requirements for the product [2]. It is well known that, although the design activity costs approximately 10% of the total budget for a new project, typically 80% of manufacturing costs are determined during the design stage [3]. A key target in product design is the minimization of product costs, without preempting its desired level of quality functionality and value. During the product development process (PDP), cost plays a critical role and drives most of the technical and technological solutions [4]. Cost reduction can be achieved by adopting different strategies: designing cost-efficient solutions, improving manufacturing performance, increasing the competition among suppliers and/or, delocalising the production where labour cost is lower, and others [5]. Cost estimation is a design task which allows to evaluate the production costs of products before their manufacturing [6].

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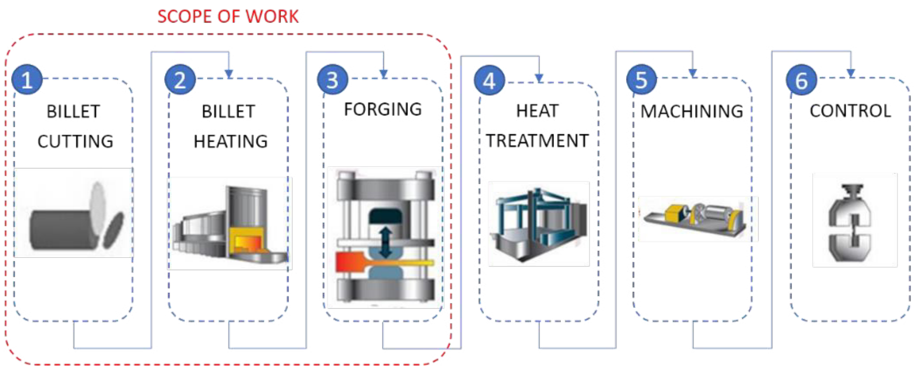

Fig. 1 Manufacturing process steps for axisymmetric forging pieces

Cost estimation activity includes a classification of cost items both for the materials and the manufacturing processes. In addition, cost estimation requires a definition of a mathematical model which integrates the cost items [7]. Cost estimation is generally linked with the so-called Design-to-Cost (DtC) methodologies aiming at the reduction of product cost during the product development process [8].

Among the several methods developed for cost estimation, they can be grouped in two main families: (i) *qualitative methods*, which are primarily based on a comparison analysis of a new product and an existing one and, (ii) *quantitative methods*, which are based on a detailed analysis of a product design, including its features and corresponding manufacturing processes [9]. *Qualitative* cost estimation methods include: *knowledge-based* methods and *intuitive methods*, which are grounded on the estimator's experience and, *analogical methods*, which are based on the manufacturing process similarity between the product to be designed and products previously estimated [9]. *Quantitative* cost estimation methods include: *analytical* methods, which are based on elementary tasks decomposition, *feature-based* methods, which use geometric features as the basis for cost estimation and, *parametric* methods founded on the relations between product characteristics and their cost [10]. Table 1 summarizes the main advantages and disadvantages of each group in terms of result: (i) *Accuracy* - how much the method is accurate and consistent with the actual cost, (ii) *Robustness* - how much the method can easily adapt to the product with different features, dimensions, etc, (iii) *Scalability* - how much the method is suitable for different production sets, (iv) *Uncertainty* - how much the method is providing a small range of cost uncertainty and, (v) *Subjectivity* - how much the method is independent by the end-user. Three levels of assessment (low, medium or high) are reported within the Table 1 based on the literature analysis [14].

Among the existing methods suitable for cost estimation, those ones based on knowledge management and definition of relationships among features, operations, materials, physical relationships, and similarity laws are considered the best in terms of the performances reported in Table 1 [9]. *Analytical* methods are the most suitable choice for the assessment of product costs during the design phase [9] [14].

Several research works are focused on cost estimation of a particular technology or domain. In relation to the technology, specific models for cost estimation were developed based on the manufacturing process such as: (i) chip metal forming [17], (ii) sheet metal [18], (iii) injection moulding [19], (iv) sand casting [10] and, (v) high pressure die casting [14].

