A Knowledge Formalization Approach for Manufacturing Cost Estimation

A knowledge formalization approach for manufacturing cost estimation

Abstract. Target pricing is a methodology to develop competitive products by determining the target price from market analyses. To guarantee the right profit margin, target cost is a direct consequence of target price. In this situation, the manufacturing cost estimation at the design phase becomes an essential task.
The paper presents a framework for collecting knowledge required for estimating manufacturing cost of components. The framework consists of: (i) a cost breakdown structure used for splitting manufacturing costs, (ii) a data model for collecting that knowledge required for defining manufacturing processes, (iii) a data model for the collecting that knowledge required for computing the manufacturing cost of each operation within a manufacturing process and (iv) a workflow for analytically estimating cost of components. The framework has been mainly conceived for managing components realized through forming and shaping processes. The result presented in this paper guarantee the following benefits: (i) knowledge elicitation on product manufacturing cost, (ii) knowledge sharing among design/engineering departments, and (iii) knowledge capitalization for decision-making process.

Keywords: Design for Manufacturing, Design to Cost, Manufacturing cost estimation, Knowledge management.

1 Introduction and state of the art

Target pricing is a methodology for determining the target price from market analyses, with the aim to develop competitive products [1]. To guarantee the right profit margin, the target cost is a direct consequence of the target price. Hence, the cost becomes a constraint that designers must consider during the product design process [2-3]. Manufacturing and assembly costs are decided during the design stage and their definition tend to affect the selection of materials, machines and human resources that are being used in the production process [4]. In this situation, the manufacturing cost estimation at the design phase becomes an essential task.

Qualitative and quantitative techniques can be employed for the product cost estimation [5]. The first ones are based on a comparative analysis between the new product and products previously manufactured, to identify similarities. Qualitative techniques are more appropriate when the cost estimation time is limited, past data or expert's knowledge is available, and the estimating accuracy requirement is not mandatory. Quantitative techniques are preferable when relationships among the cost variables are identifiable, and when more accurate cost analyses are needed. Quantitative techniques are based on a detailed analysis of the product to develop and can be further categorized into parametric and analytical methods. Using the first ones, cost is expressed as a function of its constituent variables. Parametric techniques could be effective when parameters, named also cost drivers, could be easily identified. With analytical techniques, the product cost is decomposed into elementary units, operations, and activities that represent different resources consumed during the production cycle.

The manufacturing knowledge represents the groundwork for a proper implementation of analytical cost estimation methods [6]. Knowledge can be divided in tacit and explicit [7]. Tacit knowledge refers to that expertise people carry in their minds. Hence, this is unformalized and cannot be widely used by an organization. Explicit knowledge, instead, refers to a set of information that can be articulated, codified, and stored in certain media. To make knowledge usable, a representation framework is needed to deposit and then make it accessible to everyone involved within an enterprise [8]. Few attempts are available on this aim. Streppel [9] developed a framework for cost estimation and cost control where the product is divided into different levels: assembly, component and feature. Each of these levels has its own cost attributes, such as geometry, material, production process, and product planning. Zhang [10] analysed knowledge representation for unit manufacturing processes using an ontology model. Unitary process or operation is represented as an element (block) connected with others. These blocks are: incoming and outgoing flows (energy and materials), machines (equipment), tools, process capacity. Kang [11] used an ontology knowledge model for sequencing a machining process. The knowledge model incorporates information on process characteristics, the relationship between machining characteristics and machining processes, and the process capability to meet production requirements. Kulon [12] developed a knowledge-based engineering (KBE) system for the integration of hot forging design process into a single framework to capture the experience and knowledge of the designers. In this framework, the forged part is classified and defined according to its characteristics, such as material and features (holes, tolerances, etc.). On the same aim, Shehab [13] presented an intelligent KBE system for product cost modelling of machining and injection moulded products at the design stage of the product life cycle. The main feature of those systems is their link with feature-based CAD systems which allow the definition of raw material, machining processes and related parameters based on a set of design and production parameters. Even if these systems estimate the product development cost (including the assembly phase), they show some limitations concerning the covered technologies (i.e. injection moulding, machining processes) and there is no evidence that it can be extended to other processes.

To summarize, the state-of-art shows how dedicated cost models were developed to address specificity of each manufacturing process. However, when multiple technologies are adopted for producing complex products, the manufacturing cost estimation activity requires a concurrent assessment of several processes as well as the definition of a precise cost breakdown structure (material, setup, equipment, consumable, etc.). To date, methods available for the elicitation of manufacturing cost related knowledge, for different technologies, have not developed yet.

