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ORIGINAL ARTICLE

A framework for analytical cost estimation of mechanical components based on manufacturing knowledge representation

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Abstract

This paper presents a novel framework for manufacturing and cost-related knowledge formalization. This artefact allows industries to capitalize the knowledge of experienced practitioners in the field of manufacturing and assembly, so that it can be used by designers for quickly and analytically estimating the production costs of components during product development. The *framework* consists of the following: (i) a *cost breakdown* structure used for splitting out the manufacturing cost, (ii) a data model (*cost routing*) to collect the knowledge required to define a manufacturing process, (iii) a data model (*cost model*) for collecting the knowledge required to compute the manufacturing cost of each operation within a manufacturing process, and (iv) a *workflow* to define the manufacturing process. The proposed framework provides several advantages: (i) knowledge formalization of product manufacturing cost, (ii) knowledge sharing among design/engineering departments, and (iii) knowledge capitalization for decision-making process. The proposed framework is used to formalize the knowledge required for analytically estimating the manufacturing cost of open-die forged components. Results highlight that the framework addresses the most important requirements for a knowledge-based cost estimation system.

Keywords Manufacturing knowledge · Product design · Knowledge elicitation · Manufacturing cost estimation · Design to cost · Computer-aided process planning

1 Introduction and literature review

To develop competitive products, "should costing" and related activities are included in design methodologies for determining the target price of the product [1]. To guarantee the right profit margin, the target cost of the product is a direct consequence of the target price. Hence, cost becomes a design constraint that engineers must consider during the product development process and must control across the project life cycle.

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The production cost must be managed during the design phase and not just accounted during manufacturing activities. Furthermore, according to the paradox of costs, although design costs consume approximately 20% of the total budget of a new project, typically 80% of manufacturing costs are determined during the design phase [2, 3]. Manufacturing and assembly costs are decided during the design stage, and their definition tends to affect the selection of materials, machines and human resources that are used in the production process [4]. In this situation, manufacturing cost estimation at the design phase becomes an essential task. However, for reducing as much as possible the time commitment of designers, cost estimation at the design phase is only feasible if the evaluation is automatically carried out starting from the virtual prototype of the product (i.e., a combination of a 3D CAD model, geometrical and non-geometrical attributes, and product manufacturing information). Therefore, when a detailed product cost estimation is required, knowledge formalization is a requirement.

Regarding the product development process, research studies have addressed product cost determination from different angles. In particular, the most important research in this area has been conducted from two perspectives: (i) design and (ii) manufacturing. From the "design" perspective, several design methodologies have been proposed, including qualitative and quantitative approaches for cost estimation [5]. The qualitative approaches are mainly based on developing a comparative analysis between the new product and the products previously manufactured, to identify product similarities. Qualitative approaches are more appropriately implemented when past data or the expert's knowledge is available, and the estimating accuracy requirement is limited. These techniques can further be categorized into analogical and intuitive techniques [6, 7]. Analogical techniques, such as the use of regression analysis models or back propagation methods, employ similarity criteria based on historical cost data. Unfortunately, the use of these methods requires access to large databases of previously manufactured products; however, this access is not always available. In addition, analogical methods are not useful when the features of the new product differ significantly from those of the previously produced products [8]. Intuitive methods are based on the use of the previous knowledge and experience of technologists and, for this reason, are much more prevalent. A drawback of the intuitive methods is that their effectiveness is related to the categorization of knowledge based on the field of expertise where the industry is operating (e.g. the metal cast industry) [8]. The quantitative approaches are preferable when cost attributes can be linked and when a higher level of accuracy is needed. Quantitative techniques are based on a detailed analysis of the product design and can be further categorized into parametric and analytical methods [5]. Parametric methods allow the definition of a product cost as a function of its constituent attributes. Parametric techniques can be effective when parameters, also called cost drivers, can be easily identified. Parametric models are generally used to quantify the unit cost of a given product. A wide range of parametric models can be found in the literature, and in recent years, several models for different applications, such as brake disks [9], injection moulding components [10, 11], moulds [12], and machine parts, have been developed [13–15]. As shown in the previous cases, due to their low scalability for use in other contexts, parametric models have been developed for single processes or products.

Analytical methods allow product costs to be broken up into elementary items, operations, and activities that represent different resources consumed during the production cycle. Several authors exploit analytical methods and apply them to specific products, such as moulds [16], packaging products [17], or processes such as machining [18, 19]. In some cases, analytical methods are used together with feature-based design approaches [17, 19]. Other authors, instead, exploit hybrid systems that combine several approaches, such as analogical and analytical approaches [20] or even analytical and parametric approaches, as described by Ravi [21]. This hybrid approach was used to estimate the cost of a casting process according to the 3D solid model of the part and its attributes (i.e. material, geometry, quality and production requirements). The authors used analytical equations to estimate material and process (energy and work) costs, while a parametric model driven by the part complexity was developed for tooling cost estimation. This cost estimation model was used to "educate" designers and engineers with scarce knowledge about manufacturing processes. By adopting the same approach, several researchers proposed hybrid techniques to estimate the production cost of specific products and components [22–25]. The state-of-the-art techniques related to the "design" side reveal that reaching the desired level of granularity in cost breakdown is still an open question for design purposes. A gap in the definition of manufacturing cost items and their relationships (mathematical models) with product design features is noticed. In addition, the cost estimation of a product requires the availability of many related manufacturing processes that commonly are not available at the design stage. Cooperation between designers and production technologists is mandatory for achieving this goal but will be negatively affected by the iterations that may arise in this phase. The time-to-market will be significantly improved if designers can be supported by methods and tools that automatically construct the manufacturing process and calculate the related cost of a product. This aim can be pursued only by collecting, classifying and leveraging the manufacturing knowledge required for cost estimation.

From the "manufacturing" perspective, production knowledge represents the groundwork for a proper implementation of analytical cost estimation methods [26]. Knowledge can be divided into tacit and explicit knowledge [27]. Tacit knowledge is the knowledge that people carry in their minds. Hence, this knowledge is not formalized and not 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 data framework for knowledge collection is needed to deposit knowledge and then make it accessible to everyone involved within an enterprise [28–32]. Toward this aim, Streppel [33] developed a framework for cost estimation and cost control where the product is divided into different levels: the assembly, component and feature levels. Each one of these levels, such as the geometry, material, production process and product planning, has its own cost attributes. Even if the approach is very promising, it does not provide any solution to calculate the sequence of operations starting from the virtual model of the product. A similar drawback is noticed also in the work proposed by Zhang [34], in which an ontology model was used to represent the knowledge related to manufacturing processes. Product manufacturing knowledge is a particular knowledge that illustrates how a product can be optimally manufactured. This study does not identify a framework for collecting the cost items: the focus of the authors is related to the structure of single operations, which by focusing on, the authors miss the opportunity to calculate the sequence of the whole operations of the process. Kang [35] used an ontology knowledge model for sequencing a machining process. The knowledge model incorporated information on process characteristics, the relationship between machining characteristics and machining processes, and the process capability to meet production requirements. The processing of a given component was drawn up according to its features (holes, pockets, etc.) and according to the type of tolerances and roughness required. Each machine had different capabilities, and therefore, the choice depended on the product features. The mentioned work focused only on the machining process, not providing a knowledge model that can be shared with other manufacturing processes. Several works on knowledge formalization for forming processes are available in the literature. To capture the experience and knowledge of the designers, Kulon [36, 37] developed a knowledge-based engineering (KBE) system for the integration of a hot forging design process into a single framework. In this framework, the forged part is classified and defined according to its characteristics, such as material and features (e.g. holes and tolerances). Unlike the approach in this paper, the knowledge-based system proposed in this work mainly focuses on the deformation step and not on the whole forging process (billet cutting, billet heating, etc.). Toward the same aim, Shehab [38] presented an intelligent KBE system for the product cost modelling of machining and injection moulded products at the design stage of the product life cycle. The system estimates the product development cost, including the assembly phase costs. The proposed KBE system is limited to only injection moulding and machining processes, and there is no evidence that it can be extended to other processes. These state-of-the-art techniques related to the "manufacturing" side show how dedicated cost models were developed to address the specificity of each manufacturing process. Generalized methods for the elicitation of the manufacturing knowledge of different technologies have not yet been developed. Furthermore, when multiple technologies are adopted for the manufacturing of complex products, several processes need to be included by different cost models, and the cost estimation framework requires the inclusion of additional cost items (setup, equipment, consumable, etc.), which is not formalized by adopting dedicated methods. Table 1 summarizes the main limitations of the methodologies retrieved from the literature review.

Considering the limitations highlighted by the literature review, the goal of this research work is to define a *framework* based on manufacturing knowledge formalization, for the analytical cost estimation of mechanical components. The *framework* consists of four main constructs used for formalizing and applying the knowledge required for the cost estimation of products realized through forming and shaping processes:

- A *cost breakdown structure* used for splitting out the manufacturing costs.
- A data model (*cost routing*) for collecting the knowledge required for defining 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.
- A *workflow* for defining a manufacturing process from 3D virtual prototypes.

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 the analytical computation of the *cost breakdown structure* components.