For forging processes, different models have been developed based on the process's peculiarities. In particular, a model for hot-forging process cost estimation has been proposed by Berlioz et al. (1999) [20] as well as a tool for cold-forging process has been proposed by Bariani et al. (1993) [21]. Attention in the cost estimation process of forging technology was drawn to the forging dies [22]. However, even if the cost of tooling is one of the most impactful items in the overall component cost, other cost items (e.g. material cost) are missing. An interesting approach has been given by Masel et al. (2010), which present a rough cost estimation by mean of a parametric model [23]. The parametric model provides an accurate estimate of the forging die volume based on the part's geometry, which is one of the most significant cost drivers in the manufacturing of axisymmetric parts. However, the available model for cost estimation of forged components is not accurate for a comparative analysis due to the missing items related to the forging process (e.g. heating). In addition, each forging process (e.g. open-die, closed-die, etc.) has specific features and requires a specific cost model.

Analytical models are more accurate than parametric ones and, for this reason, they are more suitable for the product cost estimation of this technology. Designers and engineers could benefit from an analytical model for cost estimation of open-die process, providing a better insight (cost breakdown) for cost analysis than the general method currently used in practice (e.g. knowledge of skilled employees). Indeed, following the standard practice in forging industry, the cost estimation activity is mainly performed by one or few experts without the possibility to be replicated or analyzed by other actors along the design process. In addition, by coupling the cost estimation model and DtC rules, it is possible to define a holistic framework for cost analysis and optimization and to give a tangible tool for the daily design activities.

Table 1 Comparison of different cost estimation methods

Method family	Method type	Accuracy	Robustness	Scalability	Uncertainty	Subjectivity
Qualitative	Knowledge-based methods [11]	Low	Low	Low	High	High
	Intuitive methods [12]	Low	Low	Low	High	High
	Analogical methods [13]	Low	Low	Medium	High	Medium
Quantitative	Analytical methods [14]	High	High	High	Low	Low
	Feature based methods [15]	High	Medium	High	Medium	Low
	Parametric methods [16]	Medium	High	High	Medium	Low

The paper attempts to define an analytical model for cost estimation of axisymmetric components manufactured by open-die forging technology. The boundary of the proposed work is limited to the forging technology, excluding subsequent processes (e.g. machining) which have an extensive literature concerning cost estimation models [17] [24] [25]. The analytical model is grounded on the evaluation of geometrical features which characterize the axisymmetric part. By using the geometrical product information, the model allows to provide a detailed cost breakdown considering the manufacturing phases of the open-die forging process and the material characteristics. The novelty of the present work is an analytical model, which uses numerical parameters and mathematical equations for the assessment of product cost in the early phase of product design for the open-die process application, which is currently not addressed by the literature. In particular, those equations allow to combine a set of different parameters belonging to three categories: (i) geometrical features of the product under design such as shape, dimensions, area and volume, (ii) manufacturing aspects of the forging process such as machine, process temperature, forces and number of strokes, and (iii) materials properties such as strain rate strength and shear stress.
The paper is structured as follow: section 2 reports a description of the cost estimation model adopted for axisymmetric pieces manufactured with open-die forging technology. Section 3 describe how this model can be adopted in a real case study: cylindrical discs of an axial compressor. Lastly, Section 4 summarizes the main outcomes of the proposed approach and future developments in this field.

2. Open die forging methodology

The open die forging cost model presented in this work has been made by combining several contributions coming from the scientific and industrial literature with the knowledge of technicians and suppliers (cost engineers, production technologists and designers). The proposed model was implemented in a specific cost analysis tool [26], which can load the CAD file of the component to be analyzed for a geometrical features recognition.

The model (Equation 1) provide an insight of the cost items involved in the total cost of forging components (C_{tot}). It considers the cost of raw material ($C_{material}$), the cost of billet cutting ($C_{cutting}$), the cost of billet heating ($C_{heating}$) and the cost of forging process ($C_{forging}$). This cost model does not account the cost of other operations such as machining and heat treatments. Furthermore, accessory costs (e.g. overheads costs and load/unload costs) are not considered in this analysis.

$$C_{tot} = C_{material} + C_{cutting} + C_{heating} + C_{forging} \qquad (1)$$

In the following, those different terms are described in detail.

