Proceedings in Manufacturing Systems, Volume 8, Issue 1, 2013 ISSN 2067-9238

# PROCESS PLANNING - A BETTER, CHEAPER AND FASTER NEW PRODUCT

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***Abstract:*** *Process planning is a group of instrumental actions to the achievement of the output of an operation's system in accordance with a specified measure of effectiveness. It consists of devising, selecting and specifying processes, machine tools and other equipment to convert raw material into finished and assembled products. This paper presents an approach developed for supporting management at the earliest stage of manufacturing; in another words this approach which is called QCLPP (Quality, Cost, Lead time based Process Planning) is a toolkit for process planner to estimate manufacturing cost as well as manufacturing cycle time and product quality; using both QFD and FMEA tools to enhance life-cycle quality of ownership, this approach is also based on DFP to estimate the manufacturing cycle-time (time that elapses from work order release to completion) of a new product that will be made in a manufacturing system that makes other products as well. To estimate manufacturing cost and the cost of risks related to a process plan, ABC and CbFMEA are deployed in this approach. For each resource combination, the output data is gathered in a selection table that helps for detailed process planning in order to achieve higher level of efficiency. A software program has been developed; it aims at supporting process planner to achieve goals fixed by the company based on this approach. A case study is presented in order to illustrate the approach and prototype system in this paper.*

***Key words:*** *ABC, DFP, QFD, FMEA, Lead-time, CAD/CAM, Manufacturing Cost.*

## 1. INTRODUCTION

Today the manufacturing world is facing major pressure due to the globalization of markets. Firms have been striving to respond quickly to market requirement and needs, which is why enterprise performance requires the control of cost quality and manufacturing cycle-time as early as possible in the product development cycle [1 and 2].

This paper proposes an approach to develop a new tool that can support the process planner in order to satisfy the strategic performance objectives of the enterprise (cost, quality and lead-time). This approach includes tools which have proven their ability to increase companies' profitability by reducing costs, improving product quality and reducing the time-to-market. In order to estimate the time spent by the product in the manufacturing system known as manufacturing cycle-time, Design For Production method (DFP) is used in this approach which also includes the Activity Based Costing (ABC) method to roughly estimate manufacturing cost and finally both Quality Function Deployment (QFD) and Failure Mode and Effect Analysis (FMEA) tools are used to determine manufacturing resources with appropriate process capability to produce product characteristics required by costumers.

In this paper, manufacturing lead time is defined as the time interval from the starting time to the completion.

To date, many research and development efforts have been devoted to develop a number of different methods in order to evaluate the impact of development process on product quality, cost and lead-time. Shaw [3] developed an interface between process planning and design, to assist designers to develop better products in a timely manner. Chin [4] proposed an approach to carry out the preliminary process planning for quality in which the QFD and the process FMEA are incorporated. Maropolous [5] presented a new time based process planning architecture that consists of three levels corresponding to aggregate management and detailed planning. An aggregate process tool-kit which aims at giving the designer a way of visualizing the likely product consequences of design decisions is developed. Such aggregate process planning enables the identification of product technology requirements, the selection of process and equipments, the generation of product route, the evaluation of a factory configuration. Hassan [6] developed an approach using QFD, FMEA and ABC to determine key process resources with estimation of manufacturing cost.

Feng [7] developed a conceptual process planning prototype for the preliminary manufacturability assessment of conceptual design in the early product design stage. It aims at determining manufacturing process, selecting resources and equipment and roughly estimating the manufacturing cost. Mandar [8] presented a method for estimating manufacturing cycle-time of a new product that will be made in a manufacturing system that makes other products as well. This method shows the

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benefits of reducing manufacturing cycle time and how those benefits yield increased profitability. Jeffery [9] proposed Design For Production tool which aims at determining how manufacturing a new product design affects the performance of the manufacturing system by analyzing capacity requirement and estimating the manufacturing cycle-times.

Although the above mentioned efforts are made to improve product development in which manufacturing cost, product quality, manufacturing cycle-time are usually used separately as optimization or assessment indices for manufacturing system or particularly process planning, very few researches have incorporated quality and lead time in process planning and management in order to determine key process alternatives with an adequate process capability (tradeoffs) and capacity. The QCLPP approach is a useful method to asses processes involved in manufacturing a new product. In another words, this new tool helps process planners to verify if the selected resources (fixturing tools, machine tools, etc) could respond to customer requirements in terms of quality, and lead-time. In addition, decisions like increasing or decreasing cutting speed or feed rate, the process planner could verify immediately with this tool the impact of these decisions on product quality lead time and even on product cost.

The rest of this paper is organized as follows; methods and tools used in our approach are presented. Thereafter, the QCLPP is described in section 2. In the Third section, the prototype system is presented. In section 4, case study is presented. The last section, section 5, incorporates the conclusions of the paper.

### 1.1. Quality function deployment (QFD)

The QFD technique “is a systematic procedure for defining customer needs and interpreting them in terms of product features and process characteristics. The systematic analysis helps developers avoid rushed decisions that fail to take the entire product and all the customer needs into account” [10]. It is a process that involves constructing one or a set of interlinked matrices, known as ‘quality tables’. The first of these matrices is called the “House of Quality” (HOQ). The house of quality matrix has two principal parts; the horizontal part, which contains information relevant to the customer, and the vertical part, which contains corresponding technical translation of their needs. The basic process underlying QFD resides in the centre of the matrix where the customer and technical parts intersect, providing an opportunity to examine each customer’s voice versus each technical requirement, for a detailed description of QFD formation process [11].

### 1.2. Failure Mode Effects Analysis (FMEA)

FMEA is a disciplined approach used to identify potential failures of a product or service and then determine the frequency and impact of the failure. It is an approach that is often referred to as a “bottom up” approach, as it functions by means of the identification of a particular cause or failure mode within a system in a fashion that traces forward the logical sequence of this condition through the system to the final effects [12]. The main idea is to generate a risk priority number (RPN) for each failure mode. The higher the risk number, the more serious the failure could be, and the more important it is that this failure mode be addressed.

The traditional FMEA involves ambiguity with the definition of risk priority number: the product of occurrence (O), detection difficulty (D), and severity (S) subjectively measured in a 1–10 range. The three indices used for RPN are ordinal scale variables that preserve rank but the distance between the values cannot be measured since a distance function does not exist. Thus, the RPN is not meaningful.

A cost-based FMEA alleviates this ambiguity by using the estimated cost of failures, [13 and 14] proposing a new technique called FMERA (Failure Modes, Effects, and Financial Risk Analysis) that identifies and prioritizes the process part of potential problems that have the most financial impact on an operation. Alternatives can be evaluated to maximize the financial benefits. Adding columns concerning failure costs to standard FMEA table, a cost-based FMEA table is obtained.

### 1.3. Activity-Based Costing (ABC)

ABC assumes that cost objects (e.g., products) create the need for activities, and activities create the need for resources. Accordingly, ABC uses a two-stage procedure to assign resource costs to cost objects. In the first stage, costs of resources are allocated to activities to form Activity Cost Pools. These activities are allocated in the second stage to cost objects based on these object’s use of the different activities. In order to differentiate between the different allocations at the two stages, the first-stage allocation bases are termed ‘‘resource cost drivers’’ and the second-stage bases “activity cost drivers”, [15 and 16]. Figure 1 illustrates the concept of ABC method.

### 1.4. Design for production (DFP)

DFP refers to methods that determine if a manufacturing system has sufficient capacity to achieve the desired throughput and methods that estimate the manufacturing cycle time of a new product. DFP can also suggest improvements that decrease capacity requirements (which can increase the maximum possible output), reduce the manufacturing cycle time, or otherwise simplify production [7 and8].

These methods require information about the new product’s design, process plans of existing products, and production quantity along with information about the manufacturing system that will manufacture these products.

With DFP method, manufacturing system is characterized by the machines performance like the mean time to

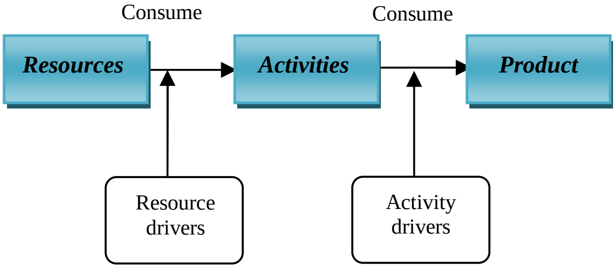


**Fig. 1.** The concept of ABC.

failure ($m^f_j$) and mean time to repair a machine ($m^r_j$). The products are characterized by the job size (number of parts) and the desired throughput ($D_i$) number of parts per hour of factory operation, the sequence of machines that each job must visit; the mean setup time (per job) at each machine ($s_{ij}$) and its variance ($c^s_{ij}$); the mean processing time (per part) at each machine ($t_{ij}$) and its variance ($c^t_{ij}$); the yield at each machine that a job must visit ($y_{ij}$) (the ratio of good parts produced to parts that undergo processing).

