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(Value, Risk)-based Performance Evaluation of Manufacturing Processes

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Abstract: A value/risk -based performance evaluation framework is proposed in the context of manufacturing processes at the industrialization phase of product development. Various risk factors of the manufacturing process are identified through Failure Mode and Effect Analysis (FMEA) and then embedded in the process plan models. Modelling and simulation are then employed for determining the value a process plan can create and the risk it is exposed to. Alternative scenarios are developed, simulated and compared with a reference scenario. The methodology is illustrated with a case study issued from parts manufacturing but is applicable to a wide range of other processes.

Keywords: Performance Evaluation, Decision Support, (Value, Risk) Pair, Manufacturing Processes, Manufacturing Simulation

1. INTRODUCTION

Due to competitive market environments, industries are struggling to deal with the uncertain and changing business needs to satisfy customers by providing products of high quality at low cost and at the right time. This has led to the development of many managerial practices such as JIT, investing in advanced manufacturing technologies such as CAD/CAM, emphasizing quality, concurrent engineering and integrated product and process design. This view has been reported in the work of David and Robert (2005). To assess the success when implementing these techniques, companies use performance measures. However, it has been found that traditional performance measures are no longer adequate to evaluate the performance of the current industrial practices.

Indeed, performance evaluation has long been based on the accounting concept of cost. Until the mid-70's, it was mostly the only performance evaluation criterion. From then on, industry realized that traditional performance measures do not reflect the real performance of their practices (Kaplan and Cooper, 1997). This feeling led researchers and academia to consider non-financial measures. Later on, quality became a performance measure besides cost. Initially, quality was measured as conformity to product specifications but with the advent of Total Quality Management, the emphasis shifted away towards customer satisfaction (Neely et al., 2005). JIT philosophy, flexibility and responsiveness made time an important performance measure as described by Stalk (1988). Porter (1998) introduced the value chain concept to measure process based performance. More recently, many new performance measures have been emerging such as agility, reactivity and so on.

The introduction of so many performance measures evolved into performance measurement systems (PMS). In an attempt to integrate the different dimensions of performance, Kaplan and Norton (1992, 1996, 2004) developed balanced scorecards to integrate strategic, operational and financial measures. SMART-Strategic Measurement Analysis and Reporting Technique was developed at Wang Laboratories, Inc. by Lynch and Cross (1992) who tried to link operational performance measures with strategic objectives and company vision. More details about PM are available in the literature by Nudurupati et al. (2011).

Each of the performance measurement approaches has both relative strengths and weaknesses. The most common weaknesses of the PMS follow. Firstly, performance is not measured in a holistic fashion. Secondly, little guidance is given to choose and implement performance measures. Thirdly, they do not often provide a mechanism to quantify performance measures.

To overcome the difficulties associated with the current performance measurement systems, companies should focus on processes, not on whole organization, an idea supported in the literature (Kueng, 2000). Kueng further analysed that none of the above PMS fulfils the criteria to be process-based and could measure performance holistically at the same time. In addition, developed PMSs are mostly designed for existing systems and mainly focus on existing business processes or production systems. There exists no formal performance measurement system, to our knowledge, that could measure the performance at product and process design phases. More recently, Bosch-Mauchand et al. (2010) have proposed value-based performance evaluation for the product industrialization phase.

To measure the performance of processes in an integrated manner, risk assessment should be performed in addition to evaluating the other performance dimensions at early phases of the product life cycle. However, it is often ignored or evaluated independently. Larson and Kusiak (1996) proposed

a risk assessment approach but only model the macro-decision structure of the concurrent design process.

In brief, a new performance measurement approach is needed which can help companies to evaluate performance of their processes in an integrated manner. The problem can be solved to a great extent if different dimensions of performance are integrated and presented, for ease of use, in the form of a single performance measure.

In this paper, a value/risk-based performance evaluation framework to assess the value and risk of a process in a coupled manner is proposed. The conceptual framework in the current study is aimed at manufacturing processes but could also be extended to any kind of business processes.