According to Ashby [40], manufacturing processes are classified into *finishing*, *forming/shaping* and *joining processes*. Since there are great differences among such processes, the framework presented in this paper has been conceived for forming/shaping processes. Joining and finishing are beyond the boundaries of this framework. Typical forming processes are *casting* (e.g. sand, die, investment), *moulding* (e.g. injection, compression, blow moulding), *deformation* (rolling, forging, drawing), *powder* (e.g. sintering, HIPing), *machining* (e.g. cut, turn, drill, grind) and *heat treatments* (e.g. quench, temper).

The paper is structured as follows: After this introduction, which includes a literature review on product cost estimation, Section 2 presents the proposed manufacturing cost breakdown, the data models for knowledge formalization and the workflow for estimating the product manufacturing process and related costs. In Section 3, the framework is applied for collecting the knowledge for estimating the open-die forging process and its cost. Section 4 presents benefits and limitations of the proposed framework. At the end, Section 5 summarizes the outcomes of this study and presents selected proposals for future work.

2 Materials and methods

Knowledge-based systems (KBS) or expert system (ES) use knowledge to resolve problems that necessitate significant human experts for the solution [41]. According to the general architecture of an expert system [42], the database, which contains information in terms of fact or heuristics based on user interest of specific problem domain, is on the most important element. Knowledge can be classified in rule-based system (RBS), frame-based system (FBS), object-oriented

Table 1 State-of-the-art limitations

Requirement	Context	Perspective	State-of-the-art
Detailed cost breakdown structure to be used for in-depth cost analyses	Cost breakdown	Design and manufacturing	In the literature, various cost breakdown schemas can be found, but some details are always missing (for example, the differentiation between contaminated and uncontaminated waste) [6, 17, 21, 25, 30, 34].
General cost breakdown structure to be used for forming processes	Cost breakdown	Manufacturing	Many cost breakdown schemas are found in the literature, but all of these refer to specific manufacturing processes: • Machining [6]. • Forging [25]. • Casting [21].
Workflow for defining manufacturing processes from 3D virtual prototypes of components	Workflow	Manufacturing	All the workflows available in the literature refer to specific manufacturing processes: • Machining [17, 38]. • Assembly products [33]. • Forging [36]. • Injection moulding [33].
General structure for collecting knowledge-based rules for defining a manufacturing process	Cost routing	Design and manufacturing	Various examples of cost routing are available in the literature, but they generally refer to specific manufacturing processes: • Machining [19, 20, 28, 35, 39]. • Casting [8]. • Forging [36].
General cost model to be used for forming processes	Cost model	Design	In the literature, there are many cost models, but all of these refer to specific manufacturing processes: • Forging [25]. • Casting [21]. • High-pressure die casting [24].
Cost model to provide cost breakdown according to the structure proposed in Section 2.1.	Cost model	Design	Some authors organize cost model rules in accordance with their idealized cost breakdown [6, 21, 25].

system (OOS) and case-based reasoning (CBR). The manufacturing knowledge for cost estimation is here formalized according to RBS (used for defining production rules) and OOS methods (used for defining the overall structure of the costing-related objects, such as cost routing and cost model). Several languages can be employed for representing knowledge. Considering the RBS and OSS systems used for manufacturing knowledge representation, the Unified Modelling Language (UML), defined by the Object Management Group (OMG), is the suggested language for knowledge modelling.

This section provides a detailed description of the framework for the analytical cost estimation of mechanical components. Section 2.1 defines a logical sequence that represents the whole manufacturing process for transforming a raw material into the final product, including the *cost breakdown* structure. Section 2.2 provides the model (*cost routing*) used for collecting the manufacturing-related knowledge, Section 2.3 provides the model (*cost model*) used for collecting the cost-related knowledge considering each operation within a manufacturing process, and starting from a component's 3D virtual prototype, Section 2.4 describes the *workflow* in the component's manufacturing cost estimation.

2.1 Manufacturing process data structure and cost breakdown data structure

A manufacturing process (Fig. 1) is the logical sequence of operations needed to transform a raw material into the final product. The description of a manufacturing process for product cost analysis implies the following: (i) the representation of the characteristics of the product to be manufactured (geometrical features, components required, etc.), (ii) the available technology

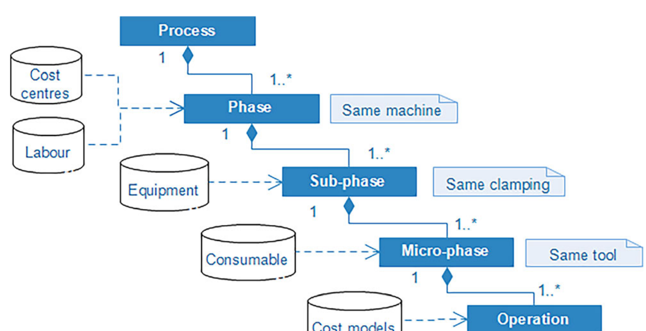

Fig. 1 Schematic model of a generic manufacturing process (UML class diagram)

(machines, services, etc.) and (iii) the tasks/operations required to achieve these features. Each task of a generic manufacturing process is defined based on the geometrical product features and other features that are affecting the process (status of the machines, characteristics of the raw material, etc.) [43].

A working plan consists of several phases and group of operations performed with the same machine or in the same cost centre. Within a single phase, operations can be further grouped into sub-phases, in which operations are realized with the same work-piece clamping. For each clamping, different tools can be used in the manufacturing of the final part. Operations realized through use of the same machine, work-piece clamping and tools are grouped into micro-phases.

Based on the proposed structure, which describes the set of manufacturing processes required to develop a mechanical product/component, a cost breakdown data structure is necessary to collect information of each phase and micro-phase. The tree in Fig. 2 represents a schema for collecting the costs of each item present in a manufacturing process. The costs are divided into six categories: (i) *material*, (ii) *machine*, (iii) *labour*, (iv) *equipment*, (v) *consumables* and (vi) *energy*. This organization is a result of the literature analysis and combines the retrieved information to reflect the most common classifications for the cost estimation of different manufacturing processes and the cost items generally used in the manufacturing technologies [44–47].

The *material* category refers to the costs of raw material necessary to produce a specific part/component. The raw material cost (also called gross cost) is the sum of the parts' net cost and waste cost. Material waste is divided in two categories: (i) scraps and (ii) defected parts. Authors define scraps as the material in excess of what is necessary for processing (e.g. flash in the forging process). For example, scraps can be contaminated with lubricant, which decreases their value because additional cleaning and decontamination operations are required for their reuse. Defected parts refer instead to non-compliant components realized during the initial process start-up or during production. A typical example of start-up waste can be found in the plastic injection process when a change of the component colour is made; initial pieces will

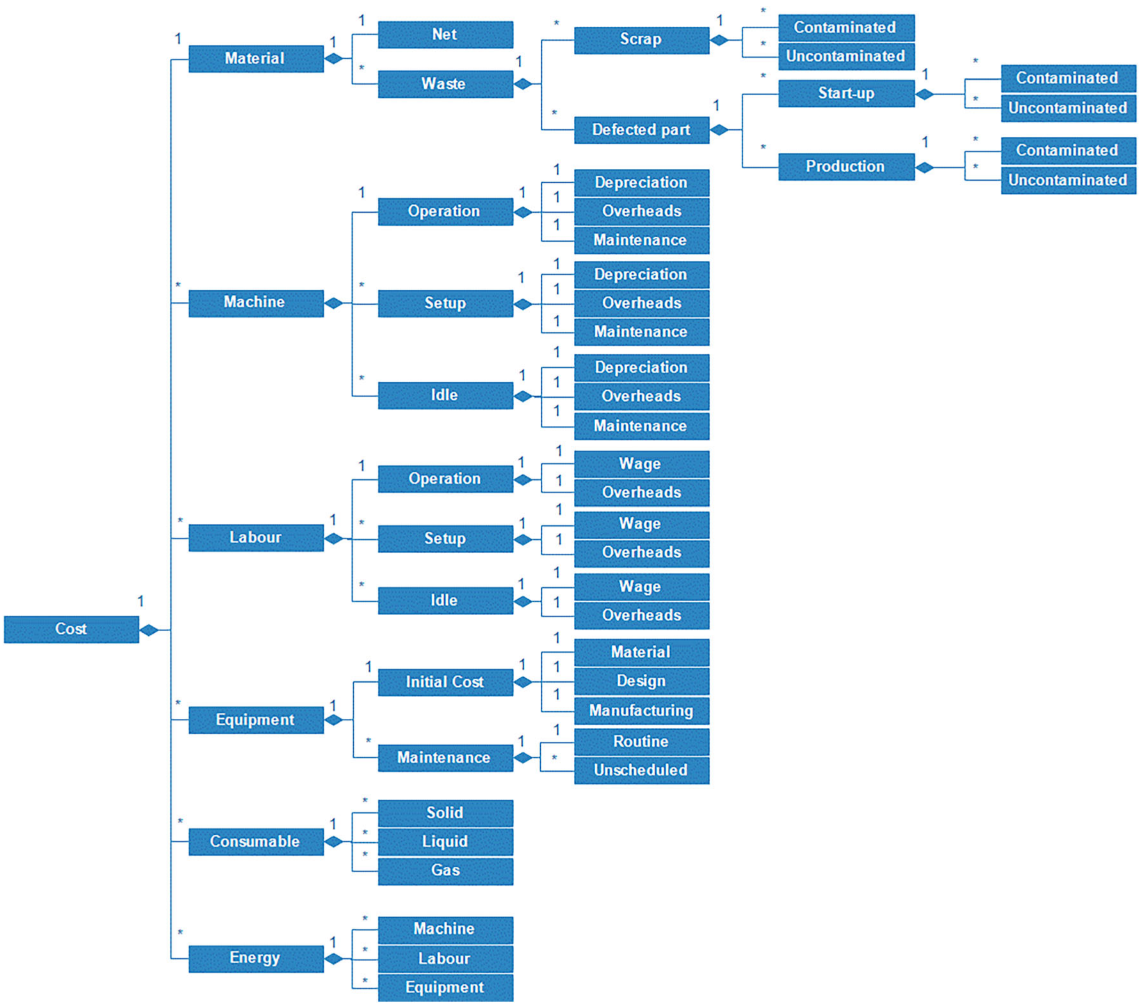

Fig. 2 Cost breakdown structure (UML class diagram)

not be of the expected colour, but there will still be some leftover pieces from the previous colour that remained inside the moulds. Both types of defected parts, i.e. those realized during start-up and those realized during production, are also classified into contaminated and uncontaminated pieces.