Following the limitations highlighted by the literature review, this research work aims at defining a *framework* for formalizing knowledge required for analytically estimating the manufacturing cost of mechanical components, to be employed for shaping processes.

The *framework* consists of four main constructs:

- a *cost breakdown structure* used for splitting the manufacturing cost of a component;
- a *procedure* for defining a manufacturing process;
- a data model (*cost routing*) for collecting knowledge to be used for estimating a manufacturing process;
- a data model (*cost model*) for collecting the knowledge required for computing the manufacturing cost of each operation within a manufacturing process.

The proposed approach, grounded on the analysis of product virtual models (e.g. CAD models with its features), can be used by designers and engineers for analytical computing the *cost breakdown structure* of components.

2 The knowledge formalization approach

2.1 Manufacturing cost breakdown data structure

A cost breakdown data structure (Fig. 1) is necessary to collect cost-related information of each production phase with the aim to standardize the output of a cost estimation activity. Manufacturing costs can be divided into six macro categories: (i) material, (ii) machine, (iii) labour, (iv) equipment, (v) consumables and (vi) energy. This organization is a result of literature analysis, combining and generalizing the most common classification methods (different manufacturing technologies were analysed) [14-17]. The material category refers to the costs of raw material necessary to produce a specific part/component. The raw material cost is the sum of the part net cost and waste cost. Material waste is divided in two categories: (i) scraps and (ii) defected parts. For scraps, authors intend the excess of material necessary for processing (e.g. flash in the forging process). Defected parts refer instead to non-compliant components realized during the initial process start-up or during production.

Machine and *labour* categories refer to the cost-centres used for performing an operation. These costs are further classified in *operation*, *setup* and *idle*. For each process operation, according to the degree of automation, one/none machines and/or one/multiple workers can be employed. The hourly cost rate of a machine considers its maintenance, overhead and depreciation, whereas, the rate for an operator considers its wage and overhead. The *operation* sub-category refers to the manufacturing operations (e.g. chip removal, plastic deformation, etc.) that directly contribute toward the realization of the final component. This item is considered a product direct cost. The *idle* sub-category refers to a passive manufacturing phase when, for example, one operation has been completed, and tooling or materials for the next one is not yet completed or available. The *setup* sub-category refers to those operations, such as tool setting and machine cleaning, required before beginning the production. These operations are independent by the batch dimension; hence, the related cost must be split for the batch quantity for calculating the setup cost for each component.

The equipment category refers to those tools, such as mould jigs and fixtures, required for performing a specific process operation. The cost is the sum of its initial expenditure and maintenance cost during its usage. The initial expenditure considers the cost for its design and manufacturing, plus the material cost. This cost is independent by the production volume; hence, the related cost must be split for the production volume for calculating the equipment cost for each component.

The *consumables* category refers to those materials that enable the process itself (e.g. lubricants used for forging, gas cutting assistance for laser cutting, etc.). This is a direct and accessory cost directly allocated to the cost of each component.

The *energy* category refers to the energy vectors (e.g. electricity, water, steam, etc.) that guarantee the process working. Energy may be requested by machines and/or equipment and the related cost is function of their power and working time.