The squared coefficient of variation (SCV) of a random variable equals its variance divided by the square of its mean. Other notations used are as follow:

| | |
|---|---|
| $I$ | set of all products |
| $R_i$ | sequence of machines that product *i* must visit |
| $R_{ij}$ | subsequence that precedes machine *j* |
| $Y_{ij}$ | cumulative yield of product *i* through $R_{ij}$ |
| $Y_{ij}$ | cumulative yield of product *i* through $R_i$ |
| $x_i$ | release rate of product *i* (jobs per hour) |
| $A_j$ | availability of a machine *j* |
| $V_j$ | set of products that visit machine j |
| $c^r_i$ | SCV of batch inter-arrival time of part *i* |
| $t^+_j$ | aggregate process time at machine *j* |
| $c^+_j$ | SCV of the aggregate process time |
| $t^*_j$ | modified aggregate process time at machine *j* |
| $c^*_j$ | SCV of the modified aggregate process time |

The cumulative yield is the product of the yields at each machine that the product visits is calculated using the following equations.

$$Y_{ij} = \prod_{k\epsilon R_{ij}} y_{ik}, \tag{1}$$

$$Y_i = \prod_{k\epsilon R_i} y_{ik}. \tag{2}$$

### 1.4.1. Arrival aggregation

The batch arrival rate of a part type is its demand divided by the average batch-size arriving at the first machine, and adjusted by the overall yield rate to fulfill the demand, Eq. (3).

$$x_i = \frac{D_i}{B_i Y_i} \quad . \tag{3}$$

The aggregated batch arrival rate at the machine j is the sum of the batch arrival rates of all part types is calculated with Equation (4).

$$\lambda_j = \sum_{i\epsilon V_j} x_i, \tag{4}$$

$$V_j = \{i\epsilon I : j\epsilon R_i\}. \tag{5}$$

The SCV of aggregated inter-arrival time at the first machine can be approximated by the weighted average of the SCV of batch inter-arrival time of all part types, Eq. (6).

$$c_1^a = \frac{\sum_{i\in I} c_i^r x_i}{\sum_{i\in I} x_i}, \tag{6}$$

$$c_i^r = \frac{2-Y_{ij}}{B_i Y_{ij}}. \tag{7}$$

### 1.4.2. Processing time aggregation

The mean processing time (per part), the mean setup time (per batch), batch size, desired throughput and machine availability are used at this stage to calculate the aggregated processing time.

- **Batch processing time**

The mean batch process time is the sum of the mean batch setup time and the mean total processing time. The mean total processing time is the mean single-part processing time multiplied by the mean number of parts in the arrived batch, Eq. (8).

$$t_{ij}^+ = B_i Y_{ij} t_{ij} + s_{ij}. \tag{8}$$

The variance of batch processing time is the sum of the variance of setup time and total processing time. The variance of total processing time is contributed by the variance in single-part processing time and the variance in the arrived batch-size, Eq. (9).

$$\left(t_{ij}^+\right)^2 c_{ij}^+ = B_i Y_{ij} t_{ij}^2 c_{ij}^t + s_{ij}^2 c_{ij}^s. \tag{9}$$

- **Aggregation**

The aggregate process time of jobs at machine j is the weighted average of all the jobs that visit machine j. Each product is weighted by its release rate, Eq. (10). Equation (11) calculates the mean of the square aggregate process time, which can be used to determine the SCV ($c_j^+$).

$$\mathrm{t}_\mathrm{j}^+ = \frac{\sum_{\mathrm{i}\in \mathrm{V}_\mathrm{j}} \mathrm{x}_\mathrm{i} \mathrm{t}_\mathrm{ij}^+}{\lambda_j}, \tag{10}$$

$$\left(t_j^+\right)^2 \left(c_j^+ + 1\right) = \frac{\sum_{i\in V_j} x_i \left(t_{ij}^+\right)^2 \left(c_{ij}^+ + 1\right)}{\lambda_j}. \tag{11}$$

- **Downtime adjustment**

Equation (10) gives the SCV of aggregated processing time at the machine without considering machine unavailability. However, due to the machine failures or downtime (e.g., scheduled maintenance), the actual processing time will take longer thus needs to be adjusted. The percentage of time that a machine is available is $A_j$, depending on the mean time to failure ($m^f_j$) and mean time to repair a machine ($m^r_j$), Eq. (12):

$$A_j = \frac{m_j^f}{m_j^f + m_j^r}. \tag{12}$$

The adjusted mean aggregated time and SCV of aggregated time become:

$$t_j^* = \frac{t_j^+}{A_j}, \tag{13}$$

$$c_j^* = c_j^+ + 2A_j\left(1 - A_j\right)\frac{m_j^r}{t_j^+}. \tag{14}$$

### 1.4.3. Flow variability propagation and cycle time calculation

At this step, two factors are determined, which are: machine utilization, cycle time at station $j$.

- **Machine utilization**

The average utilization rate $u_j$ at a machine $j$ is the percentage of time that it is busy. It is calculated by the following equation:

$$u_j = \frac{t_j^*}{n_j} \sum_{i \in V_j} x_i. \tag{15}$$

- **Approximation for cycle time calculation**

The variability of inter-departure time at each machine is propagated from the variability of inter-arrival and processing time. It can be approximated by the following equation:

$$c_j^d = 1 + \frac{u_j^2}{\sqrt{n_j}}\left(c_j^* - 1\right) + \left(1 - u_j^2\right)\left(c_j^a - 1\right), \tag{16}$$

$$c_j^a = c_{j-1}^d \quad , \quad 2 \le j \le J. \tag{17}$$

With all the information about ($c^a{}_j$), ($c^*{}_j$), $x_i$ and ($t^*{}_j$) through the manufacturing system, they can be used to calculate the cycle time at each machine.

The first term on the right hand side of Eq. (18) is the approximated queuing time. It can be seen that the queuing time is composed of three factors: variability, utilization, and processing time. The mean system cycle time is the sum of the machine cycle times:

$$TT_j^* = \frac{1}{2}\left(c_j^a + c_j^*\right) \frac{u_j^{\left(\sqrt{2n_j+2}-1\right)}}{n_j\left(1-u_j\right)} t_j^* + t_j^*, \tag{18}$$

$$TT_i = \sum_{j \in R_i} TT_j^*. \tag{19}$$

## 2. QCLPP APPROACH

Aiming to estimate manufacturing cycle time, we roughly estimate the manufacturing cost as well as the failure cost and to meet quality requirements. This method begins with information given by product design and selected manufacturing process and the QFD and FMEA analysis results from design phase. QCLPP is a systematic and structured planning process, in which each step is supported by appropriate methods and tools. As shown in Fig. 2, the steps for QCLPP process are:

- Selection of process alternatives using QFD information and a quality measure index, called the composite process capability (CCP), adopted from [4 and17];
- Process failures analysis using process FMEA;
- Estimation of the manufacturing cycle time;
- Assessment of non-quality (failure) cost using cost-based FMEA;
- Estimation of the manufacturing process cost.

### 2.1. Selection of process alternatives

This step uses information indicated in the product engineering drawing, mainly geometric characteristics, the dimension tolerance, the geometric tolerance and roughness, all these information represent the quality characteristics which are translated into process element $x_j$ and their target levels. In order to achieve the process element level, it is required to select appropriate process alternatives $a_j$ based on part information and manufacturing resources.

### 2.1.1. Estimating the capability of the process element

Based on the process alternative, the capability of each process element, referred to from now on as an element capability, is defined as:

$$Ce_j = \left(1 + \frac{x_j - x_j^0}{U_j - L_j}\right)^{\nu_j}$$

if $x_j$ is a large-better index;

$$Ce_j = \left(1 - \frac{x_j - x_j^0}{U_j - L_j}\right)^{\nu_j},$$

if is a small-better index $j = 1, 2, \ldots, n$. (20).

$Ce_j$ is the capability of $e_j$; $x_0$, $x_j$ the standard or benchmark and the current value of quality value of $e_j$, respectively; $g_j$ the correlation coefficient, set by empirical machining data, and $v > 0$; $L_j$, $U_j$ the technical feasible lower and upper bounds of the process element ($e_j$) level; $n$ the number of process elements ($e_j$). When the process element level is at a bench-mark level, the capability of the process element is set as the standard value ”1”.