Machine and *labour* categories refer to the cost centres used for performing an operation. These costs are further classified into *operation*, *setup* and *idle*. For each process operation, according to the degree of automation, one/no machine and/or one/multiple worker(s) can be employed. The hourly cost rate of a machine comprises its maintenance, overhead and depreciation cost, whereas the rate for an operator comprises the operator's wage and overhead. The *operation* sub-category refers to the manufacturing operations (e.g. chip removal, plastic deformation) that directly contribute toward the realization of the final component. These items are considered a product's 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 are not yet completed or available. In this condition, the machine is theoretically available, but it does not perform any work. This item is also considered a product direct cost. The *setup* sub-category refers to those operations, such as tool setting and machine cleaning, required before beginning the production. These operations are independent of the batch dimension; hence, the related cost must be split according to the batch quantity for calculating the setup cost for each component. Therefore, the machine setup cost is considered an indirect cost.

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 the initial expenditure and the maintenance cost during its usage. The initial expenditure considers the cost for its design and manufacturing plus the material cost. This cost is independent of the production volume; hence, the related cost must be split for the production volume for calculating the equipment cost for each component. Therefore, the equipment cost is considered an indirect cost.

The *consumables* category refers to those materials that enable the process itself (e.g. lubricants used for forging, gas cutting assistance for laser cutting). This item 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) that guarantee that the process works. Energy may be required by machines and/or equipment, and the related cost is function of their power and working time. This item is considered a product direct cost.

2.2 Manufacturing cost routing

A cost routing is defined as a hierarchical data model of five constructs (light blue classes in Fig. 3), each containing sets of attributes and rules for generating manufacturing processes from 3D virtual prototypes of components. The hierarchical structure is required since the manufacturing process is defined through a multi-step approach (Section 2.4), starting from the setting of a production scenario to the calculation of the elementary operations necessary for transforming a raw material into a finished part. A manufacturing cost routing does not contain direct information for computing the cost of a process (cost models contain such knowledge).

Rules within a cost routing are required for generating a manufacturing process and can be classified into three groups: (i) *validity rules* used for establishing only the feasible manufacturing solutions among all the possible ones (required for multi-scenario simulation); (ii) *priority rules* used for sorting the feasible solutions, with the aim of selecting the best one (required to identify the optimized production process); and (iii) *calculation rules* used for computing process parameters (required for evaluating and sorting the manufacturing solutions) (see Fig. 3).

The five constructs of a cost routing are as follows:

- *Production scenario*: This is the first container of knowledge required for defining a manufacturing process and consists of a list of production strategies. A scenario could represent the context (e.g. the facilities and production technologies available) in which the manufacturing process is realized (e.g. make vs buy). At this level, validity and priority rules are required for establishing the production scenario in which a component is realized.
- *Production strategy*: This strategy defines the overall process to be used for realizing a component and contains a list of pairs, i.e. raw material and manufacturing strategies, that roughly determine the overall manufacturing process (e.g. machining from block vs machining from casting). For this element, validity and priority rules are both required for defining a specific production strategy.
- *Raw material strategy*: This strategy defines the raw material (e.g. commercial semi-finished material, casted/forged elements) to be used for realizing the final component. The characteristics of the raw materials are extracted from a related raw material feature, automatically computed by specific feature recognition algorithms. For this element, only validity and calculation (used for determining the size of a stock) rules are applicable.
- *Manufacturing strategy*: This strategy defines the specific manufacturing process to be used for transforming a raw material into a finished component (e.g. casting vs forging) and consists of a list of operations bundles. Each one has a list of validity and priority rules only.
- *Operations bundle*: An operations bundle 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,

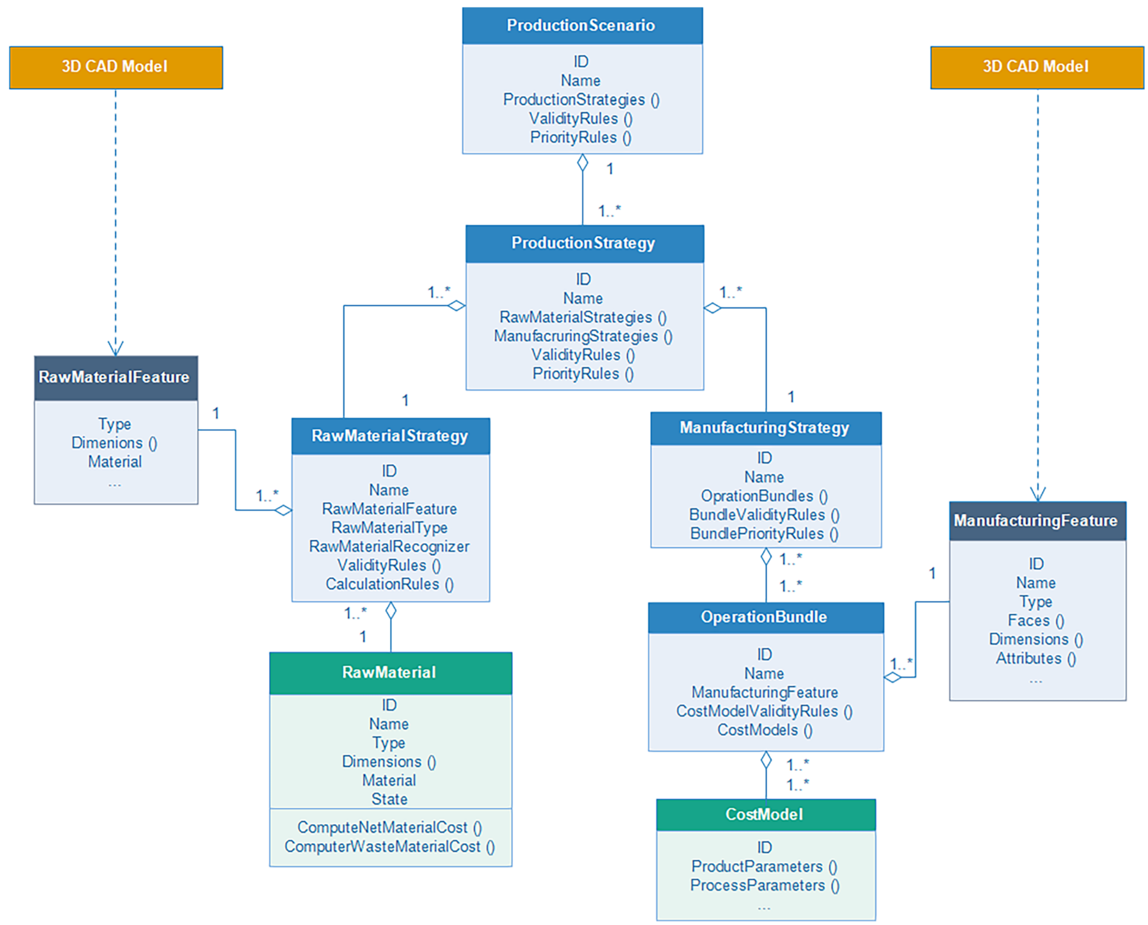

Fig. 3 Manufacturing cost routing structure (UML class diagram)

hole diameter, hole shape, minimum tolerance, minimum roughness). PMFs (e.g. holes, cut-outs, chamfers, fillets, turning features, welding features) are computed by feature recognition algorithms, which are encapsulated within specific recognizers: there is one specific recognizer for each kind of product to be analysed (e.g. a turned axisymmetric part, milled prismatic part, casted part or a forged part). A PMF can be alternatively realized by one bundle at a time. The PMF properties, different for each feature, are used within the validity rules of each bundle to establish which one is valid. The bundle is also responsible for transferring the PMF properties to the valid operations defined inside the bundle. Indeed, a bundle may contain multiple operations, whose validity is managed by validity rules defined within each operation.