2.1. Raw material cost (C_material)

2.1.1. Raw material

Material cost (Equation 2) is the most impacting item and usually make up around 50 % of forging costs [27]. Material cost ($C_{material}$) takes account the cost of raw material and the revenues from the scraps due to the recyclability of the metals used in forging process.

$$C_{material} = c_{material} \times \rho \times \left[V_{forged} \times \left(1 + \frac{S_{scale\ lost}}{100}\right)\right] - c_{scrap} \times \rho \times V_{scrap} \qquad (2)$$

The volume of forged disc (V_{forged}) refers to the volume of the part after the forging process. In open-die forging, only simple shaped parts can be obtained, so after the forging process a machining operation is mandatory to get a finished or semi-finished component.

During hot forging, the external volume of the billet is lost for oxidation, so a scale lost factor ($S_{scale\ lost}$) must be considered during analysis. Scrap volume (V_{scrap}) refers to the volume that can be recovered and which can be resold with revenues. In our case the scrap is nil, but if a cost model including machining operations is used, the scrap is the part of material removed.

2.1.2. Billet dimensions

Once calculated the total amount of material, the process dimensional constrains are set according to the billet dimensions. Based on a survey among design engineers and forged piece manufacturers, the ratio between billet height (t_{billet}) and its diameter (d_{billet}) is generally higher than 1.5 and lower than 3 to avoid inflection problems. In this model, the billet height is supposed to be close to twice the diameter. Billets are generally cut from raw bar stocks, which have fixed diameters. So, the billet diameter is calculated to be ½ of the the billet height. The diameter of the stock closest to the calculated diameter is chosen. The height of the billet will be calculated from the chosen diameter and the material needed for the whole forging process.

2.2. Cutting cost (C_cutting)

Cutting cost (Equation 3) is a cost of a preliminary operation. Cutting cost ($C_{cutting}$) combines cutting time ($t_{cutting}$) and setup time ($T_{setup\ (cutting)}$) to estimate the overall process time and multiplying it for hourly cost of the process ($c_{cutting}$).

$$C_{cutting} = \left(t_{cutting} + \frac{T_{setup\ (cutting)}}{Batch}\right) \times c_{cutting} \quad (3)$$

The method of cutting off bars is determined by the edge condition required for subsequent operations and by the base area of the billet. Bar sawing usually produces a uniform cut edge with few or no microstructure deformations close to the cutting section. Separation of billets by shearing is a process without material loss and with considerably higher output with respect to sawing, abrasive cutting, or flame cutting. While in sawing, machine size selection is only a function of maximum bar weight and cutting area of the billet, in billet shearing also the cutting force is involved in machine selection. Shearing force ($F_{shearing}$) can be calculated by Equation 4 [28] [29].

$$F_{shearing} = 1{,}15\ Y_{shear}\ A_{billet} \quad (4)$$

The equivalent material shear stress (Y_{shear}) is function of shear temperature. In case of hot cutting, equivalent shear stress is around 2/3 of the flow stress of material at forging temperature, while in case of cold cutting, equivalent shear stress is about 2/3 of tensile strength of the material.

Billet cutting time depend on the machine type used for the operation and its size. In case of sawing machine (Equation 5(4), the cutting time is function of cutting rate ($R_{cutting}$) [29], while in shearing (Equation 6), the time required depend by the machine stroke rate ($n_{stroke-shearing\ machine}$) [29].

$$t_{cutting} = R_{cutting}\ A_{billet}\ (sawing) \quad (5)$$

$$t_{cutting} = \frac{60}{n_{stroke-shearing\ machine}}\ (shearing) \quad (6)$$

2.3. Heating cost (C_heating)

A billet or bar must be heated over the material recrystallization temperature prior to forging. This process enables a part to be forged with minimum pressure and produces finished parts that have a reduced residual stress, thus making it easy for machining or heat treatment. Generally, heating take place in gas or electric convection furnaces. For any forging material, the heating time must be enough to bring the center of the forging stock to the forging temperature. A heating time longer than necessary results in excessive decarburization, scale, and grain growth.