### 2.1.2. Estimating the capability of the quality characteristic

The assurance capability of each quality characteristic ($Cq_i$) can be estimated by the following formula:

$$Cq_i = \sum_{j=1}^{n} W_{ij} Ce_j \text{ , } i = 1; 2; \ldots; m. \tag{21}$$

$Cq_i$ is the capability for assuring $q_i$ and $W_{ij}$ the coefficient of relationship between $q_i$ and $e_j$ $\sum_{j=1}^{n} W_{ij} = 1$; $m$ the number of quality characteristics ($q_i$).

### 2.1.3. Estimating the Composite Process Capability of all quality characteristics

The CCP reflects the overall degree of assuring all the quality characteristics. Owing to every quality characteristic possessing the right to veto on the overall process quality according to the trade-off strategies, we adopt the multiplicative fashion to calculate the CCP as follows [18]:

$$\text{CCP} = \prod_{i=1}^{m} \left(Cq_i\right)^{\nu_i}. \tag{22}$$

With $\nu_i \in [0, 1]$, CCP reflects the overall capability level of process alternatives compared with the standard process alternatives.

It can be easily determined that the CCP of the standard process alternatives, whose quality measures are $X_0 = \left(X_1^0, X_2^0, \ldots\ldots, X_n^0\right)$, is always equal to 1. A CCP of more than 1 indicates that the overall capability level increases and the probability for assuring all quality characteristics is higher than the standard process alternatives. On the contrary, a CCP of less than 1 indicates that the overall capability level decreases and the probability for assuring all quality characteristics is lower than the standard process alternatives.

## 2.2. Analysis of process failures

The QCLPP approach uses FMEA to analyze processes of various potential failures. The focus of standard FMEA is usually on providing quality and reducing frequency of problems, severity (S) rating are usually linked to the ability to provide quality products to the customers. An occurrence (O) rating gives an indication of the frequency of the problem. Detection (D) ratings are an estimation of the effectiveness of problem prevention and containment.

The Risk Priority Number (RPN) is a product of the Severity, Occurrence, and Detection ratings: SxOxD = RPN.

The process elements in the QFD ($e_j$) are useful for determining the causes of failures and the recommended alternative actions [19]. The RPN values are related to process alternatives selected in the previous step.

## 2.3. Manufacturing cycle-time estimating

The objective of this step is to evaluate the capacity of workshops and estimate manufacturing cycle time using DFP method based on the results of previous steps.

Consider a flow line manufacturing system consisting of n machines ($1 < j < n$) which manufacture m types of parts and all these parts go through every machine in the system without skipping. Part type i ($1 < i < m$) has a desired throughput ($D_i$), and arrives in batches randomly with predetermined batch-size ($B_i$), and a SCV for its batch arrival ($c^a_j$).

Each batch of part ($i$) is processed on one machine j with mean setup time, ($s_{ij}$), mean single-part process time, ($t_{ij}$), and mean yield rate $y_{ij}$.

The average cycle time for a batch of any part type spending in machine $j$, Eq.(18), is $TT_j$. The total manufacturing cycle time is estimated by Eq. (19), and the resource utilization using Eq. (15) taking into account the availability and the yield of each machine.

## 2.4. Estimation of manufacturing cost

The total manufacturing cost is estimated using the ABC method. The manufacturing process is broken down into activities based on a decomposition of [7 and [6]. The total manufacturing cost is the sum of activity costs, Eq. (23).

$$C_{ma} = \sum_{i=1}^{N} C^i_{activities} = \sum_{i=1}^{N}\big(C^i_{machining} + C^i_{load\_uload} + C^i_{setup} + C^i_{handling} + C^i_{programming\_testing} + C^i_{overhead}\big) \tag{23}$$

$C_{ma}$ is the cost of manufacturing activities; $N$ is the total number of activities involved in the manufacture of the part.

$C^i_{machining}$ is the machining cost of activity $i$, it is calculated by Eq. (25). The first term of this equation is the cost related to machines involved in the manufacturing process, as for the second term it is the cost related to the tools performing each operation, the formula is as follows:

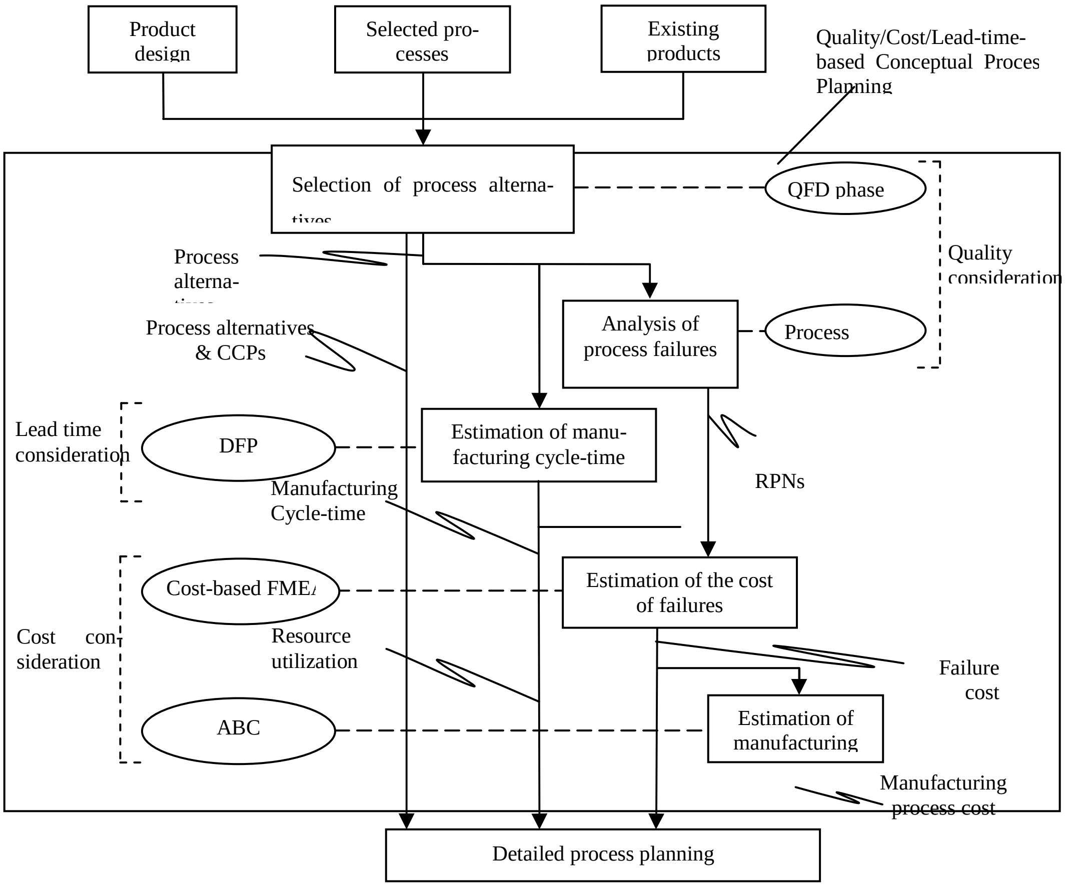


**Fig. 2.** The process of QCLPP.

$$C^i_{machining} = \sum C^i_j TT^*_j / B_i + C^i_{tool}, \tag{25}$$

where:

$$C^i_{tool} = \sum C^k_1 T^k_1 + \sum C^k_2 \frac{T^k_1}{T^k_0}. \tag{26}$$

$T^k_1$ and $T^k_0$ are the cutting time and tool life time respectively of the tool *k*. $C^k_1$ and $C^k_2$ are the cost per hour related to cutting labour and tool labour respectively of the tool *k* [20].

$C^i_{\text{load\_unload}}$ is the load and unload activity. $C^i_{\text{setup}}$ is the setup cost of activity *i*. $C^i_{\text{handling}}$ the handling cost of activity *i*. Handling is a batch-level activity.

$C^i_{\text{programming\_testing}}$ the programming and testing cost of activity *i*. Programming-testing is a product-level activity. $C^i_{\text{overhead}}$ the overhead cost of activity *i*. It is a facility-level activity.

## 2.5. Estimating the cost of failures

To estimate the financial impact of various potential failures, an extended technique, called cost-based FMEA, is used. Based on standard process FMEA and selected process alternatives from previous steps, cost-based FMEA has been used to identify and prioritize the process part of potential problems that have most financial impact.

- **Internal cost per event**

Internal failure costs are costs that are caused by products not conforming to requirements or customer needs and are found before delivery of products to external customers.