2.3 Manufacturing cost model

A manufacturing operation is an elementary block of a more complex manufacturing process, directly instantiated by a bundle, as presented in the previous section. A *cost model* is a data model containing that knowledge required for estimating the production time and cost for each operation. A cost model is a structured object of information, as illustrated in Fig. 4, and consists of a list of product and process parameters. The product parameters are defined by the bundle and depend on the manufacturing feature associated with the bundle. The process parameters characterize the manufacturing operation from a technological standpoint. These parameters (e.g. injection temperature and pressure, mould temperature, injection tonnage, mould dimensions), 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 also contains several validity rules and calculation rules. The first are used for limiting the possible cost centres (machine and labour), energy vectors, consumables, equipment and materials applicable for a specific operation. The latter are used for calculating the consumption of the energy vector, consumables, equipment and the generation of waste. Finally, consistent with the cost breakdown presented in Fig. 2, an operation contains rules for computing the manufacturing time and cost.

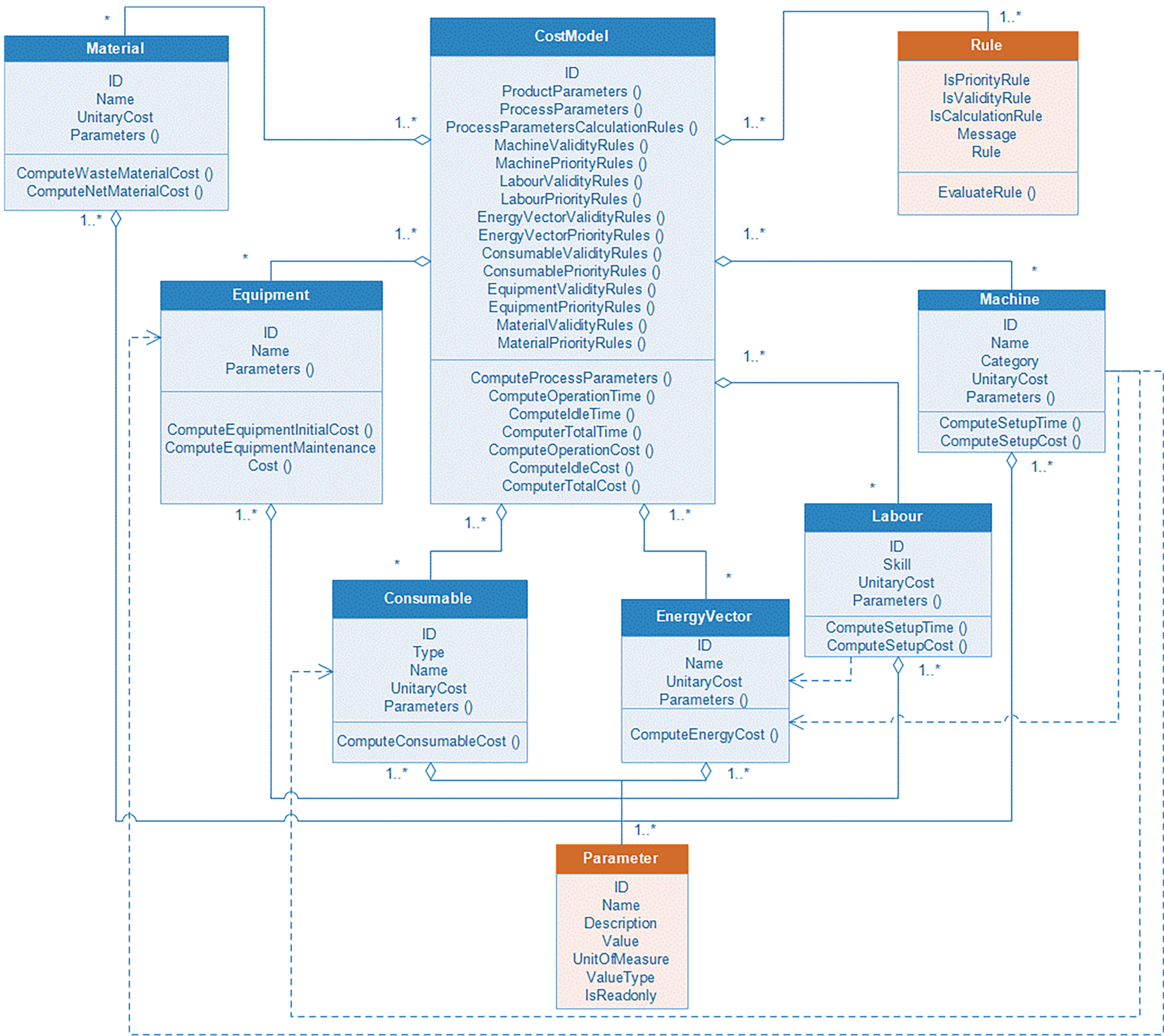

Fig. 4 Manufacturing cost model structure (UML class diagram)

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

- *Machine*: The machine is the cost centre used for realizing the operation. Each operation has a list of available machines, which are restricted by a list of validity rules (e.g. press tonnage must guarantee a camping force greater than that one required by the process, a plate size greater than the mould, an injection volume greater than the component and runner volumes). Note that process parameters are influenced by the machine (e.g. injection time depends on the press power).
- *Labour*: Labour is another cost centre that can be used for realizing the operation. Its behaviour is the same as that of the *machine*.
- *Energy*: Regarding an energy vector, such as electricity, each operation uses one energy vector, multiple energy vectors or no energy vector. The energy consumption mainly depends on the machine, product and process parameters (e.g. electricity consumption depends on the machine power and time of usage).
- *Consumable*: Regarding consumables, such as lubricants, cutting tools and cutting assistance gas, each operation uses one consumable, multiple consumables or no consumable. The consumable consumption mainly depends on the machine, product and process parameters.
- *Equipment*: Regarding equipment, such as jigs, fixture and moulds, each operation uses one piece of equipment, multiple pieces of equipment or no equipment. The equipment depends by the machine and some process parameters (e.g. batch size, production volume), while influences

other process parameters (e.g. hot chambers are used to reduce raw material scrap).

- *Waste*: Each operation generates scraps or defected parts during the process start-up or normal production. Waste depends on both the product and process parameters (e.g. process scrap refers to the runner volume) and the maturity of a process (learnability curve).

All this information contributes to the calculation of the operations cost. While at least one machine or labour is required, all the other components are optional (e.g. a consumable is not applicable for injection moulding).

2.4 Workflow for the definition of a manufacturing process

The analytical manufacturing cost estimation process, starting from a 3D virtual prototype of a component, is a sequence of multiple steps, and the calculation of its cost breakdown is presented in Fig. 2 (UML sequence diagram). The workflow consists of six decision steps (Fig. 5), each one supported by the proper knowledge required for defining a manufacturing process (combination of databases and knowledge-based rules).

The cost estimation process is based on the following set of product and process-related information:

- *3D CAD model*: This is the BRep (boundary representation) model of the component that will be further analysed for extracting process-specific attributes (e.g. stamping direction, quantity of undercuts) required for defining the manufacturing process.
- *Geometrical and non-geometrical attributes*: These attributes are the general attributes, such as overall dimensions, maximum/average thickness, weight, material and shape (i.e. axisymmetric, prismatic, sheet metal), that are retrieved from the 3D CAD model.
- *Product manufacturing information* (*PMI*): These are the attributes, such as roughness, tolerances, welding length and other attributes (e.g. surface coatings, heat treatments, surface finishing), that are related to the manufacturing process and are directly linked to the 3D CAD model.
- *Process attributes*: These attributes denote information related to manufacturing aspects, such as batch size, production volume and delivery time.

The first step (1a, 1b, 1c and 1d sub-steps) of the cost estimation process is the establishment of the overall production scenario. Indeed, the manufacturing process and the related costs first depend on the production environment (PE), which is characterized by the production facility (e.g. machine tools, tools, plant layout and overall equipment effectiveness), the raw materials' warehouse and the sourcing strategy. The selection of the right PE is usually determined by vendor ratings and supplier selection methodologies.

The second step of the cost estimation process is the definition of the production strategy and includes the selection of the raw material and manufacturing process. The selection of raw material type (e.g. commercial semi-finished product vs custom stock) and the manufacturing process type (e.g. die casting vs chip forming) is performed at the same time since these two aspects are dependent on each other. For example, the injection moulding process is valid only for thermoplastic polymers (validity rule), which are appropriate only for production volumes greater than thousands of components (priority rule). The validity of a production strategy is also triggered by the validity of the raw material and manufacturing strategy (if one of these rules are not valid, then, the production strategy where such manufacturing or raw material strategies are used will be invalidated).

