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# Cost estimation method for variation management

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Cost engineering key objectives is to ensure cost estimates' accuracy and to avoid cost overruns. In such a global context, this paper focuses on the manner through which the uncertainties as well as variations, impact the cost dimensions during different phases of product lifecycle: Tolerance allocation, Process Planning, Inspection Planning.
What is investigated is the adaptability of a modified Activity-Based Costing model in evaluation of cost regarding the activities in different stages of the product's life cycle. This effective model encloses the cost estimation of tolerancing, process and inspection planning, via the impact of variations and uncertainties (i.e. inspection risk). The aim is to take into account not only the cost but also the quality (quality-driven activity-based costing) of product.

## 1. Introduction[a]

The cost estimation is considered as a key activity to improve the tolerance allocation, to select fittest manufacturing resources or inspection allocation planning. Particular deficiency of cost estimation methods and techniques is their specific use cases and applications. For instance parametric models are appropriate to tolerance design to assess the cost impacted by tolerance allocation. The drawbacks and advantages of parametric and two other approaches in cost estimation will be compared in 3. A significant amount of research has been devoted two essential inconveniences in these approaches; costly evaluation of their required parameters and also their limited validity and generality in the industrial framework. Moreover, they are supposed to be applicable in different design stages with variant granularity of information as it is discussed in section 2.

Therefore, we propose a unified method which could be used for cost estimation in several stages of a product design cycle: Tolerance design, CAPP (Computer Aided Process Planning) and CAIP (Computer Aided Inspection Planning). Contrary to existing solutions, this method consists in assessing the subsequent costs impacted by the variation management: quality weighted cost (quality-driven ABC). To estimate the manufacturing cost of the product through an improved ABC approach, the proposed concept takes into account the quality of both product and process.

As it is shown by [1], the selection of manufacturing and product control process, including various parameters and accuracies, are strongly affected by the tolerance of the part to be machined. In the same context [2] proposed an approach for functional tolerance allocation that provides the best ratio between functional performances and manufacturing cost. They intended to consider the manufacturing constraints in the early stages of the design process, to identify the parameters with relevant impacts on product performance and its cost, as it is applied in our approach. A tight tolerance would cause a sharp increase in manufacturing cost. Also an increase in fabrication's precision may lead to a less strict control and vice versa. The assignment of an over-relaxed tolerance would also increase the total cost. The quality loss depends also on process tolerances relevance [3] usually comprised in process capability.

Through slight modifications to the classic ABC method, it could federate the costs, not necessarily covered in classical model but associated to product's

life cycle. Probabilities are involved to the activities defined in ABC. Activities are associated with cost drivers due to consumption of resources, uncertainty and variations. These latter permit us to estimate the cost regarding to activity drivers and not to activity cost as it's developed in traditional ABC.

## 2. Cost estimation methods essential to variation management

Influence of design on manufacturing cost is usually great. Considering manufacturing in early product design stage [4] avoids the errors which tend to contribute as much as 70% to the cost of production. Design for manufacturing (DFM) is an activity of assessing the manufacturability, improving design, estimating the cost in the product development stage. Moreover, variations and uncertainties are ubiquitous in product and manufacturing process design and concurrent engineering. Indeed, the inherent variations and uncertainties of manufacturing processes and resources involve a degradation of functional characteristics. Performance evaluation of design is willing to find a compromise between allocated tolerance, process precision and control uncertainty. To do so [5] co-evaluate the product, process and production system. They believe that the most important decisions are made in the design stage of "adaptable product" to respect the product functionality, quality, manufacturability, cost and performance.

The goal here is as well to put the management of variations and uncertainties in a concurrent engineering context. There is an important question that would need to be looked upon: Why cost estimation methods are essential to variation management?

At each stage of the product and manufacturing process design, it is necessary to quantify the total impact of variations on the safety, perception, performance, and end cost of the product. The costs of variations typically include scrap, downgraded product, and reduced production capacity… This paper focuses on three main activities of the product development which impact the variation and the cost: Tolerance allocation, Process planning, and Inspection planning.