2. PERFORMANCE MEASURE: VALUE/RISK

In this section, a conceptual value/risk model is presented. The idea is to map the value creation process in the presence of risk. Both value and risk are associated with a process (e.g. business process, product development process or manufacturing process). Process management aims to maximize value while risk management tries to preserve the created value (Sienou, 2009). Therefore, it is indispensable to evaluate the performance of a process in terms of the value it creates and the risk it is exposed to further to its cost.

2.1. Conceptual Value Model

Process is the source of value creation. At the lowest abstract level, it is the activity and its coordination with other activities that create value in the process for stakeholders.

To develop an activity-based value model, activity (or process) attributes, such as cost, time and quality, are defined. An activity consumes cost and time and has a certain degree of quality (process deviations) that transforms an input (tangible such as part, intangible such as information) into an output (i.e. creates an interim value) (Fig. 1). This interim value, in the context of manufacturing, can be a change of the workpiece morphology or information created as in the case of an inspection activity.

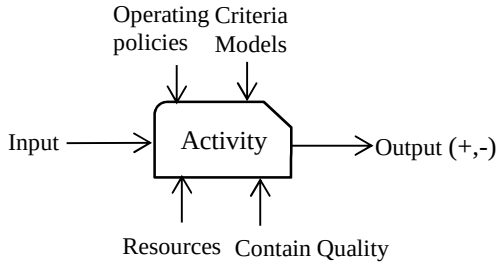

Fig. 1. Conceptual Activity-based Value Model

The overall value that a process creates, is the summation of interim values, i.e. Output v_i which itself is the appropriate balance of process attributes that accumulates "+" (or dissipates "-" in case of risk happening) along the activity chain transforming finally into a product value.

Cost and time allocation to an activity can be based on Activity-Based Costing (ABC) model and stochastic scheduling model, respectively, while process quality is largely controlled by a resource model. The operating policies govern the activities or processes in the system.

2.2. Risk Model

The current risk model is process-based and has largely been adapted from Kayis et al. (2007) and Larson and Kusiak (1996).

In the current study, qualitative and quantitative risk analyses are carried out using Failure Mode and Effect Analysis and discrete event simulation, respectively.

To measure risk quantitatively, Kaplan and Garrick defines a tuple of three parameters (S, P, C) where S represents a scenario (an event), P the probability of scenario S and C its consequence (Aven, 2010). The current model relies on these three parameters for its risk quantification.

The underlying assumption for process-based risk assessment is that each activity in a process is exposed to certain sources of risks (or risk factors (RF), e.g. cost, schedule, quality related risks…) (Fig. 2). The consequences of all risk factors on an individual activity are first combined and then aggregated all along the process.

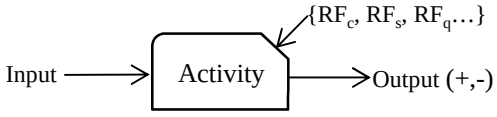

Fig. 2. Activity i Exposure to Risk Factors (RF)

The risks identified using FMEA are associated with activities and their magnitude in an individual activity is measured as:

$$R_i = \sum_{j=1}^{J} (P_{ij} \times C_{ij}) \quad (1)$$

Where, R_i is the risk magnitude in activity i, P_{ij} is the probability of a risk factor j in the activity i while C_{ij} is the consequence (or impact) of a risk factor j in the activity i. The overall risk magnitude in a process can be determined as:

$$\mathrm{R}(\mathrm{p_k}) = \sum_{\forall\, i \in \mathrm{p_k}} \mathrm{R_i} \quad (2)$$

Where $R(p_k)$ = Risk magnitude in a particular process p_k.

2.3. Value/Risk Model

The building block for the value/risk model is the combination of individual conceptual values and risk models as shown in Fig. 3. The proposed model provides a foundation for evaluating the value that an activity creates in the presence of risk.

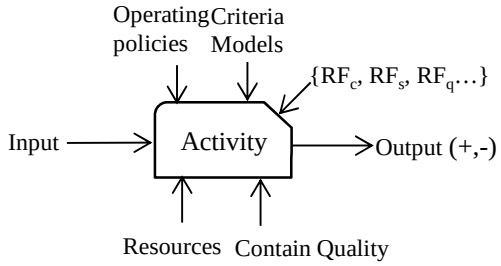

Fig. 3. Conceptual Value/Risk Model

Nota bene: The value and risk of a process depend on the objective assigned to the process.