Each potential failure event is analyzed to determine the financial risk. The internal cost per event can be estimated using the following form:

$$C^j_{ej} = Labour\ cost + Material\ cost. \tag{27}$$

$C^j_{ej}$ is the is the internal cost of event e related to activity *j*.

$$Labour\ cost = down\ time \times hourly\ labour\ cost. \tag{28}$$

Labor cost is the cost of operator work which eliminates the failure. Material cost is the cost of component replacement due to failure. Using ABC method, the cost of manufacturing activities $C_{ma}$ is estimated for the component.

- **External cost per event**

External failure costs are costs that are caused by deficiencies found after delivery of products to external customers, which lead to customer dissatisfaction. The external costs per event, in our study, are essentially the complaints cost:

$$C^j_{ee} = \text{Complaints cost}\,, \tag{29}$$

$C^j_{ee} =$ external cost of event *e* related to activity *j*.

- **Event probability**

The probability of failure events, associated to activity *j*, can be estimated via prob ($O^j$) which is the probability corresponding to the occurrence rank of the risk associated with activity *j*.

$$Number\ of\ events\ per\ year = prob\ (O^j) \times No.of\ units\ per\ year\ . \tag{30}$$

The cost of all activities related to risks can be defined as:

$$C_r = \sum_1^p prob\ (O^j) \left[prob\ (D^j) \times C^j_{ei} + prob\ (1 - D^j) \times C^j_{ee}\right] \tag{31}$$

prob ($D^j$) is the probability corresponding to the detection rank of the risk associated with activity *j*.

Therefore,

$$The\ annual\ risk\ cost\ = No.of\ units\ per\ year \times C_r \tag{32}$$

- **Implementation cost**

Implementation cost is the cost of implementing alternative action. For each failure mode, financial risk has been estimated, alternative actions have been identified and their cost has been calculated. To take into account the risk cost associated to manufacturing process, manufacturing process cost before alternative actions implementation could be defined as:

$$C_m = C_{ma} + C_r. \tag{33}$$

$C_m$ is the manufacturing process cost of an artifact. Note that it is not necessary for the alternative actions to eliminate the risk completely. Therefore, the risk cost must be taken into account even after the implementation of alternative act-ions. Manufacturing process cost after alternatives implementation is given by this equation:

$$C^j_{ee} C_{m'} = C_{ma} + C_{r'} + C_a. \tag{34}$$

$C_{ma}$ is the cost of manufacturing activities after the implementation of alternative actions. This cost may have to be recalculated if some of actions modify the manufacturing activities *Cr'* is the cost of risk-related activities after alternatives implem-enttation.

$$\mathrm{C_{r'}} = \sum_{j=1}^{P} \mathrm{prob}\ (\mathrm{O'^j}) \left[\mathrm{prob}\ \left(\mathrm{D'^j}\right) \times \mathrm{C^j_{ei}} + \mathrm{prob}\ (1 - \mathrm{D'^j}) \times \mathrm{C^j_{ee}}\right]. \tag{35}$$

prob($O'^j$) and prob ($D'^j$) are the probability corresponding to the new occurrence and the new detection rank of the risk associated with activity *j*, respectively, after the implementation of alternative actions; $C_a$ is the cost of implemented actions.

## 3. A PROTOTYPE SYSTEM

Based on the methodology described above, a prototype has been developed; called QCLPP this application aims to support the process planner at estimating manufacturing cycle time and costs, resource utilization and assessing product quality. QCLPP consists of four modules; the first one is the quality module it is dedicated to assess product quality based on process elements involved in processing the product, the second module is manufacturing cycle time module, manufacturing cost module which is responsible for estimating cutting tool

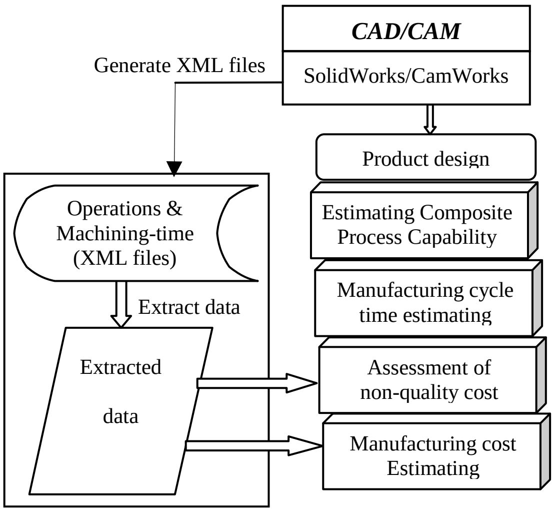


**Fig. 3.** A structure of the QCLPP prototype.

cost and manufacturing cost based on information generated by former step and manufacturing system module it serves as a decision making tool to choose among several alternative groups.

Figure 3 shows the structure model of the developed prototype. Using this application process planner starts with selecting and assessing the capability of the selected processes. Next, with browsing XML files generated by CAD/CAM systems which contains machining time of each operation, cutting tools involved in this operation; almost all information extracted from these files are displayed in the processing time table as shown in the next section (in the case study). Processing time extracted from the XML files serves also as key information to estimate cutting tools cost and therefore to estimate manufacturing costs.

## 4. CASE STUDY

To illustrate the QCLPP approach we present in this section an example of a machined part to be manufactured in a work shop which consists of several CNC machines.

Figure 4 shows the drawing of this part containing dimensions, tolerances and geometrical specifications. The raw material of this part is a low alloy steel preformed bar 110 ×110 mm² and cut into 35 mm. This part will be manufactured in a work shop which manufactures another product.

The objective of this section is to illustrate with this example the methodology followed to perform an analysis of the process planning.

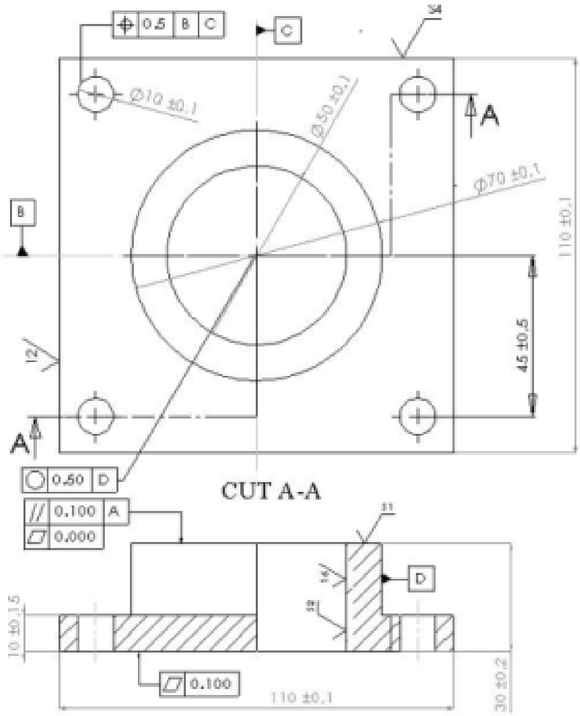


**Fig. 4.** Drawing part.

The objective of this section is to illustrate with this example the methodology followed to perform an analysis of the process planning.

### 4.1. Estimating the capability of process alternatives

Geometric characteristics are firstly identified; they are shown on the drawing part. In our example geometric characteristics identified in the drawing part are: planarity, position and circularity. The goal of this step is to select process alternatives that could manufacture this part by respecting all these geometric characteristics.