### 2.1. Tolerance allocation / preliminary process plan generation

To ensure a certain level of product quality, the tolerance allocation aims to determine the acceptable limits of the part deviations (variations). The allocation or synthesis of functional tolerances takes place generally during the detailed design and greatly impacts the design of the manufacturing process, manufacturing and product inspection. Functional tolerances' impacts

on the manufacturing cost and product quality (customer satisfaction) are then quantified. These two concepts are usually considered as conflicting goals. Most of the approaches consist in balancing the distribution of the tolerance interval [6]. These approaches focus on the requirement and the customer satisfaction while ignoring the tolerance impacts on the manufacturing process (cost, capability…)

Tolerance allocation ensures a certain level of product quality, minimizing the manufacturing costs. Some approaches are based on the Taguchi loss function, parametric equations of the cost of each tolerance, or the manufacturing cost impacted by tolerances [7] [8]. The following activity diagrams detail two approaches which include a cost assessment into the tolerance allocation activity (Fig. 1).
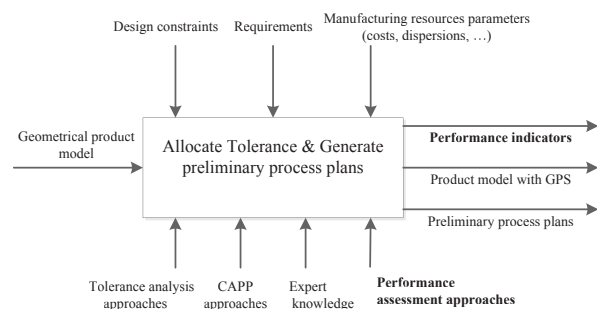


Fig. 1. Activity diagrams of Tolerance Allocation.

### 2.2. Detailed process plan elaboration and resource allocation

Process planning is a systematic determination of the activities by which a product is made in an economic and competitive way in a given environment. Among optimal process plan criteria we note the manufacturing cost, the process time, the product quality, etc. It includes the determination of manufacturing processes, the selection of resources and equipment, and the assessment of manufacturing costs and product quality. In fact, manufacturing processes and resources are selected, depending on product description, such as material, structure and tolerances.

Thus, manufacturers need to know product requirements and resource capabilities. Indeed the inherent imperfections of manufacturing processes and resources involve a degradation of product characteristics. Consequently to ensure a certain level of quality, the impact of the manufacturing resource selection or changes on product characteristics is to be evaluated. During the determination of the manufacturing processes, manufacturers take into account the interactions of product and manufacturing

resources to assess the product quality and the cost.

The following activity diagram details the activity "Generate process plans and select manufacturing resources" which include both cost and product quality assessment (Fig. 2).
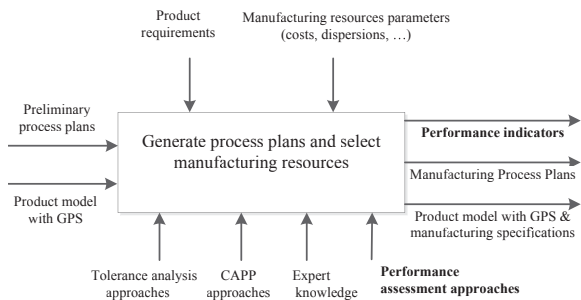


Fig. 2. Activity diagram of Process Planning.

## 2.3. Inspection / monitoring plan generation and resource allocation

Simultaneous evaluation of both cost and quality (cost weighted quality) would be realized as well while developing inspection and control system to prevent defects. In the early stage of design, the decisions strongly impact the inspection frequency (measurement cost) and accuracy (error cost) required. It is so desired to express the inspection cost in a same unified method as Tolerance design, CAPP … as it's influenced by the choice of resources that provide a certain level of accuracy.
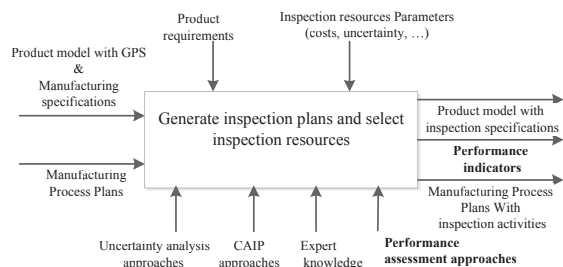


Fig. 3. Activity diagram of Inspection Planning.