3. MODELLING AND SIMULATION BASED VALUE AND RISK ASSESSMENT

This section presents a methodology for implementing the proposed value/risk model. Manufacturing processes are evaluated on the basis of the performance measures, the (value, risk) pair, using the proposed model.

The methodology draws its contents from modelling and simulation approaches. To evaluate the performance in the context of integrated product and process design using the proposed model, manufacturing processes are firstly designed from the product specifications and then modelled before experimentation in the simulation environment. The following section describes the generation and modelling of manufacturing process plans.

3.1. Manufacturing process plans

Manufacturing process plans are developed from product specification drawings. A process plan determines a sequence of steps and resources called phases and made of operations for the realization of a part component or a product.

Generation of manufacturing process plans: alternative process planning is to find more than one path for realizing a product and is a key factor for integration of design, process planning and scheduling functions. For generation of process plans, we have adopted the methodology described in Sormaz and Khoshnevis (2003).

To develop an alternative process plan, the product is decomposed into geometrical features. To manufacture each feature, process candidates are selected using inquiries to the appropriate knowledge base of the manufacturing processes.

Manufacturing process plans modelling: once alternative process plans are developed, the next step is their modelling for the purpose of evaluation. BPMN, the Business Process Modelling Notation (OMG, 2011), is used with a little modification in the task construct for risk representation in the process model (Fig. 4). In integrated product and process design, concurrency, temporality and hierarchy of processes are inevitable, therefore BPMN is employed to easily model these complexities. In addition to BPMN, IDEF3 could also be used as it has the required contents to model the current

3.2. Risk Analysis

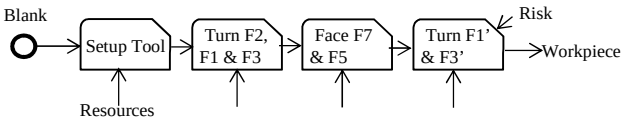

Fig. 4. Excerpt from Manufacturing Process Plan for Axle

The risks associated with early product life cycle steps are either schedule type risks such as violation of due date, cost risks (cost overrun), requirement risks, i.e. the product do not function as it is intended, and so on. The overall risk (e.g. violating due date) is the result of a risk or aggregation of a set of risks at the lowest abstract level of a process. To identify and analyse qualitatively such set of risks, the Failure Mode and Effect Analysis (FMEA) technique is employed. The developed FMEA table is elaborated with reference to the objective. For example, if the customer asks for a product with shorter lead time, then FMEA focuses on failure modes having "delay" effects (Table 1).

Table 1. Process FMEA for Schedule Risk

Process	Failure mode	Causes	Effects	*P*	*C*	*D*	*RPN*
Op 01	*High Scrap*	*Unstable process*	*Delay in mfg.*	*5*	*6*	*6*	*150*

The identified critical failure modes are then incorporated in the process plan model for quantitative analysis.

Risk-Embedded manufacturing process plans: Insertion of identified risks in the process plan model results in a so-called Risk-Embedded Manufacturing Process Plan (Risk-embedded MPP).

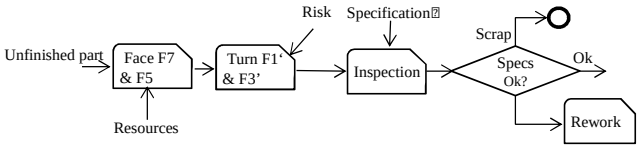

Fig. 5. Excerpt from a Risk-Embedded MPP

For instance, Fig. 5 shows a critical activity, i.e. Turn F1' & F3' subject to risk of quality, which has been identified through FMEA and incorporated in the process model.

3.3. Simulation Model

Once the Risk-Embedded MPP is ready, the next step is simulation model development for experimentation.

Input data generation: Appropriately investigating the value creation process of a process plan simulation model requires proper collection and feeding of input data to the model. Input data for simulation experiments can be divided into two categories: functional data (activities) and parameters or input variables. The former can be obtained by employing functional modelling techniques such as IDEF methods, BPMN and so on. For the latter, many tools can be employed. Tables 2 to 4 identify the input parameters for a discrete event simulation model.