The third step (3a, 3b and 3c sub-steps) of the cost estimation process is the definition of raw material features. Based on the information on the type of material, some features are assessed by the model such as the following: the type of supplied material (e.g. commercial bar, sheet metal or billet); the

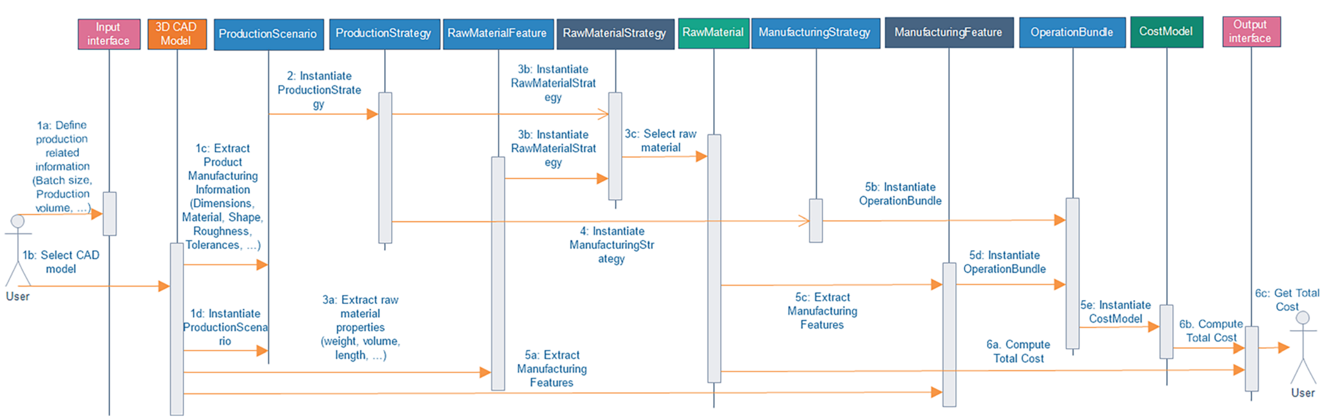

Fig. 5 Workflow for defining a manufacturing process (UML sequence diagram)

shape (e.g. circular, rectangular or solid/hollow); the dimensions (e.g. thickness, length, width and height); the supply status (e.g. hot rolled, extruded, grinded or galvanized); the volume; the weight; and the unitary cost. The type of supplied material is computed according to the product-related information previously presented, by using validity and calculation rules. For injection moulding, only thermoplastic polymer granules can be used (validity rule), while the raw material volume is computed considering the part volume plus the volume of runners (calculation rules). For computing such information, feature recognition algorithms should be employed for analysing the 3D CAD model, with the aim of defining specific raw material features consisting of a set of geometrical information required for selecting the stock [48, 49]. The raw material cost is computed by multiplying the amount of requested material by the unitary cost.

The fourth step of the cost estimation process is the definition of the manufacturing strategy to be employed for making a component/product. For example, mass products should be realized by adopting high-production processes and machines. Considering the injection moulding as example, this process is feasible only for thermoplastic materials.

The fifth step (5a, 5b, 5c, 5d and 5e sub-steps) is an intermediate phase before the calculation of the operations sequence. Indeed, a whole component or a group of its surfaces can be realized employing multiple and different operations. For example, although a specific manufacturing strategy may be already defined, a hole (according to its shape, diameter, depth, roughness, tolerance and product material) can be realized by adopting different operations. Indeed, for a milling from a block strategy, a hole can be realized with a simple drilling operation or rather from combining drilling and boring operations according to the dimensional tolerance for its diameter. The operations bundle is the container of knowledge that provides the definition of the sequence of operations required for a certain product manufacturing feature.

The sixth step (6a, 6b and 6c sub-steps) consists in combining all the valid operations calculated up to now (with related cost) to define the operations list that represents the manufacturing process of a product. The total manufacturing cost is computed by adding the raw material cost and the cost of each single operation.

3 Case study

This section presents the complete set of knowledge, organized according to the proposed framework, for analytically estimating the cost of open-die forged components. The chapter illustrates the forging process for two important axial compressor components, namely, the discs (axisymmetric components where blades are fixed on the external cylindrical surface) and the shaft (axisymmetric component connecting all the discs). Section 3.1 presents the overall forging process considered in the case study, and Section 3.2 presents both the workflow for defining a manufacturing process and the cost routing developed for open-die forging. Section 3.3 presents the cost models for this process.

3.1 Open-die forging introduction

Hot forging is an industrial process where a metal piece, heated above the recrystallization temperature, is deformed through a series of dies (the surfaces that are in contact with the work-piece), with repeated strokes of a hammer or a forging press, which permanently changes the shape of the part. Open-die forging is a type of hot forging and it is so named due to the fact that the dies do not enclose the work-piece, allowing it to flow except where obliged by the dies. Therefore, the work-piece is oriented and positioned to obtain the desired shape. This process is different from closed-die forging because open-die forging uses flat dies, whereas closed-die forging employs multiple shaped tools, such as moulds, that are used for casting processes. The size of a forged piece that can be produced in open-die is limited only by the capacity of the equipment available for heating, handling and forging.

Open-die forging operations are explained in Fig. 6. The process begins by heating a custom ingot or a billet, which is cut from a commercial bar. Depending on the dimensions and part shape, different production machines may be employed. Once the forging process is completed, even including the related heat treatments, the forged piece can be machined (e.g. milling, turning or grinding) to obtain the correct dimension, surface roughness and dimensional allowance of the part [50]. In fact, the achievable surface roughness in open-die are between 30 and 100 μm, while the dimensional allowance is

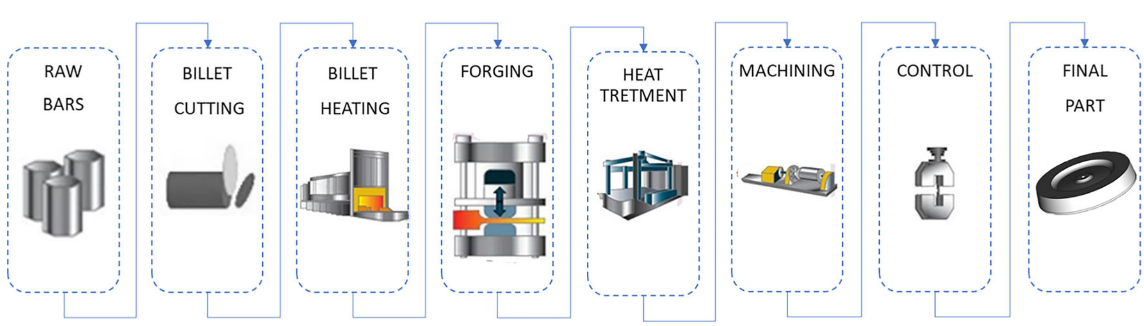

Fig. 6 Open-die forging process

Table 2 Production strategies for open-die forging

Production strategy	Raw material strategy	Manufacturing strategy	Validity rules	Priority rules
Open-die forging of disc from bar	Bar	Disc open-die forging	–	IF (Production.BatchQuantity > 10) THEN Score = 0 ELSE Score = 10
Open-die forging of disc from billet	Billet	Disc open die forging	Piece.Material.Category = "Metal" Piece.Volume > 8dm3 NOT (Piece.Shape = "Hollow") NOT (Piece.Shape = "SheetMetal")	IF (Production.BatchQuantity > 10) THEN Score = 10 ELSE Score = 0 IF (Piece.Volume > 25dm3) THEN Score = 10 ELSE Score = 0
Open-die forging of shaft from billet	Billet	Shaft open-die forging	Piece.Material.Category = "Metal" Piece.Volume > 8dm3 AND Piece.Volume ≤ 5 E03 dm3 NOT (Piece.Shape = "Hollow") NOT (Piece.Shape = "SheetMetal")	IF (Production.BatchQuantity > 5) THEN Score = 10 ELSE Score = 0 IF (Piece.Volume > 25dm3) THEN Score = 10 ELSE Score = 0
Open-die forging of shaft from ingot	Ingot	Shaft open-die forging	Piece.Material.Category = "Metal" Piece.Volume > 5 E03 dm3 NOT (Piece.Shape = "Hollow") NOT (Piece.Shape = "SheetMetal")	IF (Production.BatchQuantity > 5) THEN Score = 10 ELSE Score = 0
Forging of ring from billet	Billet	Ring open-die forging	Piece.Material.Category = "Metal" Piece.Volume > 8dm3 Piece.Shape = "Hollow" NOT (Piece.Shape = "SheetMetal")	IF (Production.BatchQuantity > 10) THEN Score = 10 ELSE Score = 0 IF (Piece.Volume > 25dm3) THEN Score = 10 ELSE Score = 0

higher than IT14. IT Grade refers to the International Tolerance Grade of an industrial process defined in ISO 286 [51]. An industrial process has an IT Grade associated with it, indicating how precise it is. This grade identifies what tolerances a given process can produce for a given dimension.

3.2 Open-die forging process calculation

According to Fig. 5, the workflow for defining a manufacturing process begins by first selecting the *production environment*. Then, the production country or plant is chosen, and the unitary costs of materials and energy and the hourly rates of machines and labour are consequently established. The rules used at this stage do not depend on the process itself but rather depend on the supply strategies of the company that is developing the product.

The selection of the *production strategy* consists of establishing the raw material and manufacturing process (Table 2). All forgeable metals can be employed in open-die, and a list of forgeable materials is available in [50]. The manufacturing strategy depends on the realized product's variables (i.e. its shape and dimensions). Generally, the open-die forging process variants can be grouped into four categories: (i) cylindrical forging (shaft-type forgings symmetrical along the piece longitudinal axis), (ii) upset or pancake forgings, (iii) hollow forging (including mandrel and shell-type forgings) and (iv) contour-type forging. In this paper, the case study considers three shapes, namely, *disc* (cylindrical shape), *shaft* (cylindrical and multi-diameter shape) and *ring* (cylindrical ring); the shapes are realized by employing the aforementioned processes.