The whole variations located at the level of part and that of the process or control are thus interrelated in our point of view (compatibility of part / process-control / resource). The expected objective of this last stage of design is to provide the best ratio between the efficiency of control/monitoring plan and the cost associated (Fig. 3).

## 3. Cost model expressions

As explained in the previous section, whatever is handled through the activity, decision making strongly requires indicators which asses the relevance of several solutions. Indeed, to find out what the most adequate cost model is, decision makers need to compare them objectively. Consequently, the major aim of this section is to focus on explicit assessment methods descriptions, and to select the ones, adapted to the particular context of variations management.

Later in this article, in accordance to the literature, one of these relevance assessment indicators on which we are focused is called "cost", knowing that it's not exclusively a financial dimension. Among the several cost assessment methods available in the literature, a classification into three main categories could be carried out: parametric, analytical and analogical methods. Fig. 4 illustrates this gathering.
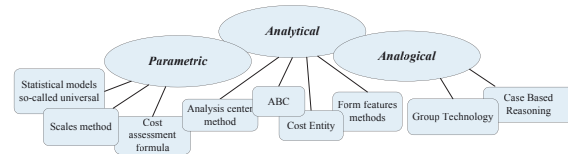


Fig. 4. Cost assessment methods classification

In order to understand the strengths and weakness of these categories, the next sections focus on several methods based on these three approaches. In order to conclude this analysis and the fitness of each method with the particular context of variations management, a comparison is proposed.

### 3.1. Analogical methods

Analogical methods are mainly based on the cost assessment of a new product or a problem from those already evaluated and stored. These are described by parameters considered as discriminatory and relevant (morphology, quality, size...) that will also describe the new product whose cost is to be estimated. Two widely used solutions based on this principle are: group technology ([9], [10] and [11]) and case-based reasoning ([12], [13] and [14]).

These methods illustrate the main issues focused by this approach. Indeed, the keys of these methods: the cases databases (containing all parameters considered as discriminatory and their values) design and the similarity analysis/adaptation algorithms are very difficult to design. Moreover, to be efficient and operational, these methods strongly need the information and data (previous cases and quantified parameters) to fulfill databases which increase their cost, and explain the reason why these solutions are currently no more used.

## 3.2. Parametric methods

All methods performing cost assessment by using mathematical relationships linking this performance indicator to other quantifiable parameters (product volume, hardness, time …) are gathered as parametric methods. Among the several references available in the literature, this section focuses on the Cost Estimation Formula.

This method is composed by three major steps:

- The first one, consists in identify and collect all data considered as influent on the cost indicator. This selection activity can be performed subjectively (experience or know-how) or objectively (principal component analysis).
- Then, the next step tries to find from several mathematical patterns the one fitting the best the relationship linking the performance indicator to the parameters selected in the previous step.
- Finally, the last step consists to validate the mathematical model by facing it to several well known cases.

Applied to tolerances cost evaluation, current approaches are mainly based on thirty years old parametric functions. In these models, the cost depends on several parameters as tolerance to be machined as well as other parameters reflecting the manufacturing context. Among a very numerous models available, mainly used parametric models are:

- Rational [15]: $\quad C(t) = A + \frac{B}{r^2}$ $\qquad$ *(1)*
- Exponential [16]: $\quad C(t) = B. e^{m.t}$ $\qquad$ *(2)*
- Power [17]: $\quad C(t) = A + \frac{B}{t^k}$ $\qquad$ *(3)*

As a conclusion, the parametric method is quick and easy to use because it directly calculates the cost of a considered set of parameters (tolerances for instance). But despite the fact that the current methods assessing the tolerance cost are mainly based on parametric approaches, this solution is difficult to deploy in an industrial environment where the input parameters are both contextual and complex. Indeed, the choice of these parameters and the relationship models with mathematical links has a limited range of validity cause depending on several characteristics (company's location, materials, manufacturing conditions, fabrication cost …). In addition, evaluation of parameters is costly both in time and resources and becomes a strategic data for companies that invest in costly design of experiments.