Heating time (t_{heat}) is a function of material and piece dimensions. For example, for a steel stock measuring up to 75 mm in diameter, the heating time per inch of section thickness should be no more than 5 min for low-carbon and medium-carbon steels or no more than 6 min for low-alloy steels [30]. Heating time per inch of section thickness increase with billet diameter [30]. For small pieces, heating cost is relatively small because a single heating is enough, but for bigger ones, several reheats between operations may be required. As consequence, the cost increases (Equation 7):

$$C_{heating} = \frac{t_{heat} \times c_{furnace}}{batch_{furnace}} \quad (7)$$

Where $c_{furnace}$ is the furnace hourly cost and $batch_{furnace}$ is the number of pieces loaded in the furnace.

2.4. Forging cost (C_forging)

The operation of forging a disc is generally called upsetting. Upset forging, is a manufacturing process that decreases the length of a workpiece to increase its diameter.

Forging cost ($C_{forging}$) can be calculated as follow:

$$C_{forging} = \frac{c_{upsetting-machine} \times N_{upsetting-stroke}}{n_{stroke-upsetting\ machine}} \quad (8)$$

Where $c_{upsetting-machine}$ is the machine hourly rate and $n_{stroke-upsetting\ machine}$ is the machine stroke rate, that are function of machine size. Larger machines have generally higher costs and low stroke rate, while, light machines are less expensive and faster. The quantity of strokes for the billet upsetting ($N_{upsetting-stroke}$) depends on machine type as subsequently described. Before computing the cost, machine must be chosen. Forging machine size limits must be compared with billet and forged piece dimensions. Once filtered the initial number of available machines that can hold the forged part, energy or load required for forging must be calculated for selecting the right machine size.

Open-die forging is realized employing hydraulic presses (load-restricted machines) and hammers (energy-restricted machines). If a hydraulic press is used, it is necessary compute the force needed to upset the piece. In this case, the operation must be carried out in one stroke and the machine must have a tonnage higher than the force for upsetting ($F_{upsetting}$) as reported in Equation 9. If a hammer is used, the energy to deform the piece must be calculated. The piece upsetting can be made with multiple strokes. The quantity of required strokes ($N_{upsetting-stroke}$) multiplied by the machine energy must be greater than the deformation energy ($E_{upsetting}$) as reported in Equation 10. Force (Equation 9) and energy (Equation 10) for upsetting are function of the piece material, part dimensions and machine characteristics [31]. The strain (ε) achieved during upsetting process is explained by Equation 11.

$$F_{upsetting} = K' \xi^{m} A_{forged} Q_a \quad (9)$$

$$E_{upsetting} = K' \xi^{m} \varepsilon V_{billet} Q_a \quad (10)$$

$$\varepsilon = \ln \frac{t_{billet}}{t_{forged}} \quad (11)$$

Strain rate strength (K') and strain rate sensitivity exponent (m) depend by the part material and forging temperature. The strain rate (ξ) is the ratio between machine ram speed (v_{ram}) and forging height after upsetting (t_{forged}), so, the energy or the force for upsetting increase with machine speed. Generally, larger machines have low ram speed, while in small machines ram speed is higher. Maximum force for upsetting occurs when the part achieves the minimum height at forging process, in fact in this condition, the forged piece achieves his maximum area (A_{forged}) and his maximum strain rate, cause its height is at the lowest value. The magnitude of the forces and energy for piece upsetting is influenced by the lubricant used at the die-workpiece interface for reducing friction. Friction multiplying factor (Q_a) is function of friction coefficient (μ) and geometry ratio (d_{forged}/t_{forged}) of the part [31].

3. Case study

The cost model presented in the previous section has been used for estimating the open die forging process cost of two cylindrical discs. Such components, mainly realized in steel or superalloy, are used within axial compressors. The external cylindrical surface is characterized by many slots where shaped blades are fixed.