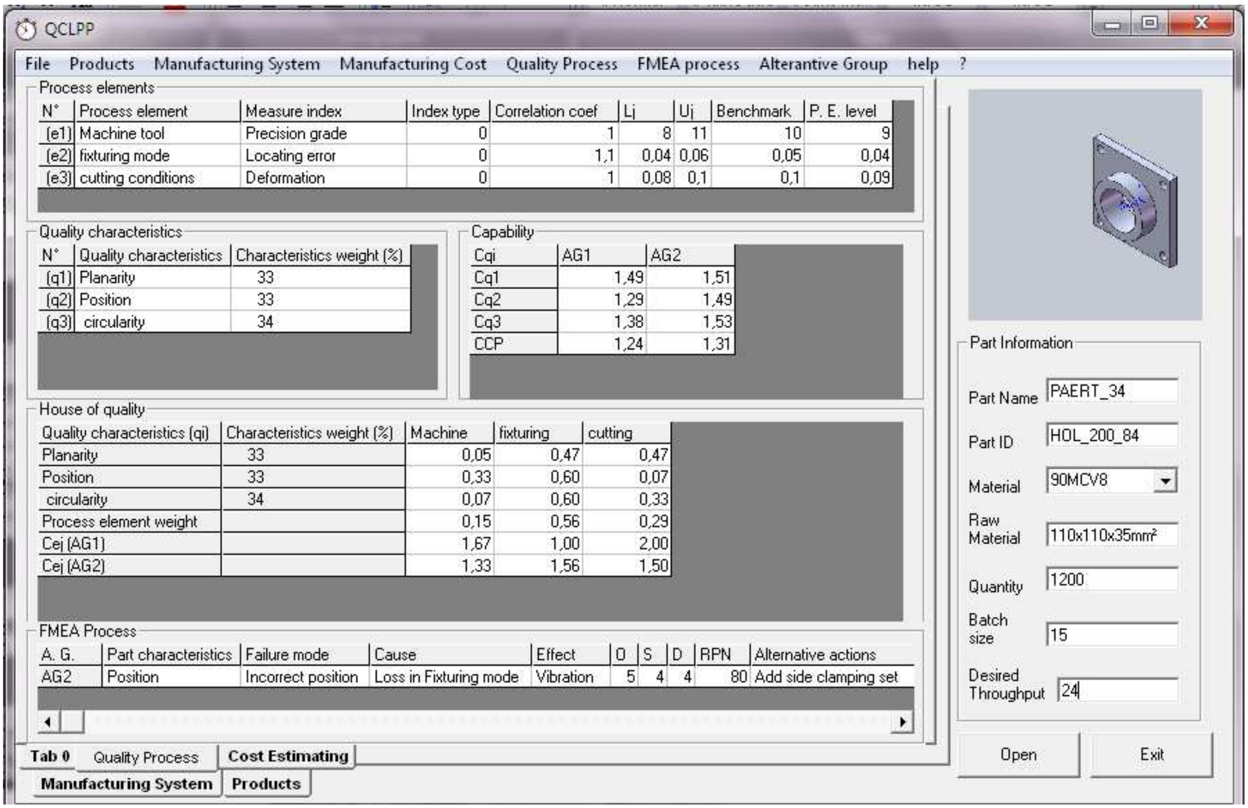
Machines and tools required to manufacture this part are presented in Table 1. Indeed, two altern-ative groups are studied, AG1: (MT1, FM1, CC1) and AG2: (MT2, FM2, CC2) and the process elements are: machining tools, fixture mode and cutting conditions.

The relationships between quality characteristics and process elements are assessed with the QFD tool. Figure 5 contains the house of quality table and the capability table. The CCP index of each alternative group is estimated using Equation (20-22). For the AG1, the CCP found is 1.24, as for the AG2 the CCP is 1.31.

*Table 1*

**Alternative groups**

| Process element | Alternative ref | Process alternative name | Measure | Process element level |
|---|---|---|---|---|
| Machining tool | MT1 | NC Milling machine. And Numerical lathe center | Precision grade | IT8 |
| | MT2 | NC Milling machine. And Numerical lathe center | Precision grade | IT9 |
| Fixturing mode | FM1 | 2 Outer spokes clamping | Locating error | 0.05 mm |
| | FM2 | Vise, Outer spoke clamping | Locating error | 0.04 mm |
| Cutting condition | CC1 | Cutting force and speed | Deformation | 0.08 mm |
| | CC2 | Cutting force and speed | Deformation | 0.09 mm |



Process elements

| N° | Process element | Measure index | Index type | Correlation coef | Lj | Uj | Benchmark | P. E. level |
|---|---|---|---|---|---|---|---|---|
| (e1) | Machine tool | Precision grade | 0 | 1 | 8 | 11 | 10 | 9 |
| (e2) | fixturing mode | Locating error | 0 | 1,1 | 0,04 | 0,06 | 0,05 | 0,04 |
| (e3) | cutting conditions | Deformation | 0 | 1 | 0,08 | 0,1 | 0,1 | 0,09 |

Quality characteristics

| N° | Quality characteristics | Characteristics weight (%) |
|---|---|---|
| (q1) | Planarity | 33 |
| (q2) | Position | 33 |
| (q3) | circularity | 34 |

Capability

| Cqi | AG1 | AG2 |
|---|---|---|
| Cq1 | 1,49 | 1,51 |
| Cq2 | 1,29 | 1,49 |
| Cq3 | 1,38 | 1,53 |
| CCP | 1,24 | 1,31 |

House of quality

| Quality characteristics (qi) | Characteristics weight (%) | Machine | fixturing | cutting |
|---|---|---|---|---|
| Planarity | 33 | 0,05 | 0,47 | 0,47 |
| Position | 33 | 0,33 | 0,60 | 0,07 |
| circularity | 34 | 0,07 | 0,60 | 0,33 |
| Process element weight | | 0,15 | 0,56 | 0,29 |
| Cej (AG1) | | 1,67 | 1,00 | 2,00 |
| Cej (AG2) | | 1,33 | 1,56 | 1,50 |

FMEA Process

| A. G. | Part characteristics | Failure mode | Cause | Effect | O | S | D | RPN | Alternative actions |
|---|---|---|---|---|---|---|---|---|---|
| AG2 | Position | Incorrect position | Loss in Fixturing mode | Vibration | 5 | 4 | 4 | 80 | Add side clamping set |

Part Information

Part Name PAERT_34
Part ID HOL_200_84
Material 90MCV8
Raw Material 110x110x35mm²
Quantity 1200
Batch size 15
Desired Throughput 24

**Fig. 5.** Capability of process alternatives.

*Table 2*

**Conceptual process planning**

| | CNC Machines | Processing time (min) | Setup time (min/lot) |
|---|---|---|---|
| **Alternative Group 1** | N. Lathe centre | 7.50 | 30 |
| | N. C. Milling machine | 6 | 30 |
| **Alternative Group 2** | N. Lathe centre | 8.57 | 30 |
| | N. C. Milling machine | 6.66 | 10 |

### 4.2. Process failure analysis

Once the alternative groups are selected, the process element and the product quality characteristics are now assessed with FMEA process. FMEA process table in Fig. 5 shows the RNP values related to the process FMEA analysis for the work piece.

The four holes are made in the same machine, but the fixturing scheme is not the same. With the vise of the second alternative group, the RNP of quality characteristic position ($q_2$) is higher than the predefined threshold, it equals to 80; therefore, there is a need for alternative actions to reduce the occurrence (O) rating. The recommended action is adding a side clamping set, and the new RNP will be 32.

### 4.3. Manufacturing cycle time estimating

The machining of this part has been simulated with the CamWorks module of SolidWorks. For the two Alternative Groups AG1 and AG2, the two machine centers selected to perform all operations of a work piece are NC milling machine and NC lathe centre.

Operations to be performed are the same for these two Alternative Groups. However, Cutting Conditions, tool path and cutting tools are not the same. Therefore processing times are not the same. Table 2 lists the total machining time on these two machines selected to manufacture the part. For AG1, the setup time for this part is 30 minutes on the lathe centre and 30 minutes on the milling machine centre; As for AG2, setup time is 30 minutes on the lathe centre and 10 minutes on the milling machine centre. In the second alternative group we are selecting a vise which is serving as a fixture tool for the two manufactured product; this choice can reduce the total manufacturing cycle time compared to the first alternative group. The desired throughput for the product to be manufactured is 24parts/day

Information related to the products to be manufactured is gathered in the same layer, 40parts/day is the desired throughput for the second product.

Manufacturing cycle time of each product is estimated with DFP method. Figure 6 is the “manufacturing cycle-time” screen sheet, which contains: Processing time table, Setup-processing time table, products table and process plans table. The processing time are extracted from XML files and displayed in the processing time table.

The setup-processing time table contains the processing rate (parts / day), the setup time and the SCV of setup time and processing time which are equal to 1.

In the next, we present an example of calculation for the first alternative group AG1. Cycle time estimating of AG2 is similar to AG1.

- **Arrival Aggregation**

Release rate is firstly calculated. Batch sizes are fixed to 15 and 25 unit/batch for the first and the second products.

Using Eq. (3), for the first product, release rate is 1.6 (batch/day), and 1.6 (batch/day) for the second one. The SCV of aggregated inter-arrival time at the first machine is determined using Eq. (6).

We need to determine the SCV of inter-arrival times for each product ($c^r_i$) using Eq. (7).

$$c^r_1 = \frac{2-1}{15} = 0.067,$$

$$c^r_2 = \frac{2\text{-}1}{25} = 0.04,$$

$$c^a_1 = \frac{1.6\times0.067+1.6\times0.04}{1.6+1.6} = 0.053.$$

- **Processing time aggregation**

The batch processing time is the sum of the mean batch setup time and the mean total processing time ($t^+_{ij}$).