## 3.3. .Analytical methods

Analytical approaches are considered as all methods that aim to evaluate the cost of a solution (or other relevance indicator) by analyzing the activities needed during its whole lifecycle (design, manufacturing, recycling…), mainly responsible for direct or indirect costs and deviations. Among the several analytical solutions available (Form Features from [18], Manufacturing Engineering Reference Model, entity cost…), this paper only focuses on the ABC method.

It consists in banning the usual and hierarchical view of the analytical approach based on the discrimination between the direct (productive) and the indirect (considered as not productive) activities.

ABC method firstly performs the splitting of the work into significant activities. Then, it identifies the consumption and causality links between the activities, resources and products. The links are quantified by three drivers:

- Resource driver, used to allocate resources between activities. This driver eases cost assessment.
- Cost driver which describes the performance level of the activity and its resource consumption.
- Activity Driver which is equal to the unit work. This driver helps to distribute the activities' costs between cost objects (hour of labor, work pieces manufactured…)

This method assesses more precisely the real product cost since it takes into account as well the indirect costs. Nevertheless, the ABC method, which seems generic and powerful enough, has to face with major issues. Indeed, the difficulty to identify and to evaluate the drivers remains the main drawback of this method.

## 3.4. Synthesis

In order to compare the different methods, outlined in the previous sections to estimate the cost, it is interesting to establish the criteria with the features expected from such methods to choose the best solution. In this study we used as discriminating features:

- Sensitivity of the assessment (repeatability and robustness): ability of method to integrate and take into account the variations of the input data.
- Adequacy of the evaluation (precision): ability of method to give accurate results considering the final product cost.

- Deployment: the difficulty of formalizing data preparatory for the evaluation of cost, usually performed by experts.
- Speed of estimation: includes both the computation time than the time required to model a new problem.
- Generality: scalability of method allows measuring the performance indicator rather than only financial dimension.

These parameters are certainly not exhaustive but they represent the needs underlined in the section 1: having an assessment method flexible, sensitive, fair and

fast. To get a more synthetic comparison, a radar diagram is proposed in Fig. 5.
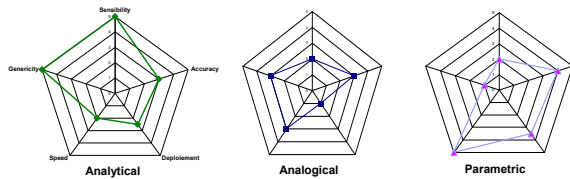


Fig. 5. Comparisons between three cost assessment approaches

In this diagram the five parameters expressed previously, are evaluated for each of three approaches. This assessment (ranging from 1 to 5) is carried out considering our experience of the methods presented in the preceding paragraphs (i.e. are still subjective).

As a conclusion of this section 3 comparing the different methods available to estimate the cost of a product, the benefits and drawbacks of the previously described solutions can be summarized as:

- Parametric: although accurate and fast to use, in their range of validity they are limited by restricted generality.
- Analogical: these methods are interesting but the preparatory phase (enrichment of knowledge base, parameters discriminating … ) is long for the results. This approach seems impossible to automate in an optimization process.
- Analytical: although the estimation process of these approaches is quite long because they generate and analyze all the operations necessary for obtaining a product, they remain attractive because of their flexibility and accuracy. Moreover, thanks to this generality, the cost evaluated can support not only financial dimension. Indeed variations can be handled by this approach. This ability is detailed and explained in the next section.