Table 2. Run Parameters for Simulation Model

Parameter Types	Categories	Value
Part Arrival	NA	*EXPO()*
Parts/Arrival	Batches	*# of units/arrival*
Replications	NA	*10*
Process Trigger	NA	*Customer order*

Table 3. Process Plan Parameters for Simulation Model

Parameter Types	Categories	Value
Operations	Operation times	*TRIA()*
Inspection	Inspection type	*Manual*
	Inspection time	*NORM()*
	# of inspections	*1 to many*
Setup	Setup time	*NORM()*
	# of setups	*1 to many*
Machine Specific	Capability of machine	$C_p = 1.67$
	Machine speed factor	$less\ or\ greater\ than\ 1$

Table 4. Scenario Parameters for Simulation Model

Parameter Types	Categories	Value
Target	NA	*D units*
Objective	Product cost	*P $*
	Quality	*Q %*
	Manufacturing time	*T minutes*

Output data collection: Once the input data are collected, simulation can be run. Simulation results will be analysed under different performance criteria. In our case, Table 5 lists the major performance criteria, namely: Product Cost (Cost of good products, Cost of scrap parts and Cost of rework), Manufacturing Time, Overall Process Yield (Multiplication of individual process yields). These performance measures are used as inputs to the value performance indicator.

Table 5. Evaluation Criteria

Criteria	Calculation Method
Product Cost	$C_{mfg.} = \sum_{i=1}^{N} C_{activity}^{i}$
Manufacturing Time	The total time an entity (part, product) spend in the manufacturing system
Process Yield	(1-Scrap parts/Total parts)

4. DECISION MAKING VIA MULTI-CRITERIA AGGREGATION

Simulation experiments can provide elementary performance measures. Performing selection among alternative process plans based solely on elementary performance measures does not provide any insight. Therefore, it is always desirable to consider multiple evaluation criteria when deciding among alternative solutions. For this purpose, the MACBETH and 2-additive Choquet integral aggregation mechanisms are used in order to fuse the performance measures of simulation runs and to provide a global measure for both value and risk.

In the multi-criteria model, criteria are formalized through a utility function employing the MACBETH procedure. Determination of interaction among criteria is carried out using fuzzy measures or Choquet capacity while aggregation is performed using the 2-additive Choquet integral.

4.1. MACBETH

MACBETH (Measuring Attractiveness by a Categorical Based Evaluation TecHnique) is a multi-criteria decision analysis approach used to determine elementary performance expressions as well as aggregated ones while comparing different scenarios (Bane e Costa and Vansnick, 1999; Clivillé et al., 2007). The elementary performance expressions set reflects decision-makers' (DMs) preferences or judgments of performance criteria with reference to fictive situations. Two situations are compared pairwise for a performance criteria and thus ordinal information is obtained, which is then transformed into cardinal information through "difference of attractiveness", which is quite natural to decision-makers who usually rely on verbal levels of attractiveness such as {null, very weak, weak, moderate, strong, very strong, extreme}.

In the current study, the MACBETH procedure is used to develop elementary performance expressions by solving inter criteria commensurability issue and to map them on a $[0, 1]$ scale. As MACBETH relies on the weighted mean to aggregate elementary performance expressions, which is often not the case in real-life examples where criteria may interact, the Choquet integral has been chosen as the operator for the aggregation of performance expressions. It can handle interdependencies among different performance expressions through a fuzzy measure or Choquet capacity.

4.2. Choquet Integral (CI)

The finite sets $\mathrm{C} = \{\mathrm{c}_1, \mathrm{c}_2 \ldots \mathrm{c}_n\}$ and $\mathrm{A} = \{\mathrm{a}_1, \mathrm{a}_2 \ldots \mathrm{a}_m\}$, representing criteria and alternatives respectively, are considered. Then, $\mathrm{a} \in \mathrm{A}$ and $\mathrm{c} \in \mathrm{C}$ can be associated with a profile $\mathrm{x}_i^a = (\mathrm{x}_{c_1}^a, \mathrm{x}_{c_2}^a \ldots \mathrm{x}_{c_n}^a)$ where x_i^a represents a partial score of criterion i in alternative a on a scale of $[0, 1]$.

