Cost-based FMEA and ABC Concepts for Manufacturing Process Plan Evaluation

Alaa HASSAN[1,2], Iman DAYARIAN[1]
[1] LGIPM Laboratory, ENSAM, 4 rue Augustin Fresnel, 57078 Metz, France
[2] Mechatronic Engineering Department, HISAT, Barza, Damascus, Syria

Ali SIADAT[1], Jean-Yves DANTAN[1]
Alaa.hassan@metz.ensam.fr
Ali.siadat@metz.ensam.fr
Jean-yves.dantan@metz.ensam.fr

***Abstract*— Cost management and quality analysis methods currently contribute to the decision support in product design and manufacturing process. One of the objectives is to evaluate a process plan in order to choose the most efficient solution in economic and qualitative terms. This study proposes a methodology based on Failure Mode and Effect Analysis (FMEA) with the financial aspects of risk, and Activity-Based Costing (ABC) in the purpose of economical evaluating the process plan. It shows how ABC and cost-based FMEA concepts can be adapted to measure quality-related costs and prioritize quality improvement efforts. Information modeling for this methodology is provided; and a case example is presented to illustrate its application.**

***Keywords*— Cost-based FMEA, Activity-Based Costing, Information Modeling, Process planning.**

I. INTRODUCTION

In today's competitive global market, the manufacturing companies are facing great on-going challenges. They are asked to react quickly and manufacture high quality, low cost products to be successful in this new environment [1]. Thus there is a need to carry out risk analysis and cost estimation methods in a methodical way to justify the decisions and ensure that the risk (risk of non-quality) and the cost constraints are taken into account from the early stages of a product design and manufacturing.

Failure Mode and Effects Analysis (FMEA) is an important method of preventive quality and reliability assurance. It involves the investigation and assessment of all causes and effects of all possible failure modes on a system, in the earliest development phases [2]. Basically, FMEA can be classified into two main types [3]: design FMEA which deals with design activities, and process FMEA which is used to solve problems due to manufacturing processes.

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 to 10 range. The three indices used for RPN (RPN = O × D × S) 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 [4]. Tarum [5] proposed a new technique, based on process FMEA, which identifies and prioritizes the process part of potential problems that have the most financial impact on an operation.

Influence of design on manufacturing cost is usually great. Errors made during the early stages of design tend to contribute as much as 70% to the cost of production. Activity-Based Costing (ABC) has become mature cost estimation and accounting methodology. The method was first discussed by Cooper and Kaplan [6]. Using ABC for cost estimation of manufactured parts is being practiced today with acceptable rate of success [7]. ABC assumes that cost objects (e.g., products) create the need for activities, and activities create the need for resources.

The ABC system has the following cost allocation bases or cost drivers: (i) unit-level bases, which assume that inputs increase in proportion to the number of units produced; (ii) batch-level bases, which assume that inputs vary in proportion to the number of batches produced; (iii) product-level bases, which assume that inputs are necessary to support the production of each different type of product; and (iv) facility-level bases, which simply sustain a facility's general manufacturing process.

However, product development is usually a techno-economic process; hence there is always a trade-off between quality goals and limited budgets. This paper focuses on the process planning as a phase of product development process. It shows how cost-based FMEA method could quantify the financial risk of a process plan. We propose an approach, a framework which uses the cost-based FMEA and ABC concepts to estimate the manufacturing cost of the product taking into account the risk and quality control cost. This approach enables designers to improve manufacturing process plan, it can serve as a useful information system to support decision making in product development.

II. PROCESS PLAN EVALUATION APPROACH

A process plan is a systematic determination of the activities by which a product is made in an economic and competitive way in a given environment [8]. The criteria to choose the optimal process plan are numerous; among them we note the manufacturing cost, the process time, the product quality, etc.

Process planning is an activity process plan which is the detailed specification for the manufacture of a part meeting the design specifications. It aims at determining manufacturing processes, selecting resources and equipment, and estimating manufacturing costs. Our objective here is to evaluate a 'roughly' generated process plan in order to minimize the manufacturing cost and improve the product quality. Fig. 1 shows an activity model of the proposed approach.