## 4. Cost estimation generalization via Activity-Based Costing

A global design approach requires systematic analysis and estimations, justifying the decisions taken from conception to production. To do so, performance evaluation in our approach reflects two aspects: cost and quality. In order to estimate the cost in design stage, three essential needs are awaited. The applied method is expected to be:

- Precise enough to provide an accurate performance evaluation.
- Coherent in evaluation approach to be applicable in different design stages with variant granularity of information.

- Flexible enough to be expanded and to incorporate the tolerance impacts, process uncertainties and variations.

ABC seems responding to these requirements. Its analytic model permits to be adaptable and to treat the variations as well as the cost. In order to obtain an analytic expression for the variation–cost relationship, it is required to retrieve and designate the evolution of cost through the activities. ABC method proposes to dissociate the activities and to follow the evolution of direct and indirect costs.

Thus an activity and a resource view associated to product life cycle would be required. As a general rule [19] the final cost will be calculated through the (Equation 4):

$$Cost = \sum Activity\ driver * Cost\ driver * Resource\ driver * Resource\ cost \qquad (4)$$

A generic view encompasses the activities to completion of a product from the design stage and manufacturing to maintenance and product retirement. It permits us to rely our approach on design stage where we take into account the impacts of conception on the subsequent activities of products life cycle. To investigate the applicability of ABC, we conduct our study on particular activities, taken into account in design stage, which directly affect the cost:

- Manufacturing (milling, forging, casting, …)
- Product remanufacturing
- Reassortment (multiple assembly tries)
- Process monitoring (detective / corrective)
- Process maintenance (regular / preventive)
- Product inspection (sampling rate / total inspection)
- Apart from these direct activities, but naturally linked to them, two other important expense sources which increase the final cost, are due to the emergence of:
- Internal failure (product scraping, product recycling, …)
- External failure (product maintenance, customer loss, customer claim)

Proposed quality-driven ABC aims to balance the manufacturing cost and successive expenses, and product satisfaction throughout the tolerance and variations analysis. Certain concepts are associated to activity, resource and cost drivers in ABC; the uncertainty, activities occurrence probabilities and efficiency…

- Activity occurrence: Probability that an activity appears in the process (for example, the probability of a reprocessing activity occurs in the manufacturing process).

- Activity efficiency: Probability that an activity leads to conform products to geometrical tolerances.

Despite the original approach of ABC which aims to evaluate only financial dimension, the analysis of consumption and causality links allow to adapt this approach to the analysis of variations too. Several works [20] [2] try to use this approach to evaluate both cost of a solution and analyze its deviations.

What is emphasized in our approach is the fact that the variations would particularly impact the Activity driver and so the final cost in Equation 4. This is while Resource driver and Resource cost could be considered as constants. In other words, to compare the solutions relevance in design stage, we believe that the evolution of Activity drivers affects the cost in a significant way, which is not necessarily the case for the cost associated to resource consumption. Therefore, Equation 5 would be inspired from the Equation 4.

$$Cost = \sum Activity\ driver\ Activity\_resource\ cost \quad (5)$$

This is particularly true for the preliminary design stage where the granularity of the information is relatively limited. Through this section the aim is to anticipate the flexibility and adaptability of this approach by elaborating the activity drivers in each of the three design stages separately as stated in section 2: tolerance allocation and preliminary process plan generation, detailed process plan elaboration and resource allocation, and inspection or monitoring plan generation and resource allocation. Progressing through these stages, the objective is to solidify the conception. Thus, number of activities stated before, which are taken into account increase. A general final model is then presented.

### 4.1. Tolerance allocation / preliminary process plan generation

At this design stage the information is strictly limited to the product model and manufacturing parameters as associated costs (

Fig. 1). Thus, rather than functional requirements, tolerances are also assigned subject to the constraints originating from the activity of manufacturing as machine tools' dispersions [21]. While allocating the tolerances, ensuring the desired quality, demand certain level of cost investment on manufacturing.