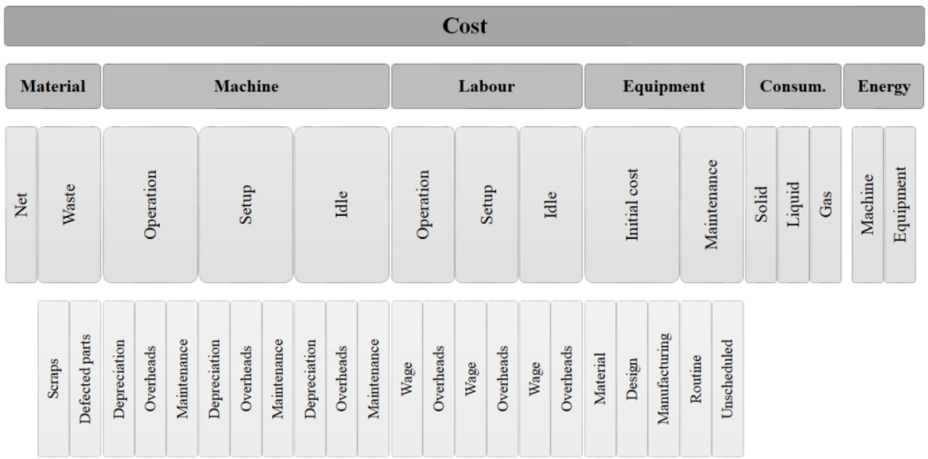

Fig. 1. Cost breakdown structure

2.2 Procedure for manufacturing process estimation

Manufacturing cost can be analytically calculated only once a manufacturing process has been defined. As stated in the introduction, since cost estimation should be carried out at the design stage, is rather important to use/define a method through that it is possible to establish the best or all the feasible manufacturing processes able to transform a raw material in a finished component. This section presents a step-by-step approach, that starting from the virtual prototype of a component, it is able to define a manufacturing process plan.

The workflow consists of five decision steps, each one supported by a specific database and a set of knowledge-based rules (cost routing). Most of the rules described in this workflow can be classified in two types. Validity rules are used for removing manufacturing-related solutions that are not applicable in certain conditions. Priority rules are used for sorting the valid solutions. The cost estimation process is based on a set of product and process related information, which are: 3D CAD model, geometrical and non-geometrical attributes, Product Manufacturing Information (PMI) and process attributes.

The *first step* for defining a manufacturing process consists in establishing the overall production scenario. Indeed, the manufacturing process and the related costs firstly depend by the production environment (production facility, raw material warehouse and sourcing strategy).

Once defined the production environment, the *second step* aims to define the production strategy, consisting in the selection of the raw material and manufacturing process. The material selection (e.g. commercial semi-finished product vs custom stock) and the manufacturing process (e.g. die casting vs chip forming) should be carried out at the same time since the last one depends by the raw material and vice-versa. For example, the injection moulding process is valid only for thermoplastic polymers (validity rule), whereas it is convenient only for producing thousands or more components (priority rule).

The *third step* aims to define raw material, the first outcome of this procedure. The information to be calculated are the type of material (e.g. commercial bar, sheet metal, billet), shape (e.g. circular, rectangular, solid/hollow), dimensions (e.g. thickness, length, width, height), supply status (e.g. hot rolled, extruded, grinded, galvanized), volume, weight and unitary cost. For the injection moulding, only thermoplastic polymers granules can be used (validity rule), while the raw material volume is computed considering the part volume plus the volume of runners (selection/calculation rules). For the calculation of such information, feature recognition algorithms should be employed for analysing the 3D CAD model with the aim to compute a specific raw material feature, consisting of a set of geometrical information required for selecting the stock. The raw material cost is computed by multiplying the amount of requested material by the unitary cost.

The *fourth step* aims to define the manufacturing strategy to be employed for making a component/product. A manufacturing strategy consists of a list of operations bundles, described in the next step. Each one has a list of validity and priority rules. A manufacturing strategy is triggered by validity rules. Considering the injection moulding as example, this is valid only for thermoplastic materials.