The mean batch processing time of the first product ($i$ = 1) at the lathe centre ($j$ = 1) and the milling machine centre ($j$ = 2) are:

$$t^+_{11} = 15\times1\times(7.50\div60)+(30\div60) = 2.38 \quad \text{hours},$$

$$t^+_{12} = 15\times1\times(6\div60)+(20\div60) = 2.00 \quad \text{hours}.$$

The mean of the batch processing time for each item on each machine are then obtained. Since the part pro[cessing times on each machine are exponentially distributed, SCV ($c^t_{ij}$) and ($c^s_{ij}$) are equal to 1.

The SCV of total processing time on each machine is calculated using Eq. (9).

$$(2.38)^2 c^+_{11} = 15\times1\times(7.5\div60)^2\times1 + (30\div60)^2\times1$$

Since all machines are perfectly reliable ($A_j$ = 1), $c^*_j = c^+_j$ and $t^*_j = t^+_j$.

$$c^+_{11} = 0.09,$$

$$c^+_{12} = 0.10.$$

The adjusted aggregate process times of jobs at the lathe centre and the milling machine are calculated as follows:

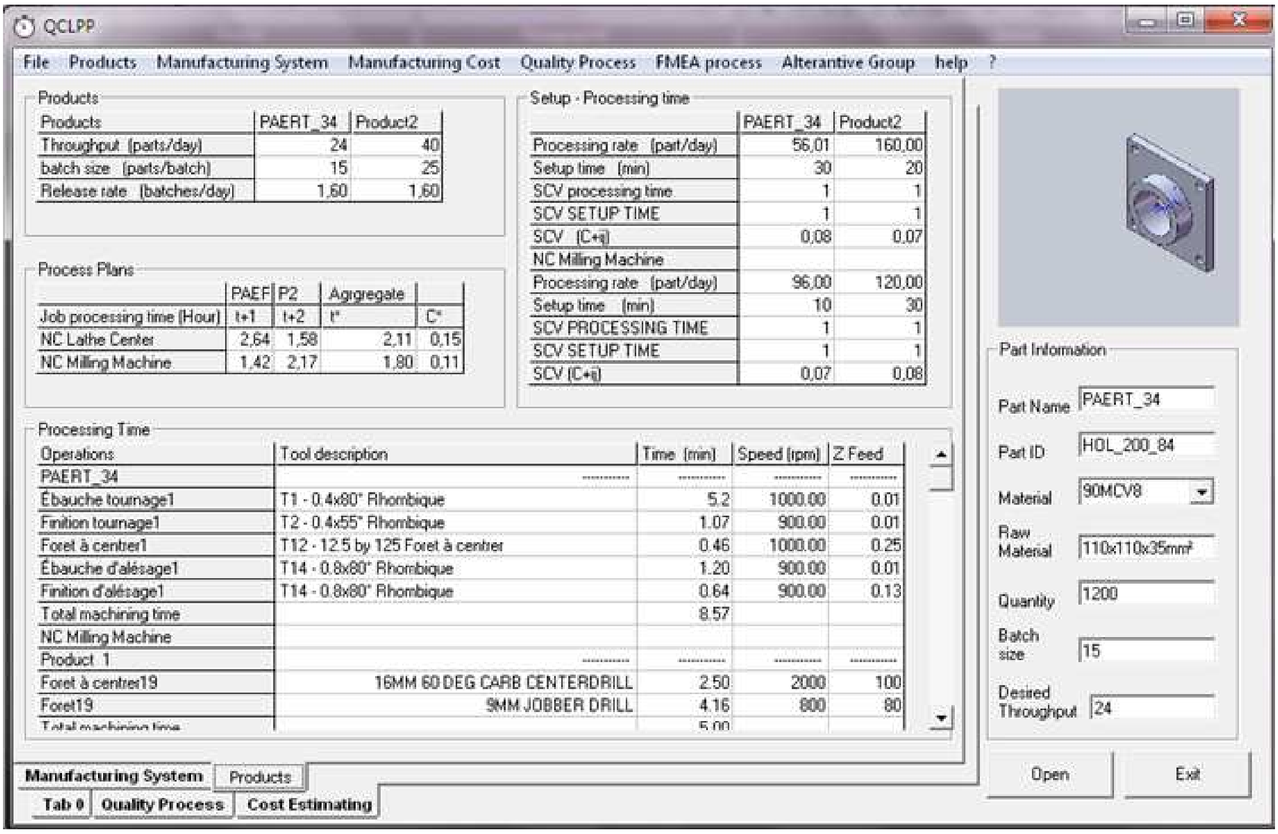
$$t^*_1 = \frac{1.6\times2.38+1.6\times1.75}{1.6+1.6} = 2.07 \quad \text{hours},$$

$$t^*_2 = \frac{1.6\times2.00+1.6\times2.00}{1.60+1.60} = 2.00 \quad \text{hours}.$$

And the SCV of the adjusted aggregate process times are calculated using Eq. (14).

$$(2.07)^2\left(c^*_1+1\right) = \frac{1.6\times(2.38)^2\times(0.09+1)+1.6\times(1.75)^2\times(0.1+1)}{1.6+1.6},$$

$$(2.00)^2\left(c^*_2+1\right) = \frac{1.6\times(2.00)^2\times(0.10+1)+1.6\times(2.00)^2\times(0.06+1)}{1.85+1.9},$$



Products

| Products | PAERT_34 | Product2 |
|---|---|---|
| Throughput (parts/day) | 24 | 40 |
| batch size (parts/batch) | 15 | 25 |
| Release rate (batches/day) | 1,60 | 1,60 |

Process Plans

| | PAEF | P2 | Agrgregate | |
|---|---|---|---|---|
| Job processing time (Hour) | t+1 | t+2 | t* | C* |
| NC Lathe Center | 2,64 | 1,58 | 2,11 | 0,15 |
| NC Milling Machine | 1,42 | 2,17 | 1,80 | 0,11 |

Setup - Processing time

| | PAERT_34 | Product2 |
|---|---|---|
| Processing rate (part/day) | 56,01 | 160,00 |
| Setup time (min) | 30 | 20 |
| SCV processing time | 1 | 1 |
| SCV SETUP TIME | 1 | 1 |
| SCV (C+ij) | 0,08 | 0,07 |
| NC Milling Machine | | |
| Processing rate (part/day) | 96,00 | 120,00 |
| Setup time (min) | 10 | 30 |
| SCV PROCESSING TIME | 1 | 1 |
| SCV SETUP TIME | 1 | 1 |
| SCV (C+ij) | 0,07 | 0,08 |