The more the concerned manufacturing activity is resource consuming, the more Activity_resource cost indicator (Equation 5) increases. In the proposed model in [22], $C_{manu}$, $C_{remanu}$ and $C_{reassort}$ are as well sum of the resources' costs. Equation 6 is derived from this model and adapted to the provided definitions in this paper.

Depending to the strategy, other resource costs could be added to the equation.

$$Marketable\ Product\ Total\ Cost = \frac{1}{P_C}(C_{manu} + C_{remanu}.OccP_{remanu} + C_{reassort}.OccP_{reassort}) \quad (6)$$

Where

- $P_C$: Occurrence probability of conform product, which depends on requirements, part tolerances and manufacturing resource dispersions. $1 / P_c$ is the final efficiency of all activities. To produce a conform product; it is exigent to produce $1 / P_c$ products. This driver reflects the impact of tolerance allocation and preliminary process plan.
- $OccP_{remanu}$: Occurrence probability of remanufacturing activity which depends on the part tolerances, the manufacturing resources and the criteria to determine if the product is subjected to remanufacturing.
- $OccP_{reassort}$: Occurrence probability of reassortment activity which depends on the part tolerances, assembly process and the assembly process dispersions (chain of dimensions).
- To ensure the function of product, the aim is to select the manufacturing resources in a strict way.

### 4.2. Detailed process plan elaboration and resource allocation

Being given the Geometrical Product Specifications from the previous stage and the resources allowed dispersions; the objective is to elaborate the manufacturing process activities and to select precisely the manufacturing resources (Fig. 2). A manufacturing resource with less deviation, guarantees a tight tolerance and so the assembly. In other words, based on the general characteristics of a production cost-tolerance model, tight tolerances lead inevitably to higher production costs [23]. So trough the same manufacturing resource, the activity drivers in equation 6 increase. Low capability indicator which expresses the ratio between the tolerance intervals to realize and the deviation of the manufacturing resource, declines the occurrence of products conform to the specifications ($P_C$). Consecutively it leads to an increase on $OccP_{remanu}$ and $OccP_{reassort}$. The tendency is to find a compromise between the resources' provided capability and cost. As well the elevated capability of a more accurate manufacturing resource causes definitely an increase on Activity_resource cost (Equation 5). Uncertainties as manufacturing resource properties and variations on manufacturing activity parameter impact activity drivers [24].

Furthermore the cost of non-quality due to resource selection could be added to this function. The term would estimate the cost of failure occurrence. The more

it is contributed to manufacturing cost, the less is the probability of failure occurrence. To calculate the failure cost (Equation 7), Activity-resource costs (Equation 5) associated to failures, as the cost of recycling or client reclamation, are usually fixed. So the objective is usually to decrease two activity drivers and failure emergence probabilities through:

- $OccP_{IntFailure}$: Occurrence probability of internal failures,
- $OccP_{ExtFailure}$: Occurrence probability of external failures, could be estimated through FMEA method [25].

Total Failure Cost = $(C_{prd\ scrp} + C_{prd\ recycle} + …)$. $OccP_{Int.Failure.Occ} + (C_{prd\ mntc} + C_{rclmntn} + …)$. $OccP_{Ext.Failure.Occ}$ (7)

Where

- $Cprd_{scrap}$: Cost of internal product scraping
- $Cprd_{recycl}$: Cost of product recycling
- $Cprd_{mntc}$: Cost of external product maintenance
- $Cprd_{rclmtn}$: Cost of customer reclamation

The failure cost is minimal if occurrence and detection of problems are in the same phase. As a delayed detection increases the cost, the worst case would be a failure detected by client, originated from design phase. In Equation 8 external failure cost (product maintenance, customer loss, and customer claim) is often more elevated than internal failure cost (product scraping, product recycling …). To avoid the external failure and minimise the failure cost, general tendency in manufacturing resource selection is to increase the capability. In Equation 4, it leads to increase the resource and so the manufacturing cost. The objective is to minimise the total final cost. Process monitoring, maintenance and product inspection are essential activities to prevent failure occurrence and cost increases.