A. A1 – Estimate activities cost

Manufacturing process can be decomposed into activities. In this paper, ABC method is used to estimate the manufacturing cost. Cost estimating equations are described in the following equations [9], [10].

$$C_{ma} = \sum_{i=1}^{N} C^{i}_{activity}$$

$$= \sum_{i=1}^{N} \begin{pmatrix} C^{i}_{machining} + C^{i}_{load-unload} + C^{i}_{setup} + \\ C^{i}_{handling} + C^{i}_{programming-testing} + C^{i}_{overhead} \end{pmatrix} \quad (1)$$

C_{ma} cost of manufacturing activities.

i an index.

N the total number of manufacturing activities applied to manufacture an artifact.

$C^{i}_{machining}$ machining cost of activity i.

$C^{i}_{load-unload}$ load and unload cost of activity i.

C^{i}_{setup} setup cost of activity i.

$C^{i}_{handling}$ handling cost of activity i.

$C^{i}_{programming-testing}$ programming and testing cost of activity i.

$C^{i}_{overhead}$ overhead cost of activity i.

B. A2 – Analyse process failures using cost-based process FMEA

Activity A2 is to analyse process failure modes using cost-based process FMEA method. The process FMEA is used to analyze the potential failure modes of a product, caused by a process. Based on standard process FMEA, cost-based FMEA has been used to identify and prioritize the process part of potential problems that have most financial impact. Alternative actions cost can be estimated to maximize the financial benefits.

Based on existing process FMEA, cost-based process FMEA is carried out by adding the following steps:

1) Cost per event: each potential failure event is analysed to determine its financial risk. The failure cost can be estimated using the following form [4]:

$$C^{j}_{e} = \text{Labour cost} + \text{Material cost} + \text{Opportunity cost} \quad (2)$$

C^{j}_{e} cost of event e related to activity j

Labour cost = down time × hourly labour cost (3)

Labour 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.

Opportunity cost = down time × hourly opportunity cost (4)

Opportunity cost is the cost incurred when a failure inhibits the main function of the system and prevents any creation of value.

2) Event probability: the probability of failure events, associated to activity j, can be estimated in the following equation: $prob(O^{j}) \times prob(D^{j})$

$prob(O^{j})$ the probability corresponding to the occurrence rank of the risk associated with activity j

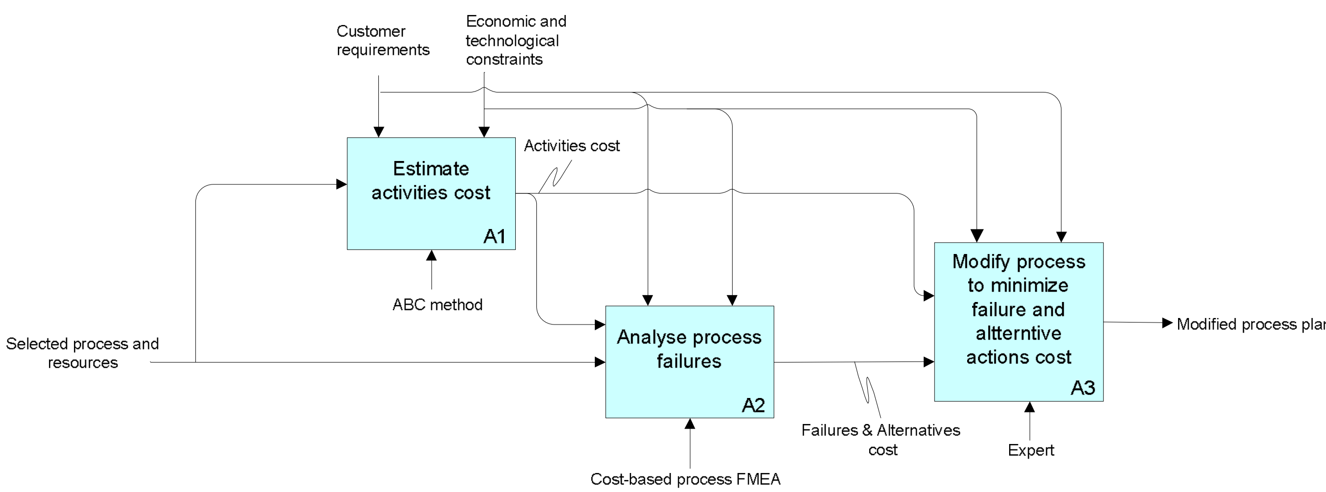

Figure 1. Activity model of process plan evaluation approach.