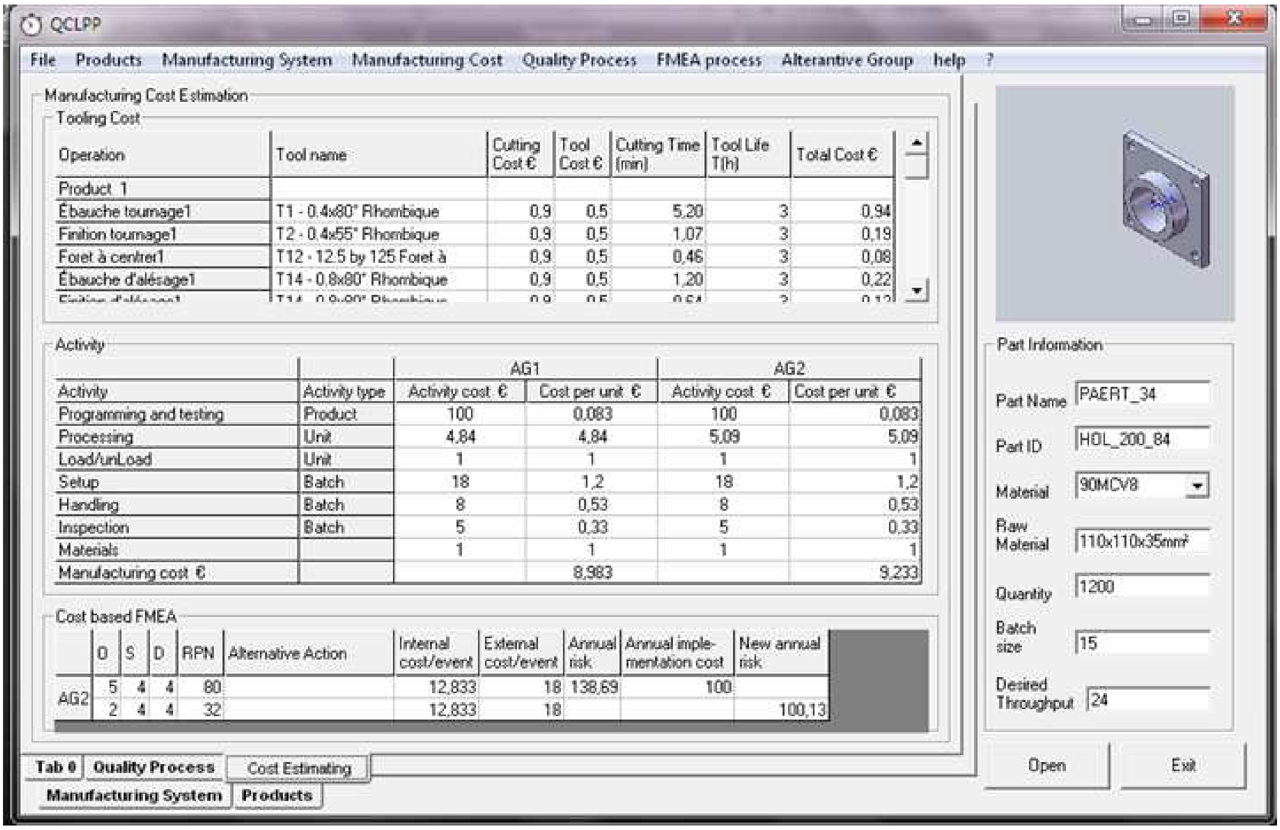
Processing Time

| Operations | Tool description | Time (min) | Speed (rpm) | Z Feed |
|---|---|---|---|---|
| PAERT_34 | .......... | .......... | .......... | .......... |
| Ébauche tournage1 | T1 - 0.4x80° Rhombique | 5.2 | 1000.00 | 0.01 |
| Finition tournage1 | T2 - 0.4x55° Rhombique | 1.07 | 900.00 | 0.01 |
| Foret à centrer1 | T12 - 12.5 by 125 Foret à centrer | 0.46 | 1000.00 | 0.25 |
| Ébauche d'alésage1 | T14 - 0.8x80° Rhombique | 1.20 | 900.00 | 0.01 |
| Finition d'alésage1 | T14 - 0.8x80° Rhombique | 0.64 | 900.00 | 0.13 |
| Total machining time | | 8.57 | | |
| NC Milling Machine | | | | |
| Product 1 | .......... | .......... | .......... | .......... |
| Foret à centrer19 | 16MM 60 DEG CARB CENTERDRILL | 2.50 | 2000 | 100 |
| Foret19 | 9MM JOBBER DRILL | 4.16 | 800 | 80 |
| Total machining time | | 5.00 | | |

Part Information

Part Name: PAERT_34
Part ID: HOL_200_84
Material: 90MCV8
Raw Material: 110x110x35mm²
Quantity: 1200
Batch size: 15
Desired Throughput: 24

**Fig. 6.** Manufacturing Cycle-time estimating.



Manufacturing Cost Estimation

Tooling Cost

| Operation | Tool name | Cutting Cost € | Tool Cost € | Cutting Time (min) | Tool Life T(h) | Total Cost € |
|---|---|---|---|---|---|---|
| Product 1 | | | | | | |
| Ébauche tournage1 | T1 - 0.4x80° Rhombique | 0,9 | 0,5 | 5,20 | 3 | 0,94 |
| Finition tournage1 | T2 - 0.4x55° Rhombique | 0,9 | 0,5 | 1,07 | 3 | 0,19 |
| Foret à centrer1 | T12 - 12.5 by 125 Foret à | 0,9 | 0,5 | 0,46 | 3 | 0,08 |
| Ébauche d'alésage1 | T14 - 0.8x80° Rhombique | 0,9 | 0,5 | 1,20 | 3 | 0,22 |

Activity

| | | AG1 | | AG2 | |
|---|---|---|---|---|---|
| Activity | Activity type | Activity cost € | Cost per unit € | Activity cost € | Cost per unit € |
| Programming and testing | Product | 100 | 0,083 | 100 | 0,083 |
| Processing | Unit | 4,84 | 4,84 | 5,09 | 5,09 |
| Load/unLoad | Unit | 1 | 1 | 1 | 1 |
| Setup | Batch | 18 | 1,2 | 18 | 1,2 |
| Handling | Batch | 8 | 0,53 | 8 | 0,53 |
| Inspection | Batch | 5 | 0,33 | 5 | 0,33 |
| Materials | | 1 | 1 | 1 | 1 |
| Manufacturing cost € | | | 8,983 | | 9,233 |

Cost based FMEA

| | O | S | D | RPN | Alternative Action | Internal cost/event | External cost/event | Annual risk | Annual implementation cost | New annual risk |
|---|---|---|---|---|---|---|---|---|---|---|
| AG2 | 5 | 4 | 4 | 80 | | 12,833 | 18 | 138,69 | 100 | |
| | 2 | 4 | 4 | 32 | | 12,833 | 18 | | | 100,13 |

Part Information

Part Name: PAERT_34
Part ID: HOL_200_84
Material: 90MCV8
Raw Material: 110x110x35mm³
Quantity: 1200
Batch size: 15
Desired Throughput: 24

**Fig. 7.** Manufacturing cost and cost of failure estimating.

$$c_1^* = 0.11,$$

$$c_2^* = 0.10.$$

The adjusted aggregate process times are gathered in the process plans Table in Fig. 7.

- **Flow variability propagation and cycle time**

Machine utilization is calculated using Eq. (15). The aggregate process time calculated previously is key information to estimate machine utilization, for the two machines:

$$u_1 = 2.07 \times \frac{(1.6+1.6)}{8} = 82.80\ \%,$$

$$u_2 = 2.00 \times \frac{(1.6+1.6)}{8} = 80.00\ \%.$$

For the AG2:

$$u_1 = 2.11 \times \frac{(1.6+1.6)}{8} = 84.40\ \%,$$

$$u_2 = 1.80 \times \frac{(1.6+1.6)}{8} = 72.00\ \%.$$

Resource utilization table in the manufacturing system sheet, Fig. 8, contains the values $u_1$ and $u_2$ of the two alternative groups, and the chart is automatically updated.

The SCV of inter-arrival times at the second machine is:

$$c2a = c1\ d = 1 + 0.82\ 2 \times 0.15 - 1 + 1 - 0.82\ 2 \times 0.062 - 1 = 0.121.$$

Manufacturing cycle time is approximated by Eq. (18). For the lathe centre:

$$TT_1^* = \frac{1}{2} \times (0.053+0.11) \times \frac{0.828}{(1\text{-}0.828)} \times 2.07 + 2.07 = 2.88\ .$$

And manufacturing cycle time at the milling machine is:

$$\mathrm{TT}_2^* = \frac{1}{2} \times (0.121+0.1) \times \frac{0.80}{(1\text{-}0.80)} \times 2.00 + 2.00 = 2.77\ .$$

And the total manufacturing cycle time for this part is the sum of the manufacturing cycle time at the two machines, it equals to: 5.65H.

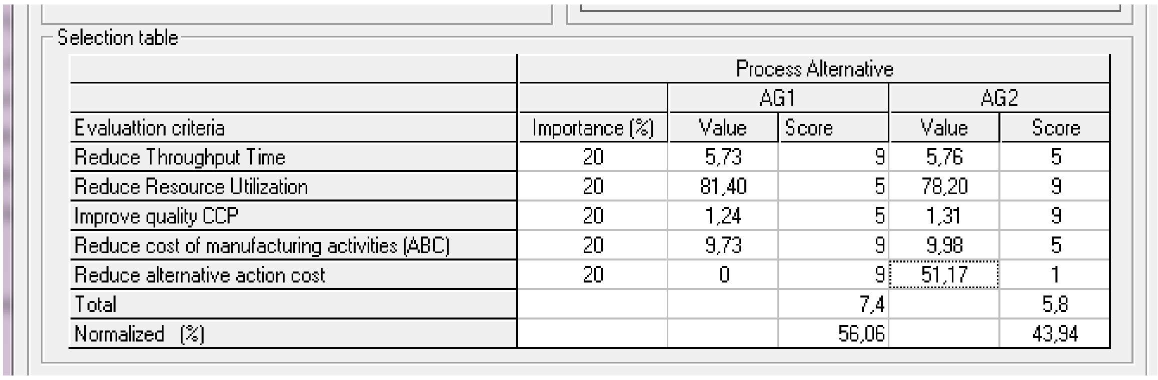
For the AG2, the total manufacturing cycle-time of this product is: 5.73H.