The material and the manufacturing process are then closely related. However, the manufacturing process also depends on the shape of the piece, its dimensions, the required tolerances and its surface roughness.

The *raw material strategy* consists in selecting the initial stock and is a function of the amount of material needed for the final piece (Table 3). Material costs usually make more than 50% of the forging costs, and a significant proportion of this material is waste [25]. The material cost is determined by the weight of the forged part (RawMaterial.Density*Piece.Volume)

Table 3 "Billet" raw material strategy

Validity rules	Calculation rule
Piece.Volume > 8dm3 Piece.Volume ≤ 5 E02 dm3	IF (Piece.Shape = "Axysimmetric" THEN RawMaterial.CrossSectionType = "Circular" ELSE RawMaterial.CrossSectionType = "Prismatic") RawMaterial.Material = Piece.Material RawMaterial.Volume = (Piece.Volume+BilletCutting.Waste.Volume+Machining.Volume) * (1 + ScaleLoss.Percentage/100) RawMaterial.Width = Round((2 RawMaterial.Volume / π)^(1/3);-1) RawMaterial.Length = (RawMaterial.Volume * 4) / (π * RawMaterial.Width^2) RawMaterial.Cost = RawMaterial.Volume * RawMaterial.Density * RawMaterial.UnitaryCost – (Machining.Volume+ BilletCutting.Waste.Volume) * RawMaterial.Density * Scrap.UnitaryRevenue

Table 4 "Disc open-die forging" manufacturing strategy

Manufacturing strategy validity rules	Operations bundles	Bundles validity rules	Bundles priority rules
NOT (Piece.Shape = "Hollow" Piece.Shape OR Piece.Shape = "Hollow" Piece.SheetMetal)	Open-die forging	Always valid	N/A (no alternative bundles available)
	Non-destructive test	Piece.NDTRequested	N/A (no alternative bundles available)
	Heat treatment	Always valid	N/A (no alternative bundles available)
	Turning with multitasking lathe	Piece.GeneralRoughness < 25 Piece.GeneralTolerance < IT14	IF (Production.BatchQuantity < 10) THEN Score = 10 ELSE Score = 0
	Turning + milling	Piece.GeneralRoughness < 25 Piece.GeneralTolerance < IT14	IF (Production.BatchQuantity ≥ 10) THEN Score = 10 ELSE Score = 0

and by the wastes generated during the process. The cost for defected parts can be considered negligible in this example because a wrong part can be remodelled during the process. The waste losses (scraps) depend on the "production strategy" adopted and on the size of the component. Scraps can be divided into (i) waste during billet cutting (BilletCutting.Waste.Volume), (ii) scale oxidation losses (ScaleLoss.Percentage) and (iii) the machining allowance loss for chip forming (Machining.Volume).

Due to the heating of the material, scale loss is always present in hot forging. The outer surface of the hot metal is generally oxidized, and during the deformation, the oxidized film breaks and falls down in the form of scale. Scale is generally a percentage of total volume and is a function of the material forged. Machining loss should be considered only if a chip-forming process is present after the hot forging. The amount of machining loss depends on the part dimensions.

The amount of raw material depends on the volume of the component and therefore on the amount of material necessary for the entire process. For medium-small-sized components (Piece.Volume > 8dm3 AND Piece.Volume ≤ 5 E02 dm3), the stock is a billet cut from a commercial bar. To avoid inflexion problems, the ratio between the billet height (RawMaterial.Length) and its diameter (RawMaterial.Width) is generally higher than 1.5 and lower than 3. In parts with a larger volume (Piece.Volume > 5 E02 dm3), the maximum commercial size diameter of the stock could lead to a ratio greater than 3. In this case, if the instability limits are exceeded, a custom stock (ingot) is used instead of a billet [50].

Once the stock strategy is defined, the *manufacturing strategy* can be selected (Table 4). A manufacturing strategy covers all the bundles available for a given strategy. For the open-die forging process, the manufacturing strategies are divided according to the type of component (disc, shaft and ring).

For example, Table 5 shows an analysis of an open-die forged disc of a gas turbine. After the forging process, the chip-forming operations are required to achieve the final dimensional tolerances and surface roughness. For this part of the process, there are 5 bundles: (i) open-die forging, (ii) non-destructive test, (iii) heat treatment, (iv) turning with the multitasking lathe and (v) turning plus milling. The open-die forging bundle consists of the following four principal operations:

Table 5 "Open-die forging" operations bundle

Operations	Operation validity rules	Product parameters
Billet sawing	RawMaterial.CrossSectionDimension1 > 300 mm	Operation.Area = RawMaterial.CrossSectionArea
Billet shearing	RawMaterial.CrossSectionDimension1 ≤ 300 mm	Operation.Area = RawMaterial.CrossSectionArea
Billet heating	Always valid	Operation.Width = Piece.Width * Furnace.BachtSize Operation.Height = Piece.Height
Billet forging (upsetting)	Always valid	Operation.Width = Piece.Width Operation.Height = Piece.Height Operation.ProjectedArea = (π* Piece.Width^2)/4 Operation.Volume = Piece.Volume
Billet forging (radial blow)	Always valid	Operation.Width = Piece.Width Operation.Height = Piece.Height Operation.ProjectedArea = (π* Piece.Width^2)/4 Operation.BlowNumbers = 12

- Billet cutting (sawing is alternative to shearing)
- Billet heating
- Forging (upsetting)
- Forging (radial blow)

3.3 Open-die forging cost calculation

Once the sequence of operations connected to the open-die forging process is established, to explore how the proposed framework can be used for defining open-die forging cost models, it is possible to do an in-depth examination of each single operation. For the sake of brevity, this section focuses only on the forging process for a cylindrical disc. Appendix Table 8 summarizes the cost models of the "open-die forging" bundle.

3.3.1 Billet cutting (sawing or shearing)

The method of cutting off bars is determined by the edge condition required for subsequent operations and by the billet cross-section area. The sawing process usually produces a uniform cut edge without damaging the material microstructure. Billet separation by shearing is a process without material loss and with a production rate considerably higher than that from sawing. Furthermore, the shearing process does not require cutting fluids. Shearing is preferable; however, while in sawing, machine size selection is only a function of the maximum bar weight and cutting area of the billet, in billet shearing, the cutting force is also involved in machine selection. The cutting force is function of the billet's cross-section and the billet material [52]. Therefore, if there is not a shearing machine with enough cutting force, sawing must be chosen. For this reason, a billet with a cross-section width larger than 300 mm has to be cut with a band saw machine.

3.3.2 Billet heating

Generally, heating takes place in gas or electric convection furnaces. Furnace typology is based on the type of machines available in the forging plant. For any forging material, the heating time must be enough to reach the forging temperature within the centre of the forging stock. Heating time is function of material and piece dimensions. For example, for a steel stock measuring up to 75 [mm] in diameter, the heating unitary time (minutes per inch of section thickness Heating.Unitary.Time) should be no more than 5 [min] for low-carbon and medium-carbon steels or no more than 6 [min] for low-alloy steel. Heating unitary time also increases with billet dimensions [50].

3.3.3 Billet upsetting

Upset forging is a manufacturing process through which the billet cross-dimension is increased to the length detriment. First, for discarding of invalid machines, the hammer or press dimensional limits must be compared with billet and forged final shape dimensions. Second, the energy or load required for forging must be calculated for refining the machine size selection. Open-die forging is realized by using hydraulic presses (load-restricted machines) or hammers (energy-restricted machines). This choice is related to the types of machines available at the forging plants. If a hydraulic press is used, the deformation force of the billet is calculated, and the operation must be carried out in one stroke. The machine must have a tonnage higher than the force for upsetting (Upsetting.Tonnage). Vice versa, if a hammer is used, the energy to deform the piece must be calculated. In this situation, piece upsetting can be made by using multiple strokes. The number of strokes (Operation.BlowNumbers) multiplied by the energy of the machine must be greater than the deformation energy (Upsetting.Energy). The magnitude of the forces and energy in upsetting is influenced by the kind of lubricant used at the die-work-piece interface. Lubricants serve to separate the die and work-piece surfaces, thereby reducing friction. The lubricant type is function of the forged material.

3.3.4 Billet radial blowing

To reduce barrelling after upsetting, the piece is rotated 90° and radially deformed. The quantity of strokes (Operation.BlowNumbers) for lateral surface flattening is a function of the piece diameter and barrelling amount, but generally, 12 radial strokes are enough to achieve the required radial deformation. This operation is generally carried out in the same forging machine used in upsetting because the energy or the force required for radial forging is lower than that required for upsetting.