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

Number of events per year = $prob(O^j) \times prob(D^j) \times No.of\ units\ per\ year$ (5)

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

$$C_r = \sum_{j=1}^{P} C_e^j \times prob(O^j) \times prob(D^j) \qquad (6)$$

with $P \leq N$, therfore, the annual risk cost $= No.of\ units\ per\ year \times C_r$

Implementation cost is the cost of implementing alternative action.

C. A3 – Modify process to optimize failure and alternative actions cost

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

$$C_m = C_{ma} + C_r \qquad (7)$$

C_m manufacturing process cost of an artifact.

FMEA analysis results in recommended alternatives which modify the manufacturing process plan in order to reduce the risks. Note that it is not necessary for the alternative to eliminate the risk completely. Therefore, the risk cost must be taken into account even after the alternatives implementation. Manufacturing process cost after alternatives implementation is given by this equation:

$$C_{m'} = C_{ma} + C_{r'} + C_a \qquad (8)$$

C_{ma} cost of manufacturing activities after the alternatives implementation. This cost may have to be recalculated if alternatives modify the manufacturing activities.

$C_{r'}$ cost of risk-related activities after alternatives implementation.

$$C_{r'} = \sum_{j=1}^{P} C_{r'}^j$$

$$C_{r'}^j = C_e^j \times prob(F'^j) \times prob(ND'^j) \qquad (9)$$

$prob(O'^j)$ the probability corresponding to the new occurrence rank of the risk associated with activity *j*, after the alternatives implementation.

$prob(D'^j)$ the probability corresponding to the new detection rank of the risk associated with activity *j*, after the alternatives implementation.