The test aimed to evaluate the robustness of the proposed cost model. The process parameters and costs items estimated using the cost model, were compared with actual values measured in cooperation with two forge masters. Both factories are equipped with several hydraulic presses, from 200 up to 30000 tons (intermediate dimensions: 1000, 2500, 5000 and 10000 tons). Furthermore, workshops are employed for medium-sized batch dimensions (from dozens up to hundreds of components each batch).

The test was focused on two carbon steel cylindrical discs (Fig. 2). The shape obtained from the open die forging process is a cylinder. After the forging process, the disc is machined to realize the final shape, consisting of external cut-outs for blades and holes for tie-beams. For this reason, the models considered in this test are the initial billet (component 1, Fig. 2) and the forged disc (component 2 Fig. 2), both characterized by a cylindrical shape. Component 3 of Fig. 2 is a shape obtained from a preliminary machining process (the analysis of this process is out of the scope of the present paper). The batch size considered for this test was 20.

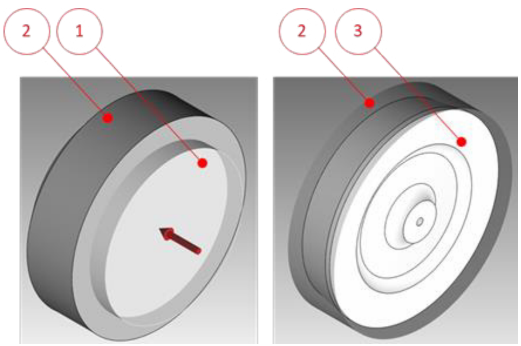

Fig. 2 Components shape used as case study. The red arrow indicates the forging direction. 1) billet, 2) forged disc, 3) pre-machined disc

Estimated and actual process parameters (Table 2) mainly refer to the raw material (circular billets), overall forging process and manufacturing cost items. For clarity, actual costs and parameters presented in (Table 2) refer to only one of the two workshops (the most collaborative in sharing information). For confidentiality reasons, cost values were dimensionless to the total manufacturing cost of Disc A. The unitary cost of raw material and the hourly rate of the cost centers used for estimating the manufacturing cost were the same ones shared by the forge master (required for avoiding bias). N/Av and N/ap symbols mean, respectively, a lack of actual data (not available) or the impossibility to compute the deviation between two process parameters (not applicable).

Table 2 Comparison (Dev.) between estimated (Est.) and actual (Act.) open die forging parameters for two different discs. (*) cost value used as reference

Attributes	UoM	Component A		Component B		
Material	-	ASTM A471		ASTM A471		
Disc diameter	mm	775		569		
Disc thickness	mm	196		147		
Parameter	**UoM**	**Est.**	**Act.**	**Est.**	**Act.**	**Dev.**
Billet diameter	mm	600	600	450	450	0.0%
Billet thickness	mm	344	340	246	254	2.2%
Billet weight	Kg	763	754	308	316	1.9%
Billet cutting time	Min	204	180	115	105	11.4%
Billet heating time	Min	111	120	49	60	12.9%
Billet upsetting time	Min	0.7	1.0	0.5	0.7	27.1%
Billet radial deform. time	Min	4.0	5.0	3.0	3.5	17.1%
Billet rotation time	Min	2.0	3.0	2.0	2.5	26.7%
Press setup time	Min	70	120	70	100	35.8%
Billet deformation force	tons	3772	N/Av	2080	N/Av	N/Ap
Press size	tons	5000	5000	2500	2500	0.0%
Raw material cost	-	70.0	69.0	28.2	28.9	1.9%
Billet cutting cost	-	7.0	5.9	3.7	3.4	14.2%
Heating cost	-	18.7	15.7	7.5	7.9	11.8%
Forging cost	-	4.4	3.1	1.4	2.3	39.8%
Total manufacturing cost	-	100.0*	93.7	40.8	42.5	5.3%

By the result analysis related the raw material, it is possible to notice that the absolute average deviation (*Dev.*, Equation 12) between the estimated (*Est.*) and actual (*Act.*) parameters is very low. This is a direct consequence of the low complexity of the raw material used for cylindrical discs. This conclusion stimulates authors to extend the boundary conditions of the presented cost models and related validation toward more complex geometries, such as shaped discs or multi-diameter shafts.