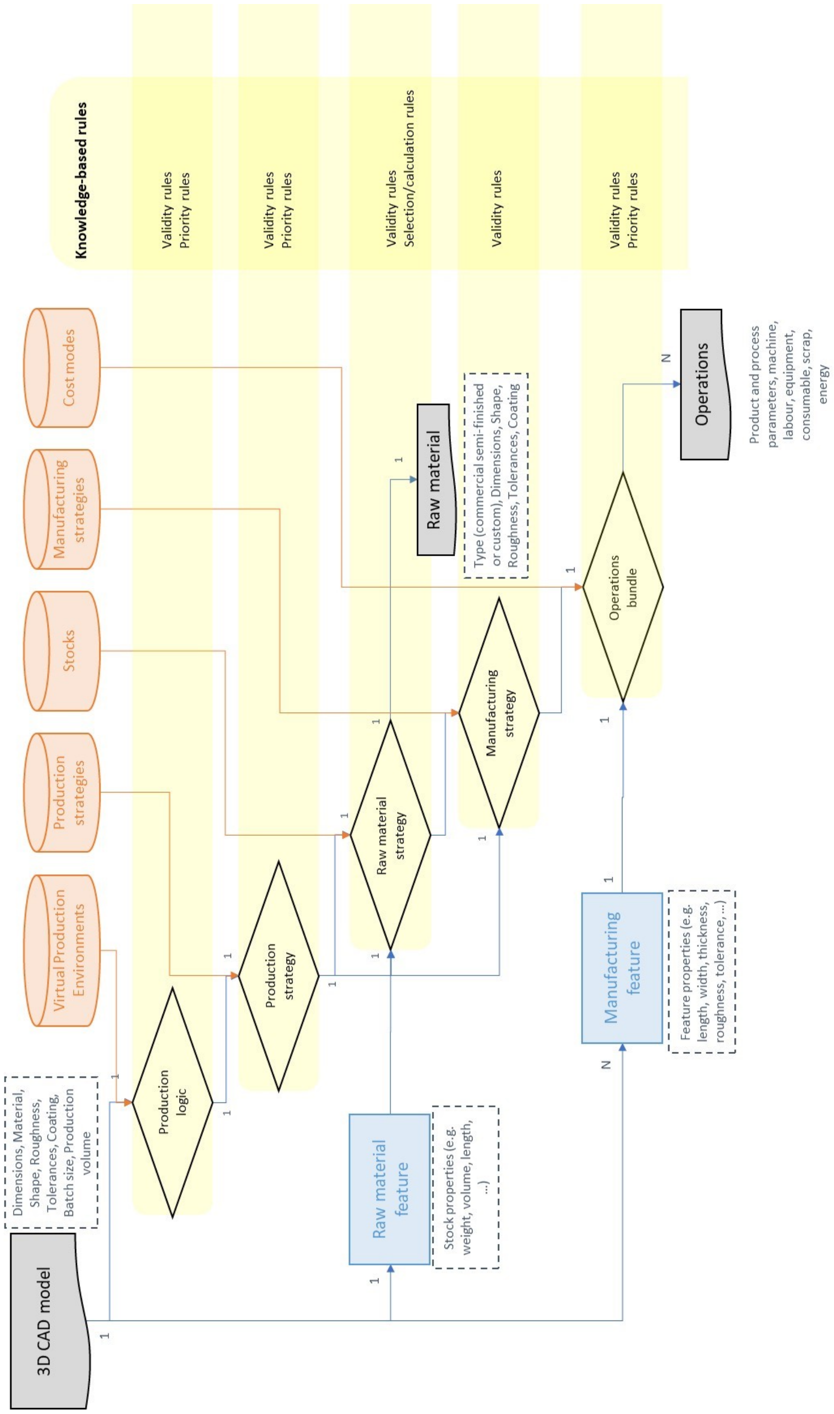

Fig. 2. Workflow for defining a manufacturing process

The *fifth step* is an intermediate phase before the calculation of the operations sequence. Indeed, a product can be realized employing multiple and different operations. For example, a hole, according to its shape, diameter, depth, roughness, tolerance, product material, production volume can be realized adopting different operations despite already a specific manufacturing strategy was yet defined. For simplifying the definition of an operations sequence, the concept of operations bundle has been defined. This one consists of a group of operations required to produce a specific product manufacturing feature (PMF). A PMF is an object consisting of a list of faces and properties (e.g. hole depth, hole diameter, hole shape, minimum tolerance, minimum roughness,). The latter are bundle dependant and are used for establishing the operations bundle to be used. PMFs (e.g. hole, cutout, chamfer, fillet, turning, welding) can computed by feature recognition algorithms (their description is beyond the scope of this paper). The bundle is also responsible for transferring the PMF properties to the valid operations defined in its inside (the bundle contains one or multiple validity rules for each operation). For each bundle, a list of validity rules is also defined.

By assembling all the valid operations within the valid bundles, for a specific manufacturing strategy, it is possible to define the operations list that represent the manufacturing process of a product.

2.3 Manufacturing cost model

Cost model is a data model containing that knowledge required for estimating the production time and cost for each operation. Cost model can be considered as a structured object of information as illustrated in Fig. 3. It consists of a list of product and process parameters. The first ones define the shape and dimension of the operation to be carried out, while the second ones characterize the manufacturing operation from the technological standpoint. These parameters (e.g. injection temperature and pressure for injection moulding), computed using specific calculation rules, are based on the product parameters, other information available from a database and analytical/empiric calculation rules. The latter could be retrieved from industrial and scientific literature.

A cost model contains also several validity and calculation rules. The first ones are used for limiting the possible cost centres (machine and operator) energy vectors, consumables, equipment and wastes applicable for a specific operation. The second ones are used for calculating the consumption of energy vector, consumables, equipment and the generation of waste. At last, an operation contains rules for computing the manufacturing time and cost, respecting the cost breakdown presented in Fig. 1.