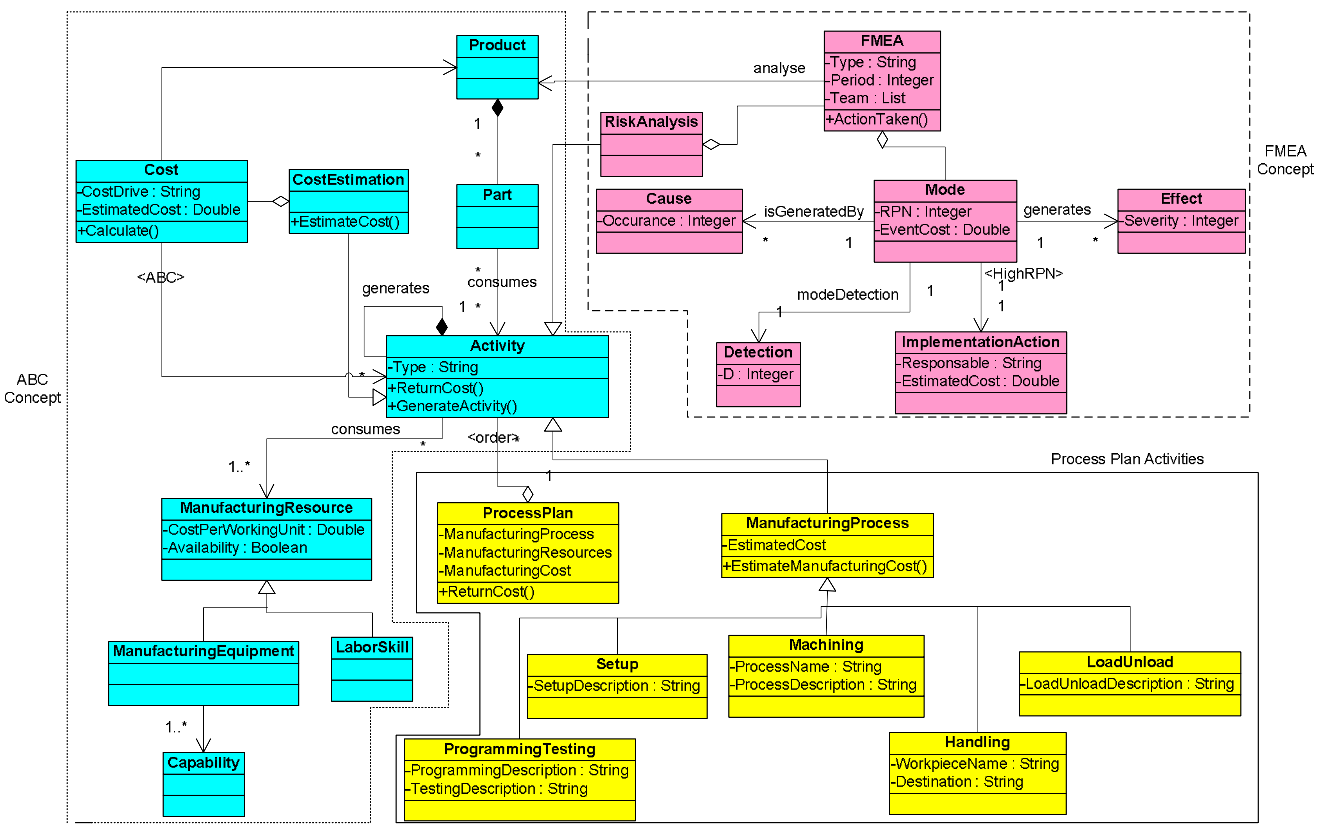

Figure 2. Class diagram for process plan evaluation.

C_a the cost of implemented actions.

For a manufacturing process plan, we have estimated the risk and manufacturing costs. The modification of this process could be translated in terms of selecting alternative resources which lead for reducing, as much as possible, the risk and manufacturing costs to achieve an optimal quality/cost ratio. Once the resources are selected, the designers have to prioritize the recommended alternative actions in order to reduce the most of risks (i.e. improve product quality) and to minimize the cost.

III. INFORMATION MODEL FOR PROCESS PLAN EVALUATION APPROACH

To structure the information exchanged between the various stages of the proposed approach, an object model was proposed. Fig. 2 shows a class diagram UML (Unified Modeling Language) for the process plan evaluation approach [1], [10], [11], and [12].

The main classes are: Product, Activity, FMEA, CostEstimation, ManufacturingResource, and ManufacturingProcess. The Product class is mainly made up of a number of parts; it consumes activities (Activity class). The class ManufacturingResources represents the resources consumed by the activities. The associations between Product, Activity, and ManufacturingResource classes are based on ABC principle. ManufacturingProcess represents a generic process which can be specialized further. The ProcessPlan consists of a sequence of activities. FMEA class represents one of the methods used to conduct risk analysis represented by the class RiskAnalysis which is also an activity.

IV. A CASE STUDY

The axis of a centring system will be studied to illustrate the application of the proposed methodology for process plan evaluation. The objective of the centring system system is to support the work-piece and to position it compared to the base. Fig. 3 shows the system design decomposition of the centring system.

This study deals with the axis only, two machines (Machine 1 and Machine 2) are available to machining it. We suppose that the annual cadence is 42,000 parts (axis), with 500 parts for each batch. Our objective here is to estimate the risk, manufacturing, and alternative cost for each machine in order to select the best combination of machines and alternatives. The quantitative estimates in this study should be considered as illustrative only.

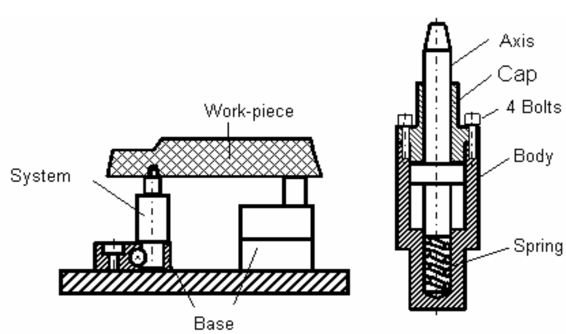

Figure 3. Centring system decomposition.