To aggregate the partial scores, the Choquet integral can be used. For weight determinations of single criterion or coalition of criteria, Choquet capacity will be defined first.

Let $\mathrm{P(C)}$ denote the power set of C, then a discrete fuzzy measure of C is a set function $u: \mathrm{P(C)} \rightarrow [0,1]$ satisfying the axioms: (i) $\mathrm{u}(\emptyset) = 0, \mathrm{u(C)} = 1$ and (ii) $\mathrm{u(C)} > u(\mathrm{C}')$ if C' is a subset of C. The first axiom refers to boundary condition while the second one to monotonicity.

The discrete CI of $\mathrm{x} = \{\mathrm{x}_1, \mathrm{x}_2 \ldots \mathrm{x}_n\}$ with respect to u is then defined as (Grabisch and Labreuche, 2009):

$$\mathrm{C_u(x)} = \sum_{i=1}^{n} (\mathrm{x_i} - \mathrm{x_{i-1}}).\, \mathrm{u(C')} \qquad (3)$$

We use a special case of the CI called 2-additive CI where interactions among criteria pairs are considered. This type of CI can be defined as:

$$C_u(x) = \sum_{i=1}^{n} v_i x_i - \frac{1}{2}\sum_{i=1}^{n} I_{ij}|x_i - x_j| \qquad (4)$$

Where C_u models vectors of elementary performance expressions, v_i denotes a Shapely index with $\sum_{i=1}^{n} v_i = 1$ that represents importance of criterion i relative to all other criteria and I_{ij} represents interaction between criteria (c_i, c_j) , ranging in [-1,1].

5. APPLICATION

The case study is based on a hypothetical company which machines and assembles mechanical systems on a make-to-order (MTO) basis. The company under study aims to evaluate manufacturing processes based on the proposed value/risk -based performance evaluation framework.

The reference product for this case study is a mechanical locator (Fig. 6), a work holding device used for centring of job on a machine-tool.

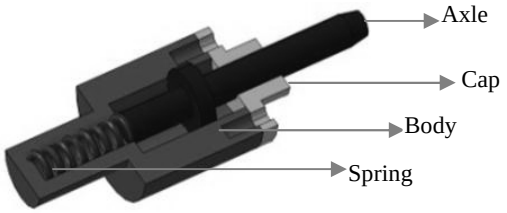

Fig. 6. Mechanical Locator

To illustrate the use of the proposed framework within the company, a manufacturing scenario is defined.

5.1. Case study: Manufacturing Scenario

The company under study receives an order for *N* mechanical locators from a customer with a lead time of *D* days. Due to short lead times, the customer compromises on the product quality and therefore demands for mid-range quality products. The price of the product is kept at *P*. The company has sufficient resources at its disposal, therefore all parts except those which can be purchased at cheaper rates in market, are manufactured in the manufacturing facility.

For the current scenario, let us assume that the company purchases springs and bolts from the market while the three other parts, namely axle, body and cap, are machined at the facility. We further assume that all raw materials and the purchased parts are available whenever needed.

To fulfil the demand of the customer and create value for stakeholders, the company embarked on evaluating the manufacturing scenarios before accepting the contract. The process planning expert generates multiple process plans. To choose the best process plan among several alternatives, they are modelled and evaluated in the simulation environment under different evaluation criteria, which form the basis for value measure. In addition, a risk analysis is carried out for the manufacturing scenario under consideration.

5.2. Risk Analysis for Manufacturing Scenario

Recalling from the manufacturing scenario, the critical parameter for order fulfilment is shorter lead time. Therefore, a due date is set for the order fulfilment. Failing to deliver product at due date will cost \$2/unit time tardiness. In addition, upper bound cost is set to \$*P*. The FMEA Table is developed to identity critical activities and parameters in the process plan to meet the due date target (Table 6). For shorter lead times, parameters such as the number of inspections, machine/tool setups and assembly logical parameter (part fitting cycle) are investigated.