### 4.3. Inspection / monitoring plan generation and resource allocation

Being given the manufacturing process plan and Geometrical Product Specifications to respect, this design stage is dedicated to the generation of monitoring and inspection plan (Fig. 3). The non-conformity of product to specifications elaborated by design, and also the problems encountered during the production will be detected by product inspection. Furthermore process monitoring or preventive maintenance policy, could provide an effective reduction of cost due to intervention related to the degradation or failure on production means [26]. The choices during product and process design, strongly impact the frequency and cost of these latter. The objective in this stage is to limit the level of accuracy and frequency of inspection to "just necessary" and to find a compromise between them. At this stage

the granularity of information is considerably coarse. Therefore cost evaluation would be more accurate. The cost model admits not only the manufacturing activity cost for quality (Equation 6) but also the inspection, monitoring and maintenance activities to estimate the cost of marketable product. It could be defected but not detected due an inefficient inspection or monitoring plan. Thus it would be necessary to take into account two more activity drivers, as inspection uncertainties, rather than $P_C$ in Equation 6. Two widespread activity drivers concerning the inspection uncertainties are:

- Non-detection probability, $\alpha$
- False alarm probability, $\beta$

The quality of marketable product would be certainly impacted by these uncertainties. Thus the first term of Equation 6 could be revisited in Equation 8.

$Marketable\ Product\ Fabrication\ Cost\ =$
$$\frac{C_{manu}}{P_C.(1-\alpha) + (1-P_C).\beta} + … + … \qquad (8)$$

Cost investment on inspection precision leads to reduce the monitoring or maintenance activities frequencies which are considered as activity drivers and subsequently the associated cost will be reduced. The choice of accepted risk of false alarm and non-detection is also impacted by variations and tolerances and influence the final inspection cost.

Kunzmann *et al.* [27] show that adequate measurement frequency and accuracy prevent the loss of knowledge about the systems state. They indicate the approaches to quantify the benefit of knowledge by metrology while estimating the inspection cost, responding to a question: "does the investment in metrology deliver sufficient benefits?" Here measurement cost has to be balanced against the cost, deriving from measurement and decision errors (Equation 9).

$Total\ Inspection\ Cost\ = Measurement\ Cost +$
$Error\ Cost \qquad (9)$

Regardless of inspection strategy, to calculate the measurement cost according to Equation 5, frequency impacts the activity driver and accuracy increase naturally the Activity_resource cost. While generating the inspection plan and selecting the resources, increasing the inspection cost would cause a decrease on total failure cost. The same approach as inspection cost could be applied for estimating the process monitoring cost.

In this stage with a significant level of information, it would be possible to calculate the Total Cost. In Equation 10 a general model is presented which covers the main activities to estimate this latter for a marketable product. The evolutions of the terms are in fact interrelated and they are supposed to be balanced. For

instance it is possible to relate the causes (the interest of process monitoring and maintenance) and consequences (the interest of product conformity control). The aim is to ensure the conformity of final product to specifications with a minimal associated Total Cost.

$Marketable\ Product\ Total\ Cost =$

$1\,/(P_C.(1-\alpha)+(1-P_C).\beta)*[C_{manu}+$

$C_{remanu}.OccP_{Remanu}+$

$C_{reassort}.OccP_{Reassort}+C_{monit}.OccP_{Monit}+$

$C_{maintnc}.OccP_{Maintnc}+C_{inspctn}.OccP_{Inspctn}+$

$(C_{prd\ scrpng}+C_{prd\ recyclng}+\cdots).((1-P_C).(1-$

$\beta)+P_C.\alpha)+(\,C_{prd\ maintnc}+\cdots).(1-P_C).\beta\,+\ldots]$

*(10)*

In this section the approach to the cost estimation in three design stages was provided by treating certain cost models. Activities decomposition and activity drivers definition, could be expanded and adapted, following different strategies in enterprises. Next section demonstrates the applicability of model to an industrial case.