A. *Cost estimation using ABC method*

Manufacturing cost is estimated using ABC method. For each machine, the user has to set all the activities that contribute to manufacturing and estimate their costs. Table I shows manufacturing cost calculation for Machine 1 and table II shows this calculation for Machine 2.

TABLE I. MANUFACTURING COST ESTIMATION FOR MACHINE 1.

Machine 1			
Activity	**Activity type**	**Activity cost (€)**	**Cost per unit (€)**
Programming and testing the machine	Product	21370.8	0,51
Machining	Unit	0,89	0,88
Load/Unload	Unit	0,48	0,48
Setup	Batch	229,6	0,46
Handling	Batch	468,6	0,94
Inspection	Batch	329,1	0,65
Materials		0,43	0,43
Manufacturing cost			**4.35**

TABLE II. MANUFACTURING COST ESTIMATION FOR MACHINE 2.

Machine 2			
Activity	**Activity type**	**Activity cost (€)**	**Cost per unit (€)**
Programming and testing the machine	Product	25620	0,61
Machining	Unit	0,93	0,93
Load/Unload	Unit	0,51	0,51
Setup	Batch	235	0,47
Handling	Batch	468,6	0,94
Inspection	Batch	329,1	0,65
Materials		0,43	0,43
Manufacturing cost			**4.54**

B. *Cost-based process FMEA*

One of the axis functions is to adapt the axis's cone to the work-piece. Table III shows a cost-based process FMEA table for the axis to be machined by Machine 1. Table IV shows a cost-based process FMEA table for the axis to be machined by Machine 2.

C. *Results analysis*

For each of two machines, manufacturing cost and risk cost are estimated. In our case study, the objective is to select the more suitable machine as well as the alternative action to be implemented. The results of the two precedent activities can be analysed as follows:

1) *For Machine 1:*

- The annual cost before alternative implementation (7) = annual manufacturing cost + annual risk cost = 4.35 × 42000+ 6715.8 = 189, 415.8 €/year
- The annual cost after realisation measuring tool (8) = annual manufacturing cost + annual implementation cost + new annual risk cost = 182700 + 3000 + 1549.8 = 187,249.8 €/year

TABLE III. COST-BASED PROCESS FMEA FOR AXIS WITH MACHINE 1.

Process	Part function	Failure mode	Cause	Effect	Detection	O	S	D	RPN	Alternative action	Cost per event (€)	Events/ Year	Annual risk (€)	Annual implementation cost (€)	New RPN	New annual risk (€)
Machining the cone of the axis	The cone adapts to work-piece	The cone doesn't adapt to work-piece	Dispersion of machine	Incorrect position of the work-piece	1 piece/H	6	5	6 2	150 60	Measuring tool realisation	30.83	218.4	6715.8	3 000	60	1549.80
						6	5	6 3	150 90	SPC				2 000	90	2841.30

TABLE IV. COST-BASED PROCESS FMEA FOR AXIS WITH MACHINE 2.

Process	Part function	Failure mode	Cause	Effect	Detection	O	S	D	RPN	Alternative action	Cost per event (€)	Events/ Year	Annual risk (€)	Annual implementation cost (€)	New RPN	New annual risk (€)
Machining the cone of the axis	The cone adapts to work-piece	The cone doesn't adapt to work-piece	Dispersion of machine	Incorrect position of the work-piece	1 piece/H	4	5	6 2	120 40	Measuring tool realisation	30.96	21.84	676.17	3 000	40	155.84
						4	5	6 3	120 60	SPC				2 000	60	285.70

- The annual cost after SPC method implementation (8) = annual manufacturing cost + annual implementation cost + new annual risk cost = 182700 + 2000 + 2841.3 = 187,541.3 €/year

2) *For Machine 2:*

- The annual cost before alternative implementation = 191,356.17 €/year
- The annual cost after realisation measuring tool = 193,853.04 €/year
- The annual cost after SPC method implementation = 192,916.07 €/year

The decision that will be taken depends on the financial criteria set by the organization, the resource availability, the alternative implementation possibility, etc. For example, using Machine 1 with measuring tool leads to a minimum cost of the axis in terms of manufacturing and risk as well, so it will be the best choice for the organization that looks for minimum price of its product. If the organization aims at the highest quality, using Machine 2 with measuring tool will be the best choice.