### 4.4. Manufacturing cost estimating

Manufacturing cost is estimated using the ABC method; the activities involved in the manufacturing process are: programming and testing, machining, load/unload, setup, handling, inspection and Material.

The machining cost is calculated using Equation (25). The previously estimated processing time by DFP method is incorporated in Eq. (27) used to estimate manufacturing cost on each machine. Figure 7 is cost estimating screen sheet which contains tooling cost, activity tables and cost based FMEA table.

The first table summarizes costs related to the cutting tools involved in the manufacturing process; it provides data needed to estimate tooling cost using Equation (26). We assume that the hourly cost of cutting tool is 0.9 € / h and the tool life time is 3 hours and the tool cost is equal to 0.5 €.



| | | Process Alternative | | | |
|---|---|---|---|---|---|
| | | AG1 | | AG2 | |
| Evaluattion criteria | Importance (%) | Value | Score | Value | Score |
| Reduce Throughput Time | 20 | 5,73 | 9 | 5,76 | 5 |
| Reduce Resource Utilization | 20 | 81,40 | 5 | 78,20 | 9 |
| Improve quality CCP | 20 | 1,24 | 5 | 1,31 | 9 |
| Reduce cost of manufacturing activities (ABC) | 20 | 9,73 | 9 | 9,98 | 5 |
| Reduce alternative action cost | 20 | 0 | 9 | 51,17 | 1 |
| Total | | | 7,4 | | 5,8 |
| Normalized (%) | | | 56,06 | | 43,94 |

**Fig. 8.** Process alternative selection table.

For the AG1 machining cost is 4.84 €. Finally, manufacturing cost is the sum of activities costs $C_{ma} = 8.98$ €. For the AG2 manufacturing cost is 9.23 €.

### 4.5. Failure cost estimating

Downtime to detect the failures is 15 minutes and the hourly labor cost is 2 €/H.

$$\text{Labor cost} = \frac{15\text{min}}{60} \times 2 = 0.5\ €.$$

According to results of the previous stage in terms of manufacturing costs which is 9.98 €. For the AG2: (0.5 + 9.98 = 10.48 for AG2).

External cost is supposed to be the same for AG1 and AG2 and it is equal to 18 €.

$$Cr_{GR2} = 1200 \times \mathrm{P}(5) \times [\mathrm{P}(4) \times 10.48 + (1 - \mathrm{P}(4) \times 18)],$$

$$Cr_{GR2} = 1200 \times \left[\frac{2.9}{1000} \times (0.31 \times 10.48 + (1 - 0.31) \times 18)\right] = 54\ €.$$

The implementation cost of the proposed alternative actions is 50 €.

$$Cr'_{GR2} = 1200 \times \mathrm{P}(2) \times [\mathrm{P}(4) \times 10.48 + (1 - \mathrm{P}(4) \times 18)],$$

$$Cr'_{GR2} = 1200 \times \left[\frac{2.9}{100\,000} \times (0.31 \times 18 + (1 - 0.31) \times 10.48)\right] + 100 = 100.54\ €.$$

### 4.6. Process alternative selection

Finally, results of the previous steps are gathered in a selection table, manufacturing cycle time, resource utilization, manufacturing cost and alternative action cost are the evaluation criteria to be assessed at this stage. The purpose of this stage is to select the best alternative which compromises multiple evaluation criteria. In the literature, there are a lot of methods of multiple evaluation criteria [21, 22, and 23].

In our approach we adopt the method used bay [6 and 24]. With this method the process planner gathers and prioritizes the evaluation objectives on 1–10 scale, the final score is calculated in order to identify the most suitable alternative which replies to multiple objectives, Fig. 8. The AG1 score is 56%, as for the AG2 its score is 44%, which means that the second Alternative groups is better than the first one.

## 5. CONCLUSION

The objective of this paper is to propose an approach to develop a new tool that helps process planner to improve the effectiveness of Process Planning. Quality, cost and lead-time are taken in consideration by process planner during the selection and defining the processes that have to be performed in order to transform raw material into an end product. In this paper, a QCLPP approach is presented; it is based on tools such as QFD technique and process FMEA to assess the product quality via a CCP index. The QCLPP approach also includes the ABC and DFP methods to estimate respectively the manufacturing cost and cycle-time. The output of each method is gathered in a selection table to help the process planner to select the most suitable combined alternatives in terms of quality improvement, cost and lead time meeting. A case study is presented in this paper to illustrate this new developed approach.

## 6. REFERENCES

[1] R. Kesavan, *Process Planning and cost estimation*, New Age International, Second Edition, 2008.

[2] A. Gunasekaran, *An integrated product development quality management system for manufacturing*, TQM Journal, vol. 10, No. 2, 1998, pp. 115–123.

[3] Shaw C. Feng and W. Nederbragt, *Incorporation process planning into conceptual design*, The 1999 ASME Design Engineering Technical Conferences, 1999.

[4] K-S Chin, L-Y Zheng, L. Wei, *A hybrid rough-cut process planning for quality*, International Journal of Advanced Manufacturing Technology, vol. 22, pp. 733–43, 2003.

[5] P.G. Maropoulos, H.D. Bradley, Z. Yao, *CAPABLE: an aggregate process planning system for integrated product development*, Journal of Materials Processing Technology, vol. 76, pp. 16–22, 1998.

[6] A. Hassan, A. Siadat. *Conceptual Process Planning–an improvement approach using QFD, FMEA and ABC methods*, Robotics and computer-Integrated Manufacturing, vol. 26, 2010, pp. 392–401.

[7] S. Feng, Y. Zhang, *Conceptual Process Planning – A definition and functional decomposition Manufacturing Science and Engineering*, International Mechanical Engineering Congress and exposition, vol. 10, 1999, pp. 97–106.

[8] M. Chincholkar and, J.W. Herrmann, *Reducing Manufacturing Cycle time during Product Design*, Journal of Manufacturing Systems, vol. 20, 2001, pp. 416–428.

[9] J.W. Herrmann, M. Chincholkar, *Design for production*: *A tool for reducing manufacturing cycle time*, ASME Design Engineering Technical Conference, Sept. 10-13-2000.

[10] L. Cohen, *Quality Function Deployment: how to make QFD work for you*, Addison-Wesley, USA, 1995.

[11] J.B. ReVelle, J.W. Moran, C.A. Cox, *The QFD handbook*, John Wiley & Sons, New York, 1998.

[12] R. McDermott, R. Mikulak, M. Beauregard, *The basics of FMEA*, USA: Productivity, 1996.

[13] C. Tarum, *FMERA-Failure Modes, Effects, and (Financial) Risk Analysis*, SAE 2001 world congress, March 5–8, Detroit, Michigan, USA, 2001.

[14] S. Rhee, K. Ishii, *Using cost based FMEA to enhance reliability and serviceability*, Advanced Engineering Information, vol. 17, pp. 179–88, 2003.

[15] W-H. Tsai, *A technical note on using work sampling to estimate the effort on activities under activity-based costing*, International Journal of Production Economics, vol. 43, 1996, pp. 6–11.

[16] PBB. Turney, *Common cents: the ABC performance breakthrough, how to succeed with activity-based costing. Cost technology*, Hillsboro, 1991.

[17] L-Y. Zheng, K-S. Chin, *QFD based optimal process quality planning*, International Journal of Advanced Manufacturing Technology, vol. 26, 2005, pp. 831–841.

[18] K.N. Otto E.K. Antonsson, *Trade-off strategies in engineering design*, Research in Engineering Design, vol. 3, no.2, 1991, pp. 87–103.

[19] A. Pillay, J. Wang, *Modified failure mode and effects analysis using approximate reasoning*, Reliability Engineering and System Safety, vol. 79, 2003, pp. 69–85.

[20] Ciurana, and Garcia-Romeu, M. L., *A model for integrating process planning and production planning and control in machining processes*, Robotics and Computer-Integrated Manufacturing, vol. 24, 2008, pp. 532–544.

[21] T.L. Saaty, *The Analytic Hierarchy Process*, McGraw-Hill, New York, 1980.

[22] B. Yannou, S. Hajsalem, F. Limayem, *Comparison between the SPEC method and Value Analysis for an aid in preliminary design of products*, Mécanique & Industries, vol. 3, 2002, pp. 189–99.

[23] S. Blanc, Y. Ducq, B. Vallespir, *Evolution management towards interoperable supply chains using performance measurement*, Computers in Industry, vol. 58, 2007, pp. 720–32.

[24] B. Almannai, R. Greenough, J. Kay, *Decision support tool based on QFD and FMEA for the selection of manufacturing automation technologies*, Robotics and Computer-Integrated Manufacturing, vol. 24, 2008, pp. 501–507.