## 5. Illustration of cost model employment

As mentioned before the objective in this section is to illustrate the employment of proposed model. To ease this latter the general model is applied on a single automotive part (Cover Intermediate Shaft) (Fig. 6), called CAI.
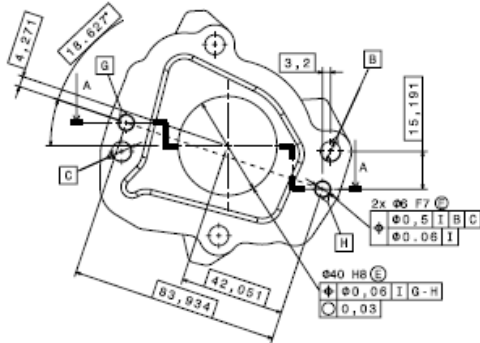


Fig. 6. Functional plan of CAI part

For the sake of brevity and clarity of application, the example is a simplified version of the industrial case. Limited information on this part does not permit us to consider all the activities mentioned in section 4. Among them, certain points associated to costs and occurrence probabilities are taken into account as well as internal

failure emergence, causing product recycling activity in the case study (Table 1).

Table 1. Final Cost estimation data on CAI

| Activity | Associated Cost / Part | Occurrence probability |
|---|---|---|
| Manufacturing (milling) $C_{manu}$ | 7.62 € | - |
| Product remanufacturing $C_{remanu}$ | 1.52 € | 0.000008 |
| Product inspection $C_{inspctn}$ | 1.60 € | 1 |
| Product recycling $C_{prd\ recyclng}$ | 3.20 € | 0.000020 |

The costs associated to Reassortment (in assembly cases), monitoring and maintenance are neglected (Not Available). Available activity drivers, required to final cost estimation are presented (Table 2).

Table 2. Activity driver data on CAI

| Activity Driver | Occurrence probability |
|---|---|
| Non-detection $\alpha$ | 0.00005 |
| False alarm $\beta$ | 0.00005 |
| Conform product $P_C$ | 0.999972 |

Thus regarding the Equation 10, through the application of experimental values, the Final Total cost equal to 9.22 € is obtained. Depending on the case study, the evolution of cost through the activities involved in the process, permits to compare the solutions. Based on design stages mentioned in 2, admitting that the appropriate tolerances are allocated for CAI part. Thus the efficiency of manufacturing process and inspection plan is to be discussed. Generated process and inspection plans as well as their resources seem to be a non-efficient solution for an industrial case due to low inspection accuracy and maximal inspection frequency. It would be better to balance the contribution to the manufacturing cost and the inspection cost.

The flexibility of model as well as the utility of associating the cost estimation with the Activity drivers (probability, uncertainty …) was desired to be illustrated through this section.

## 6. Conclusion

As shown in the previous example, proposed model tends not only to estimate the cost but also to investigate the efficiency of solutions, either on tolerance allocation or process and inspection plan generation, and the roots of non-efficiencies based on activity drivers. It could be due to resources' performance and accuracy or generated plans' efficiency.

The feasibility of activity-based costing method in quality management is undoubtedly one of the first assumptions in this paper. Consequently, the proposed model, based on ABC, seems to be compatible for

accounting quality cost, providing an accurate estimation.

The decisions taken in different design stages, impact in a significant way the final cost. Regardless of design stage, its objectives and accuracy level of information, it is required to evaluate conception alternatives' relevance. It is certainly insufficient to treat solely the financial dimension of their performance but also the variations. Investigated quality-driven ABC is flexible enough to involve the variation in analytical models even if this aspect is not treated in the original approach. This ability to evaluate at different design stages, a relevant "cost" is interesting since this performance indicator could be the objective function of an optimization. Combined with a complete manufacturing and inspection process generation algorithm, this performance indicator permits to design the fittest process.

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