In this study, FMEA analysis recommends alternatives actions to enhance the system quality. These actions have to be added to the manufacturing process activities, and they don't modify the activities of manufacturing process.

V. CONCLUSION AND FUTURE WORK

In this paper, manufacturing process planning was analysed using a new methodology based on risk analysis and cost estimation concepts. Cost-based FMEA and ABC methods were involved in selecting manufacturing resources, estimate manufacturing process risk cost and manufacturing cost. First, the manufacturing cost of the process plan is estimated using ABC method. Second, using cost-based process FMEA, the potential failure modes caused by the process are analysed and then their financial impacts are estimated. The results of the two previous steps are analysed to help the decision maker in modifying the process plan in terms of selecting alternative resources, modifying the process plan activities, and/or selecting alternative actions which lead for reducing the cost and improving the quality the product. A case study was presented to illustrate the application of proposed methodology. Furthermore, an initial information model was proposed to formalize the evaluation methodology knowledge.

Possible future work includes : (i) assessment of the process quality of the process alternative resources with the measure of the process capability, (ii) analysing the dependence between the lines of the cost-based FMEA table to establish the links between the various failures and theirs causes, (iii) QFD (Quality Function Deployment) method could be used to set up the relationships between the process elements and the product characteristics and then the interface FMEA/QFD has to be explored, developing a prototype based on the proposed UML model and specifying interfaces that facilitate decision maker task, (iv) improving modification method to involve comparing alternative manufacturing process plans in order to select the most efficient process activities and its resources.

REFERENCES

[1] X. Xu, J. Chen, S. Xie, "Framework of Product Lifecycle Costing System," Journal of Computing and Information Science in Engineering, vol. 6, pp. 69-77, 2006.

[2] D.H Stamatis, "Failure Mode and Effect Analysis: FMEA from Theory to Execution," 2nd edn, ASQ Quality Press, Milwaukee, WI, ISBN 0-87389-598-3, 2003.

[3] P.C. Teoh, K. Case, “Failure modes and effects analysis through knowledge modeling” Journal of Materials Processing Technology, pp. 253-260, 2004.

[4] S. Rhee, K. Ishii, “Using cost-based FMEA to enhance releability and serviceability,” Advanced Engineering Information, pp. 179-188, 2003.

[5] R. Cooper, R. S. Kaplan, “How Cost Accounting Distorts Product Costs,” Manage. Account, vol. 69, pp. 20–27, 1988.

[6] C. Tarum, “FMERA-Failure Modes, Effects, and (Financial) Risk Analysis,” SAE 2001 World Congress, Detriot, Michigan, USA, March 5-8, 2001.

[7] D. Ben-Arieh, L. Qian, “Activity-based cost management for design and development stage,” International Journal of Production Economics, vol. 83, pp. 169–183, 2003.

[8] G. Van Zeir, J.P. Kruth, J. Detand, “A Conceptual Framework for Interactive and Blackboard Based CAPP,” International Journal of Production Research, vol. 6, pp. 1453-1473, 1998.

[9] S. Feng, E. Song, “Information Modeling of Conceptual Process Planning Integrated with Conceptual Design,” Proceedings of DETC2000, The 5th Design For Manufacturing Conference, The 2000 ASME Design Engineering Technical Conferences. September 10-13, 2000 in Baltimore, Maryland, USA, 2000.

[10] K. Tornberg, M. Jämsen, J. Paranko, “Activity-based costing and process modeling for cost-conscious,” International Journal of Production Economics, vol. 79, pp. 75-82, 2002.

[11] A. Etienne, J.Y. Dantan, A. Siadat, A. D’Acunto, P. Martin, “Data model for CAPP systems to manage Key Characteristics variations,” Machine engineering, 4(1 & 2), pp. 107-115, 2004.

[12] A. Hassan, J-Y. Dantan, A. Siadat, “Information modeling for variation risk management during product and process design,” International Journal of Productivity and Quality Management, vol. 2, pp. 221-240, 2007.