Table 6. FMEA (Schedule Risk)

Process	Failure mode	Causes	Effects	*P*	*C*	*D*	*RPN*
Op 02	*Tech. problem*	*Insufficient maintenance*	*Delay in mfg.*	*5*	*7*	*6*	*210*

The magnitude of risk violating the due date can be calculated quantitatively in the simulation environment as:

$$R_S(PP_k) = P_i(T_i > due\ date) * C \qquad (5)$$

Where $R_S(PP_k)$ is the overall schedule risk in the process plan k, $P_i(T_i > due\ date)$ is the probability that the last activity i completion time T_i exceeds the agreed due date , and C is its consequence or impact.

To calculate the risk of cost overrun, the probability for the process that exceeds the upper bound cost is simulated. Its impact is a matter of agreement between the supplier and the customer. In the current study, a qualitative scale such as low, medium, high and critical is used to represent the impact which corresponds to 0.25, 0.50, 0.75 and 1, respectively.

As for quality risk, the probability of non-conformance stems from each critical activity. It is simulated and multiplied with the impact from the process FMEA severity rating scale.

5.3. Experimental Results

The Risk-Embedded Manufacturing process plans are simulated using Rockwell ARENA v.13.5. Ten independent replications for each process plan were run. In each replication run, process plan and scenario related parameters as described in Tables 2 to 4 were loaded into the simulation model. Table 7 summarizes performance measures and risks (R_i, i= c (cost), q (quality) and s (schedule)) for the three process plans.

Table 7. Simulation Results for mfg. process plans

	Mfg. Cost	Mfg. Time	Process Yield	R_c	R_q	R_s
MPP1	*23.97*	*20.25*	*0.70*	*0.9*	*20*	*0.18*
MPP2	*17.36*	*22.52*	*0.75*	*0.00*	*16*	*0.45*
MPP3	*18.73*	*23.6*	*0.72*	*0.00*	*09*	*0.77*

Performance measures are transformed into commensurable elementary performance and risk expressions (Table 8) employing the MACBETH methodology while relying on DM's preferences and strength of preferences (cf. §4.1).

Table 8. Elementary Performance and Risk Expressions

	Mfg. Cost	Mfg. Time	Process Yield	R_c	R_q	R_s
MPP1	*0.89*	*0.75*	*0.14*	*0.9*	*0.75*	*0.25*
MPP2	*0.11*	*0.5*	*0.71*	*0*	*0.50*	*0.50*
MPP3	*0.33*	*0.12*	*0.57*	*0*	*0.25*	*0.88*

Performance and risk expressions as well as the CI parameters (v_i & I_{ij}) are put in equation (4) to calculate the global performance measure, value and global risk (Table 9).

Table 9. Value and Risk indicator for Process Plans

	Value	Global Risk	I_{ij} & v_i for value only	
			I_{ij}	v_i
MPP1	*0.58*	*0.63*	$I_{qc} = 0.09$	$v_q = 0.18$
MPP2	*0.43*	*0.32*	$I_{cs} = 0.14$	$v_c = 0.34$
MPP3	*0.34*	*0.40*	$I_{qs} = 0.10$	$v_s = 0.48$

From Table 9, it can be concluded that process plan 1 creates more value followed by 2 and 3. However it is exposed to higher risk. It is up to the decision-maker to make a trade-off between value and risk keeping in mind the interest of the company and customer.

6. CONCLUSIONS AND FUTURE WORK

In this paper, a performance evaluation method for manufacturing processes at industrialization phase is carried out on the basis of a value/risk performance measure. The proposed measure is developed employing modelling and simulation approaches. The objective of the proposed measure is to simplify the decision-making process by integrating the different dimensions of performance into a global value measure. In addition, risk assessment is carried out to determine aggregated risk of the process.

The current framework will be extended to include more performance dimensions and risk factors. Value created will be distributed among different stakeholders on the basis of multi-criteria decision analysis method while keeping in view their contribution or importance in the project or process. In addition, cost effective risk mitigation strategy will be incorporated so that to maximize value and reduce risk in view of limited budgetary means. A risk acceptability zone vis-à-vis value will also be defined to make the proposed performance framework more robust for decision-making.

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