$$Dev. = \left(\left|\frac{Est.A - Act.A}{Act.A}\right| + \left|\frac{Est.B - Act.B}{Act.B}\right|\right)\Big/2 \qquad (12)$$

Concerning the forging process, the greatest deviation between actual and estimated manufacturing time is related to the upsetting phase, which is around 30%. The high deformation rate of this phase may cause the birth of cracks on the billet. For this aim, the deformation speed should be upper bounded according to the technological limit of each material. Furthermore, a high deviation is also observable for the press set-up time. Actual data suggests that set-up time depends by the press size [32]. Set-up is a phase difficult to objectify, because this is strongly influenced by the production planning of a workshop (e.g. set-up phases can be shortened, even eliminated, if a production line is specialized in the production of a same technological group of components). However, since this time refers to the whole production batch, its impact on each component can be neglected for batch dimensions of hundreds of components. Finally, it is worth to highlight that the rules employed for computing the press size are very strong, since, in both cases, the estimated press size were the same of the actual ones.

4. Conclusion

The major aim of the paper is to define an analytical model for cost estimation of axisymmetric components manufactured through open-die forging technology. By using geometrical product information, the model allows to provide a detailed cost breakdown considering the different phases of the open-die forging process. Two carbon steel forged discs were analyzed, by comparing the actual cost values with the cost obtained using the proposed model. Looking at the results reported in the case study, it is possible to notice that deviation between the estimated and actual parameters is very low, especially about the starting stock dimensions and the type of machinery selected. The bigger gap (approx. 30%) was recorded in the calculation of forging times.

In conclusion, the study proofs that it is possible to develop an analytical model that provides results adherent with the actual cost observed in real workshops. This is an important outcome for a complex process such as open-die forging, providing a powerful tool to the designer for a quick assessment of process costs

References

[1] S. Kalpakjian, S. Schmid, Manufacturing Processes for Engineering Materials, 6th Edition, Pearson, 2017.

[2] G. Pahl, W. Beitz, J. Feldhusen, K.H. Grote, Engineering Design: A Systematic Approach. 3rd ed. Springer; 2007.

[3] K.T. Ulrich, S.D. Eppinger, Product Design and Development, 3rd ed. USA, McGraw-Hill Inc; 2003.

[4] C. Favi, M. Germani, M. Mandolini, Development of complex products and production strategies using a multi-objective conceptual design approach. International Journal of Advanced Manufacturing Technology 2018, 95 (1–4): 1281–1291.

[5] Y. Xu, F. Elgh, J.A. Erkoyuncu, O. Bankole, Y. Goh, W.M. Cheung, P. Baguley, Q. Wang, P. Arundachawat, E. Shehab, L. Newnes, R. Roy, Cost Engineering for manufacturing: Current and future research. International Journal of Computer Integrated Manufacturing 2012, 25.

[6] M. Mauchand, A. Siadat, A. Bernard, N. Perry, Proposal for Tool-based Method of Product Cost Estimation during Conceptual Design, Journal of Engineering Design 2008, 19 (2): 159-170.

[7] A.S.M. Hoque, P.K. Halder, M.S. Parvez, T. Szecsi, Integrated manufacturing features and Design-for-manufacture guidelines for reducing product cost under CAD/CAM environment. Computers & Industrial Engineering 2013, 66: 988-1003.

[8] C. Favi, M. Germani, M. Mandolini, Design for Manufacturing and Assembly vs. Design to Cost: Toward a Multi-objective Approach for Decision-making Strategies during Conceptual Design of Complex Products. Procedia CIRP 2016, 50: 275-280.

[9] A. Niazi, J.S. Dai, S. Balabani, L. Seneviratne, Product Cost Estimation: Technique Classification and Methodology Review, Journal of Manufacturing Science and Engineering 2005, 128 (2): 563-575.

[10] R.G. Chougule, B. Ravi, Casting Cost Estimation in an Integrated Product and Process Design Environment. International Journal of Computer Integrated Manufacturing 2006, 19 (7) 676-688.