3.3.5 Total cost calculation

Once the operations that constitute the overall forging process are established, the following variables are calculated for each operation:

- Raw material required
- Operation, setup and idle time for machines and labour
- Equipment required
- Solid, liquid and gas consumables consumption
- Energy consumption for the employed vectors

Table 6 Outcomes of the framework implementation. The open-die forging case study

Requirement	Context	Outcome	Comment	Additional action
Detailed cost breakdown structure to be used for an in-depth cost analysis	Cost breakdown	Addressed	The material, machine and labour cost items are more detailed in this paper than they are in the literature. For example, the differentiation between contaminated and uncontaminated waste was not observed in the literature. Equipment, consumable and energy cost items have the same structure as that shown in the literature.	None
General cost breakdown structure to be used for forming processes	Cost breakdown	Addressed	The cost breakdown presented in this paper is general and has been tested for open-die forging (case study). The authors evaluated that it can be used also for other forming processes (e.g. injection moulding).	None
Workflow for defining manufacturing processes from 3D virtual prototypes of components	Workflow	Addressed	The workflow presented in this paper may be used for all the forming processes.	None
Workflow for defining manufacturing processes from 3D virtual prototypes of assemblies	Workflow	To be addressed	The workflow presented in this paper cannot be used for defining the manufacturing process and cost of assemblies.	A workflow for assemblies should be defined.
General structure for collecting knowledge-based rules for defining a manufacturing process	Cost routing	Addressed	The cost routing structure presented in this paper can be easily used for collecting the knowledge required for defining the manufacturing process and the related cost of single components.	None
Optimization methods for cost routing	Cost routing	To be addressed	The cost optimization of a manufacturing process should evaluate multiple and alternative solutions to find the best one. For example, the best production strategy should be defined after the evaluation of all the other valid strategies. In this case, priority rules will be neglected.	The cost routing structure for managing objectives, variables and the constraints of an optimization problem should be improved.
Process yield	Cost routing	To be addressed	The cost routing structure does not provide a method for managing process yield. Each operation should be characterized by a success rate. If an operation is not correctly performed, all the cost encountered until that operation performs correctly should be considered as extra-costs.	The cost routing structure must manage the yield for each operation within the process.
Sorting of process operations	Cost routing	To be addressed	The cost routing structure does not provide a method for sorting operations within a manufacturing process. Only validity and priority rules are managed. The operations order may depend on the process; thus, specific rules should be defined.	The cost routing structure for managing rules to be used for sorting operations should be improved.
Cost routings for joining processes	Cost routing	To be addressed	The cost routing structure cannot be used for assemblies.	Additional cost routings should be conceived for automatically estimating the cost of multi-level assemblies.
General cost model to be used for forming processes	Cost model	Addressed	A cost model has been tested for open-die forging (case study). The authors evaluated that it can be used also for other forming processes (e.g. injection moulding).	None
Cost model to provide cost breakdown according to the structure proposed in Section 2.2	Cost model	Addressed	The calculation rules of a cost model may be organized for computing the cost in accordance with the cost breakdown.	None
Optimization methods at cost model	Cost model	To be addressed	The cost model structure does not provide a method for optimizing the cost of each operation by changing technological parameters (e.g. machine, equipment, consumables) and respecting constraints. For example, the best machine may not be the cheapest one but the one that guarantees the minimum manufacturing cost.	The cost model structure for managing objectives, variables and constraints of an optimization problem should be improved.

Table 7 Qualitative evaluation of the framework

Criteria	Explanation of criteria	Available scores	Result
Completeness	Completeness addresses whether the cost model and the data structure lack some items or whether its usage requires customization	High Medium Low	High
Understandability	Understandability addresses whether the whole structure of the cost model and the and data arrangement (cost breakdown) are easy to understand	High Medium Low	Medium
Ease of use	Ease of use addresses the capability of the user to use the implemented framework without external training/help	High Medium Low	Medium
Fidelity with real-world phenomena	Fidelity addresses whether the model reflects relationships that occur in real world	High Medium Low	Medium/high
Efficacy	Efficacy addresses whether the workflow and cost model produce the desired effect (i.e. whether it achieves its goal)	High Medium Low	High
Effectiveness and generality	Generality addresses whether the overall framework can cover different applications and technologies	High Medium Low	Medium/high
Impact to user	Impact addresses whether the use of the proposed workflow including the cost routing affects the environment (organization) and the users' jobs (daily practice)	High Medium Low	Medium

The equations used for computing such variables are available in Appendix Table 8. The cost of forged components is calculated by first summing the cost of each operation included within the *open-die forging* bundle (Eq. 1).

$$C_{\text{open-die forging bundle}} = C_{\text{billet cutting}} + C_{\text{billet heating}} + C_{\text{forging (upsetting)}} + C_{\text{forging (radial)}} \quad (1)$$

The cost of the overall manufacturing process is calculated by summing the cost of each bundle (Eq. 2).

$$C_{\text{open-die forging disc}} = C_{\text{open-die forging (bundle)}} + C_{\text{chip forming (bundle)}} + C_{\text{control and treatment (bundle)}} \quad (2)$$

Finally, the cost of the forged component is calculated by summing the raw material and the process cost (Eq. 3).

$$C_{\text{forged component}} = C_{\text{open-die forging disc}} + C_{\text{Raw material}} \quad (3)$$

4 Result discussion

The proposed method has been used for modelling the manufacturing knowledge related to an open-die forging process; however, the framework can be extended to other forming processes, such as casting and chip forming.

Concerning the specific case study, the constructs of the proposed framework (cost breakdown, cost routing, cost model and workflow) have been evaluated based on a set of requirements defined within the literature analysis and the findings of the specific case study. For each requirement, Table 6 presents the results achieved in this research work and relative comments. Two outcomes for each cost item have been identified (see Table 6):

- The *requirement was addressed considering the existing state-of-the-art barriers*: the requirement obtained from the literature review was satisfied; therefore, the proposed framework is complete and more comprehensive than the one proposed in the literature.
- The *requirement needs to be addressed considering the existing state-of-the-art barriers*: based on the requirements obtained from the literature review and the analyses of the results, in future research, improvements for this item need to be made.

In addition, Table 6 reports whether outcomes resulting from the analysis of the open-die forging can be extended to other forming processes as well as to a general manufacturing process (e.g. assembly) and indicates the additional actions that are required.

The 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, in particular, for the management of different objectives, variables and constraints of an optimization problem, as well as for the

Appendix

Table 8 "Open-die forging" operations bundle and relative calculation rules

Operation	Material	Machine	Labour	Equipment	Consumable	Energy
Billet sawing	**Validity rules** N/A (material selected in production strategies)	**Validity rules** Machine.Category = (SawingMachine) Machine.MaxSizeX > Piece.Width Machine.MaxSizeY = RawMaterial.Height Machine.MaxSizeZ > Piece.Width	**Validity rules** Labour.Skill = "*Sawing Operator*"	**Validity rules** N/A (no tool required)	**Validity rules** **Solid** Consumable.Solid.Type = NA **Liquid** Consumable.Liquid.Type = "*CuttingFluid*" **Gas** Consumable.Gas.Type = N/A	**Validity rules** Energy.Vector = "*Electricity*"
	Priority rules N/A (material selected in production strategies)	**Priority rules** Minimum hourly rate	**Priority rules** N/A (only one kind of operator allowed)	**Priority rules** N/A (no tool required)	**Priority rules** N/A (only one fluid type allowed)	**Priority rules** N/A (only one energy vector allowed)
	Calculation rules **Net** Material.NetWeight = Piece.Volume * Piece.Density Material.NetCost = Material.NetWeight * Material.UnitaryPrice **Waste** Material.WasteWeight = RawMaterial.CrossSectionArea * Sawing.Waste.Percentage/100 * Piece.Density Material.WasteCost = Material.WasteWeight * Material.UnitaryScrapPrice **Balance** Material.Cost = Material.NetCost + Material.WasteCost	**Calculation rules** **Operation** ProcessTime = Machine.CuttingRate * RawMaterial.CrossSectionArea 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** **Initial** N/A (no tool required) **Maintenance** N/A (no tool required)	**Calculation rules** **Solid** N/A **Liquid** Consumable.Quantity = Consumable. Hourly.Quantity * ProcessTime **Gas** N/A	**Calculation rules** **Machine** EnergyCost.Machine = (Machine.Power * Machine.LoadFactor * ProcessTime) * Energy.UnitaryCost **Equipment** EnergyCost.Equipment = 0
Billet shearing	**Validity rules** N/A (material selected in production strategies)	**Validity rules** Machine.Category = "*HydraulicPress*" ShearingRequestedTonnage = Shearing.Tonnage Machine.Tonnage >ShearingRequestedTonnage Machine.MaxSizeX > Piece.Width Machine.MaxSizeY > RawMaterial.Height Machine.MaxSizeZ > Piece.Width	**Validity rules** Labour.Skill = "*Shearing Operator*"	**Validity rules** N/A (no tool required)	**Validity rules** N/A (no consumable required)	**Validity rules** Energy.Vector = "*Electricity*"
	Priority rules N/A (material selected in production strategies)	**Priority rules** Minimum hourly rate	**Priority rules** N/A (only one kind of operator allowed)	**Priority rules**	**Priority rules** N/A (no consumable required)	**Priority rules** N/A (only one energy vector allowed)

Table 8 (continued)