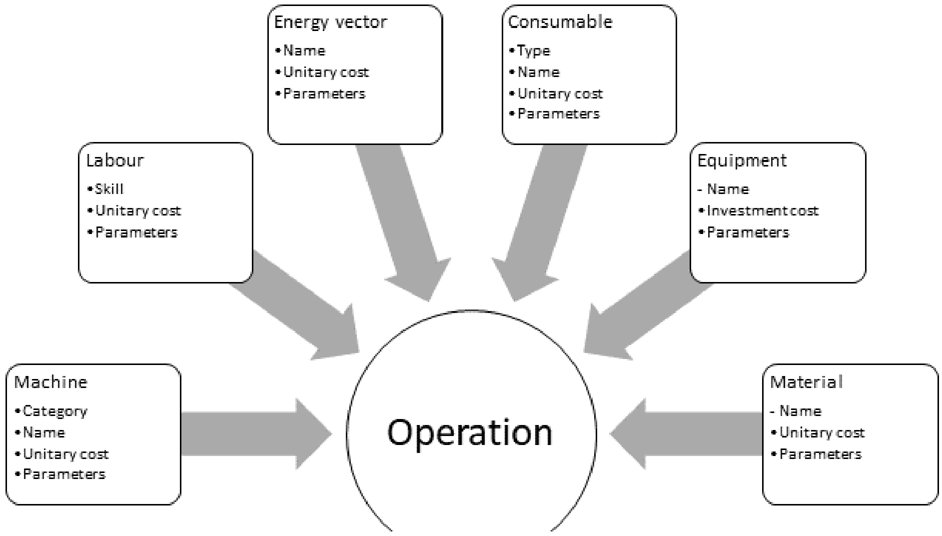

Fig. 3. Manufacturing cost model structure

To compute the process parameters, it is necessary to establish the following information (the examples refer to the injection moulding process):

- *Machine*: this is the cost centre used for realizing the operation. Each operation has a list of available machines, restricted by a list of validity rules. It is worth noting that process parameters are influenced by the machine (e.g. injection time depends by the press power);
- *Labour*: this is another cost centre that can be used for realizing the operation. Its behaviour is the same one of *Machine*;
- *Energy*: each operation may use one, multiple or none energy vector, such as electricity. The energy consumption mainly depends by the machine, product and process parameters (e.g. electricity consumption depends by the machine power and time of usage);
- *Consumable*: each operation may use one, multiple or none consumable, such as lubricant, cutting tools, cutting assistance gas, etc. The consumable consumption mainly depends by the machine, product and process parameters;
- *Equipment*: each operation may use one, multiple or none equipment, such as jigs, fixture and moulds. The equipment depends by the machine and some process parameters, while influences other process parameters;
- *Waste*: each operation may generate scraps or defected parts during the process start-up or standard production. Waste depends by both product and process parameters and by the maturity of a process.

All the previous information contributes to the calculation of the operation cost.

3 Achievements and benefits

The proposed method has been applied for modelling the manufacturing knowledge related to open-die forging and plastic injection processes. For clarifying the usage of the method proposed in the previous section, Table 1 and Appendix 1 present respectively a production strategy an a cost model for an open die forging process.

Table 1. Production strategies for the open-die forging

Production strategy	Raw material strategy	Manufacturing strategy	Validity rules	Priority rules
Disc Open Die Forging From Bar	Bar	Disc Open Die Forging	-	IF (Production.BatchQuantity > 10) THEN Score = 0 ELSE Score = 10
Disc Open Die Forging From Billet	Billet	Disc Open Die Forging	Piece.Material.Category = "Metal" Piece.Volume > 8dm3 NOT (Piece.Shape = "Hollow") NOT (Piece.Shape = "Sheet-Metal")	IF (Production.BatchQuantity > 10) THEN Score = 10 ELSE Score = 0 IF (Piece.Volume > 25dm3) THEN Score = 10 ELSE Score = 0

The other constructs previously presented (i.e. production logic, raw material strategy, manufacturing strategy and operations bundle) are not reported for confidentiality reasons.
For injection moulding and open-die forging, the constructs of the proposed framework (cost breakdown, cost routing, procedure for manufacturing process definition and cost model) have been evaluated considering a set of requirements defined within the literature analysis and the findings of the specific case study. For each requirement, Table 2 presents the results achieved in this research work and relative comments. Two outcomes for each cost item have been identified:

- *Improvement addressed considering existing barriers of the state-of-art*: the requirement, emerged during the literature review, was satisfied, hence, the proposed framework is completer and more comprehensive than the ones proposed in the literature;
- *Improvement to be addressed considering existing barriers of the state-of-art*: the requirements, emerged during the literature review and the analyses of the results, represent interesting improvement to be managed in a future research.