[11] E.M: Shehab, H.S. Abdalla, An Intelligent Knowledge-Based System for Product Cost Modeling. International Journal of Advanced Manufacturing Technology 2002, 191: 49–65.

[12] C. Rush, R. Roy, Expert judgement in cost estimating: modelling the reasoning process. Concurrent Engineering 2001. 9(4): 271–284.

[13] P. Duverlie, J.M. Castelain, Cost estimation during design step: parametric method versus case based reasoning method. International Journal of Advanced Manufacturing Technology 1999, 15(12): 895–906.

[14] C. Favi, M. Germani, M. Mandolini, Analytical Cost Estimation Model in High Pressure Die Casting. Procedia Manufacturing 2017, 11: 526-535.

[15] C. Ou-Yang, T.S. Lin, Developing an Integrated Framework for Feature-Based Early Manufacturing Cost Estimation. International Journal of Advanced Manufacturing Technology 1997, 13(9): 618-629.

[16] T. Farineau, B. Rabenasolo, J.M. Castelain, Y. Meyer, P. Duverlie, Use of parametric models in an economic evaluation step during the design phase. International Journal of Advanced Manufacturing Technology 2001, 17(2): 79–86.

[17] G. Boothroyd, P. Radovanovic, Estimating the Cost of Machined Components During the Conceptual Design of a Product. CIRP Annals 1989, 38(1): 157-160.

[18] B. Verlinden, J.R. Duflou, P. Collin, D. Cattrysse, Cost estimation for sheet metal parts using multiple regression and artificial neural networks: A case study. International Journal of Production Economics 2008, 111(2): 484-492.

[19] A. Fagade, D. Kazmer, Early cost estimation of injection molded components. Journal of Injection Molding Technology 2000, 4(3).

[20] M. Berlioz, P. Marin, S. Tichkiewitch, A Fast and Reliable Cost-Estimation Tool for Hot-Forged Parts. Integrated Design and Manufacturing in Mechanical Engineering 1999: 595-602.

[21] P.F. Bariani, G. Berti, L. D'Angelo, Tool Cost Estimating at the Early Stages of Cold Forging Process Design. CIRP Annals 1993, 42(1).

[22] S.K. Biswas, W.A. Knight, Towards an integrated design and production system for hot forging dies. International Journal of Production Research 1976, 14(1): 23-49.

[23] D.T. Masel, W.A. Young II, R.P. Judd, A rule-based approach to predict forging volume for cost estimation during product design. International Journal of Advanced Manufacturing Technology 2010, 46(1-4): 31-41.

[24] P. Watson, R. Curran, A. Murphy, S. Cowan, Cost Estimation of Machined Parts within an Aerospace Supply Chain. CE: Research and Applications 2006. https://doi.org/10.1177/1063293X06063424.

[25] X. Xu, S. Fang, X. Gu, A model for manufacturing cost estimation based on machining feature. International Technology and Innovation Conference (ITIC 2006), 2006.

[26] M. Germani, P. Cicconi, M. Mandolini, Manufacturing cost estimation during early phases of machine design. Proceedings of the 18th International Conference on Engineering Design (ICED 11) 2011.

[27] W.A. Knight, Simplified Early Cost Estimating for Hot-Forged Parts. International Journal of Advanced Manufacturing Technology 1992, 7(3): 159-167.

[28] T. Altan, G. Ngaile, G. Shen, Cold and Hot Forging: Fundamentals and Applications. ASM International 2005.

[29] T. Drozda, Tool and Manufacturing Engineers Handbook, Vol 1: Machining 4th edition. Society of Manufacturing Engineers 1983.

[30] S.L. Semiatin, ASM Handbook Volume 14A: Metalworking: Bulk Forming. ASM International 2005.

[31] J. Beddoes, M. Bibby, Principles of metal manufacturing processes. Burlington, Elsevier, 1999.

[32] G. Boothroyd, P. Dewhurst, W.A. Knight, Product Design For Manufacture and Assembly 3rd Edition. CRC Press 2011.