Operation	Material	Machine	Labour	Equipment	Consumable	Energy
				N/A (no tool required)		
	Calculation rules **Net** Material.NetWeight = Piece.Volume * Piece.Density Material.NetCost = Material.NetWeight * Material.UnitaryPrice **Waste** N/A (scraps negligible)	**Calculation rules** **Operation** ProcessTime = 1 / 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 (no tool required)	**Calculation rules** N/A (no consumable required)	**Calculation rules** **Machine** EnergyCost.Machine = (Machine.Power * Machine.LoadFactor *ProcessTime) * Energy.UnitaryCost **Equipment** EnergyCost.Equipment = 0
Billet heating	**Validity rules** N/A (material selected in production strategies)	**Validity rules** Machine.Category = "*ElectricFurnace*" OR "*GasFurnace*" Machine.MaxSizeX > Piece.Width Machine.MaxSizeY > Piece.Width* Furnace.BachtSize Machine.MaxSizeZ > Billet.Length	**Validity rules** Labour.Skill = furnace operator	**Validity rules** N/A (no tool required)	**Validity rules** N/A (no consumable required)	**Validity rules** IF Machine.Category = "*ElectricFurnace*" THEN Energy.Vector = "*Electricity*" ELSEIF Machine.Category = "*GasFurnace*" THEN Energy.Vector = "*Gas*"
	Priority rules N/A (material selected in production strategies)	**Priority rules** Minimum hourly rate Minimum energy unitary cost	**Priority rules** N/A (only one kind of operator allowed)	**Priority rules** N/A (no tool required)	**Priority rules** N/A (no consumable required)	**Priority rules** N/A (energy vector set by machine.category)
	Calculation rules **Net** – **Waste** BilletHeating.Waste.Volume (Piece.Volume+ BilletCutting.Waste.Volume+ Machining.Volume) * ScaleLoss.Percentage/100 Material.Cost = BilletHeating.Waste.Volume * Piece.Density * Material.UnitaryPrice	**Calculation rules** **Operation** IF RawMaterial.Material = "*LowCarbonStell*" AND RawMaterial.Width ≤ 75 mm THEN Heating.Unitary.Time = 5 minutes per inch ELSEIF RawMaterial.Material = "*MediumCarbonStell*" AND RawMaterial.Width ≤ 75 mm THEN Heating.Unitary.Time = 6 minutes per inch ELSEIF RawMaterial.Material = "*LowCarbonStell*" AND RawMaterial.Width > 75 mm AND RawMaterial.Width ≤ 230 mm THEN Heating.Unitary.Time = 15 minutes per inch …	**Calculation rules** **Operation** LabourProcessCost =ProcessTime * Labour.HourlyRate / FurnaceBatch * OperatorsQuantity **Setup** LabourSetupCost =SetupTime * Labour.HourlyRate / FurnaceBatch * OperatorsQuantity **Idle** LabourIdleCost = IdleTime *	**Calculation rules** N/A (no tool required)	**Calculation rules** N/A (no consumable required)	**Calculation rules** **Machine** EnergyCost.Machine = (Machine.Power * Machine.LoadFactor * ProcessTime) * Energy.UnitaryCost / FurnaceBatch **Equipment** EnergyCost.Equipment = 0

Table 8 (continued)

Operation	Material	Machine	Labour	Equipment	Consumable	Energy
		ProcessTime = Heating.Unitary.Time * RawMaterial.Width MachineProcessCost = ProcessTime * Machine.HourlyRate / FurnaceBatch **Setup** SetupTime = Machine.SetupTime / Production.BatchQuantity MachineSetupCost = SetupTime * Machine.HourlyRate / FurnaceBatch **Idle** IdleTime = 0 MachineIdleCost = IdleTime * Machine.HourlyRate / FurnaceBatch	Labour.HourlyRate / FurnaceBatch * OperatorsQuantity			
Billet forging (upset-ting)	**Validity rules** N/A (material selected in production strategies)	**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 (no tool required)	**Validity rules** **Solid** IF RawMaterial.Material = "*Aluminium*" THEN Consumable.Solid.Ty-pe = "*Solids*" ELSEIF RawMaterial.Material = "*Steel*" OR RawMaterial.Material = "*StainlessSteel*" THEN Consumable.Solid.Ty-pe = Graphite **Liquid** Consumable.Liquid.Type = NA **Gas** Consumable.Gas.Type = NA	**Validity rules** Energy.Vector = "*Electricity*"
	Priority rules N/A (material selected in production strategies)	**Priority rules** Minimum hourly rate	**Priority rules** N/A (only one kind of operator allowed)	**Priority rules** N/A (no tool required)	**Priority rules** N/A (only one consumable per material allowed)	**Priority rules** N/A (only one energy vector allowed)
	Calculation rules **Net** – **Waste** N/A (scraps negligible)	**Calculation rules** **Operation** ProcessTime = BlowNumbers /Machine.BlowRate MachineProcessCost = ProcessTime * Machine.HourlyRate **Setup**	**Calculation rules** **Operation** LabourProcessCost = ProcessTime * Labour.HourlyRate * OperatorsQuantity **Setup**	**Calculation rules** N/A (no tool required)	**Calculation rules** **Solid** Consumable.Quantity = Consumable. Hourly.Quantity* Operation.ProcessTime **Liquid** N/A	**Calculation rules** **Machine** EnergyCost.Machine = (Machine.Power * Machine.LoadFactor * Operation.ProcessTime) * Energy.UnitaryCost **Equipment**

Table 8 (continued)

Operation	Material	Machine	Labour	Equipment	Consumable	Energy
		SetupTime = Machine.SetupTime/Production.BatchQuantity MachineSetupCost = SetupTime * Machine.HourlyRate **Idle** IdleTime = 0 MachineIdleCost = IdleTime * Machine.HourlyRate	LabourSetupCost = SetupTime * Labour.HourlyRate * OperatorsQuantity **Idle** LabourIdleCost = IdleTime * Labour.HourlyRate * OperatorsQuantity		**Gas** N/A	EnergyCost.Equipment = 0
Billet forging (radial blowing)	**Validity rules** N/A (material selected in production strategies)	**Validity rules** Machine.Category = (“*HydraulicPress*” OR “*Hammer*”) Operation.RadialBlowingRequestedTonnage = N/A Machine.Tonnage > Upsetting.RequestedTonnage Machine.Energy > Upsetting.RequestedEnergy Machine.MaxSizeX > Piece.Width Machine.MaxSizeY > Piece.Width Machine.MaxSizeZ > Billet.Lenght	**Validity rules** Labour.Skill = hot “*Forging Operator*”	**Validity rules** N/A (no tool required)	**Validity rules** IF RawMaterial.Material = “*Aluminium*” THEN Consumable. Type = “*Solids*” ELSEIF RawMaterial.Material = Steel OR RawMaterial.Material = “*StainlessSteel*” THEN Consumable.Type = Graphite	**Validity rules** Energy.Vector = “*Electricity*”
	Priority rules N/A (material selected in production strategies)	**Priority rules** Minimum hourly rate	**Priority rules** N/A (only one kind of operator allowed)	**Priority rules** N/A (no tool required)	**Priority rules** N/A (only one consumable per material allowed)	**Priority rules** N/A (only one energy vector allowed)
	Calculation rules **Net** – **Waste** N/A (scraps negligible)	**Calculation rules** **Operation** ProcessTime = Operation.BlowNumbers /Machine.BlowRate MachineProcessCost = ProcessTime * Machine.HourlyRate **Setup** SetupTime = 0 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 (no tool required)	**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

management of rules to be used for sorting operations. Looking at the workflow for components, a positive outcome is its possible extension to other forming processes, while the definition of a workflow for assemblies requires future improvement.

Concerning the implementation of the proposed framework, a qualitative evaluation procedure is presented. This evaluation facilitates the understanding of the applicability of the presented framework for daily use and possible grey areas requiring improvement. The evaluation criteria have been derived from March and Smith [53] and are presented together with their explanations and related scores in Table 7. Regarding the evaluation method, according to the definition proposed by Prat et al. [54], the authors performed a *qualitative* evaluation by using a three-grade scale (low, medium and high). Qualitative feedback on the identified criteria have been derived from two groups of participants: (i) four university professors with experience in the engineering design and cost engineering and (ii) four engineers/designers from the company involved in the implementation of the case study. The framework was first presented to professors and cost engineers. Second, cost engineers used the proposed framework for process analysis and knowledge formalization.

The evaluation results show a satisfactory assessment of the framework as a whole. Considering the criteria described in the evaluation table, the highest scores are registered for "completeness" and "efficacy", which both receive a high score. Conversely, "understandability", "ease of use" and "impact to user" show the lowest score (medium); however, the scores were far from the lower bound.

5 Conclusions

This paper originated from the need to support enterprises in formalizing the manufacturing knowledge to be used for estimating the manufacturing cost of products (analytical approach) during the design process. This 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 produce mechanical components. For defining manufacturing processes, this research work presents a *knowledge-based workflow* starting from a product virtual prototype. This procedure is based on a set of repositories and *cost routings*, properly defined for collecting the knowledge required to estimate a manufacturing process. Once the process is defined, the knowledge behind a manufacturing operation (*cost model*) allows the calculation of 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 on 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 should focus on further improving the proposed framework and increasing 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. Furthermore, cost routing should manage rules required for sorting manufacturing operations. Indeed, the operations instantiated by the proposed approach may not follow the correct production order. Cost routing should also include rules for managing process yield, which may strongly influence the production cost for very innovative processes. In conclusion, the framework should be improved so that it can be adopted to estimate the cost of entire products requiring the multi-level assembly of components connected by joining operations.

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