Very positive outcomes are highlighted in relation to the cost breakdown structure and cost model, where the most important requirements were addressed. Some future improvements are required for the cost routing and for the management of different objectives, variables and constraints of an optimization problem as well as for the management of rules to be used for sorting operations. Looking at the workflow, a positive outcome is the possible extension to other forming processes, while a workflow for assemblies is required as improvement.

Table 2. Outcomes of the framework implementation: (TbA: To be addressed, A: Addressed)

Requirement	Construct	Outcome
Detailed cost breakdown structure to be used for in-depth cost analyses	Cost break-down	A
General cost breakdown structure to be used for forming processes	Cost break-down	A
Workflow for defining manufacturing processes from 3D virtual prototypes of components	Procedure	A
Workflow for defining manufacturing processes from 3D virtual prototypes of assemblies	Procedure	TbA
General structure for collecting knowledge-based rules for defining a manufacturing process	Cost routing	A
Optimization methods at cost routing	Cost routing	TbA
Process yield	Cost routing	TbA
Sorting of process operations	Cost routing	TbA
Cost routings for joining processes	Cost routing	TbA
General cost model to be used for forming processes	Cost model	A
Cost model to provide cost breakdown according to the structure proposed in section	Cost model	A
Optimization methods at cost model	Cost model	TbA

4 Conclusions

The paper originated from the need to support enterprises in formalizing the manufacturing knowledge to be used for the manufacturing cost estimation of products (analytical approach) during the design process. The paper attempts to close the research gap between detailed cost models of single manufacturing processes (available in literature for most of the knowing technologies) and the need to have a suitable framework for cost estimation that can be representative of each manufacturing technology used to realize mechanical components. The research work presented a knowledge-based procedure for defining a manufacturing processes starting from the product virtual prototype. This procedure is based on a set of repositories and cost routings, properly defined for collecting the knowledge required for estimating a manufacturing process. Once defined the process, the knowledge behind each manufacturing operation (cost model) allows calculating the manufacturing cost. Economic information is obtained according to a precise breakdown that allows designers and production technologists to evaluate in detail product and process criticalities. The framework presented in this paper allows production companies to capitalize their manufacturing best practices (often in the minds of a few qualified engineers) and make them available to all stakeholders involved in the product development and design to cost actions.

Future research will be focused to further improve the proposed framework and increase its boundaries of application. Cost routings and cost models should include rules for optimizing the manufacturing cost of a single operation as well as of the whole process.

5 References

1. Cooper R., Slagmulder R. (1997) Target Costing and Value Engineering, 1st Edition, ISBN 9781563271724
2. Pahl G, Beitz W (2007) Engineering Design: A Systematic Approach, 3rd edition (Springer).
3. Ulrich K.T., Eppinger S.D. (2011) Product Design and Development, 5th Edition (McGraw-Hill Inc.).
4. Nitesh-Prakash W., Sridhar V.G., Annamalai K. (2014) New Product Development by DfMA and Rapid Prototyping. Journal of Engineering and Applied Sciences 9(3), 274-279.
5. Niazi A., Dai J.S., Balabani S., Seneviratne L. (2006) Product Cost Estimation: Technique Classification and Methodology Review. Journal of Manufacturing Science and Engineering 128: 563-575
6. Hoque A.S.M., Halder P.K., Parvez M.S., Szecsi T. (2013) Integrated manufacturing features and Design-for-manufacture guidelines for reducing product cost under CAD CAM environment. Computers & Industrial Engineering 66: 988-1003
7. Darai D.S. , Singh S., Biswas S. (2010) Knowledge Engineering-an overview. International Journal of Computer Science and Information Technologies, Vol. 1 (4): 230-234
8. Jiang Y., Peng G., Liu W. (2010) Research on ontology-based integration of product knowledge for collaborative manufacturing. Int J Adv Manuf Technol 49:1209-1221
9. Streppel A.H., Weustink I.F., Brinke E., Kals H.J.J. (2003) A generic framework for cost estimation and cost control in product design. Journal of Materials Processing Technology 103: 141-148
10. Zhang Y., Luo X., Zhang H., Sutherland J. W. (2014) A knowledge representation for unit manufacturing processes. Int J Adv Manuf Technol 73:1011-1031
11. Kang M., Kim G., Lee T., Jung C. H., Eum K., Park M. W., Kim J. K. (2016) Selection and Sequencing of Machining Processes for Prismatic Parts using Process Ontology Model International. Journal Of Precision Engineering And Manufacturing Vol. 17, No. 3, pp. 387-394
12. Kulon J., Broomhead P., Mynors D. J. (2006) Applying knowledge-based engineering to traditional manufacturing design. Int J Adv Manuf Technol 30: 945-951
13. Shehab E. M., Abdalla H. S. (2002) An Intelligent Knowledge-Based System for Product Cost Modelling Int J Adv Manuf Technol 19:49–65
14. Chiadamrong N., (2003) The development of an economic quality cost model. Total Quality Management & Business Excellence 14(9):999-1014. https://doi.org/10.1080/1478336032000090914.
15. Wang, H.S. (2007) Application of BPN with feature-based models on cost estimation of plastic injection products. Computers & Industrial Engineering 53(1):79-94. https://doi.org/10.1016/j.cie.2007.04.005.
16. H'mida F., Martin P., Vernadat F., (2006) Cost estimation in mechanical production: The Cost Entity approach applied to integrated product engineering. International Journal of Production Economics 103(1):17-35. https://doi.org/10.1016/j.ijpe.2005.02.016.
17. Xu Y., Elgh F., Erkoyuncu J. A., Bankole O., Goh Y., Cheung W. M., Baguley P., Wang Q., Arundachawat P., Shehab E., Newnes L., Roy R., (2012) Cost Engineering for manufacturing: Current and future research. International Journal of Computer Integrated Manufacturing 25(4-5):300-314. https://doi.org/10.1080/0951192X.2010.542183.

Appendix 1: Open-die forging cost model

Material	Machine	Labour	Equipment	Consumable	Energy
Validity rules N/A	**Validity rules** Machine.Category = ("HydraulicPress" OR "*Hammer*") Machine.Tonnage > RequestedTonnage Machine.Energy * BlowNumbers > RequestedEnergy Machine.MaxSizeX > Piece.Width Machine.MaxSizeY > Piece.Width Machine.MaxSizeZ > Billet.Lenght	**Validity rules** Labour.Skill = "*Hot Forging Operator*"	**Validity rules** N/A	**Validity rules** **Solid** IF RawMaterial.Material = "*Aluminium*" THEN Consumable.Solid.Type = "*Solids*" ELSEIF RawMaterial.Material = "*Steel*" OR RawMaterial.Material = "*StainlessSteel*" THEN Consumable.Solid.Type = Graphite **Liquid** Consumable.Liquid.Type = NA **Gas** Consumable.Gas.Type = NA	**Validity rules** Energy.Vector = "*Electricity*"
Priority rules N/A	**Priority rules** Minimum hourly rate	**Priority rules** N/A	**Priority rules** N/A	**Priority rules** N/A	**Priority rules** N/A
Calculation rules N/A	**Calculation rules** **Operation** ProcessTime = BlowNumbers /Machine.BlowRate MachineProcessCost = ProcessTime * Machine.HourlyRate **Setup** SetupTime = Machine.SetupTime/Production.BatchQuantity MachineSetupCost = SetupTime * Machine.HourlyRate **Idle** IdleTime = 0 MachineIdleCost = IdleTime * Machine.HourlyRate	**Calculation rules** **Operation** LabourProcessCost = ProcessTime * Labour.HourlyRate * OperatorsQuantity **Setup** LabourSetupCost = SetupTime * Labour.HourlyRate * OperatorsQuantity **Idle** LabourIdleCost = IdleTime * Labour.HourlyRate * OperatorsQuantity	**Calculation rules** N/A	**Calculation rules** **Solid** Consumable.Quantity = Consumable.Hourly.Quantity* Operation.ProcessTime **Liquid** N/A **Gas** N/A	**Calculation rules** **Machine** EnergyCost.Machine = (Machine.Power * Machine.LoadFactor * Operation.ProcessTime) * Energy.UnitaryCost **Equipment** EnergyCost.Equipment = 0