Optimizing Performance of Manufacturing Systems by Evaluating Performance Effectiveness Function

Boyd A. Nicholds and John P. T. Mo
RMIT University, School of Aerospace, Mechanical and Manufacturing Engineering, Melbourne, Australia
Email: bnichold@bigpond.net.au, john.mo@rmit.edu.au

***Abstract*—Managing change in manufacturing companies is complex. This complexity tends to increase when organisations overstretch improvement targets above their current ability to apply adequate effort to succeed. This paper describes a performance effectiveness function that estimates performance gain that is achievable levels of effort required to apply to the improvement project. The performance effectiveness function maps the often non-linear relationship between actual performance gain and applied effort. The outcome when applying the function may be used by organisations to set realistic performance gain targets with a better chance of success and to have realistic expectations on the level of performance they may achieve from an improvement project.**

***Index Terms*—risk assessment, performance improvement, process improvement, change management, project prioritisation**

I. Introduction

Manufacturing companies are looking to optimize their system in order to increase their operational performance with the expectation of increasing their bottom-line and ability to survive and thrive against their competitors. They may determine a number of actions or projects to improve their processes but resource limitations often dictate the priority among process improvement projects so some valuable initiatives may never get a green light. Various techniques and methods are utilised to perform this prioritisation process [1], [2]. A weakness with these methods is the lack of quantitative estimate of the probability of success of achieving the desired performance gains.

The advantage of probability of success knowledge is its use in assessing risk. If the risk of process improvement project failure is too high, actions such as increase of capability, increase of effort and focus within the bounds of organisational capability, modification of scope, or even postponement can mitigate the risk. Without probability of success knowledge projects may commence and subsequently fail with negative consequences such as recriminations, disappointment and disillusionment of the workforce.

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II. Literature Review

A. Project Prioritisation

Appropriate and adequate project prioritisation is necessary to improve the chances of process improvement success. Banuelas *et al.* [3] found the most popular tools and methods used for prioritizing improvement projects within a six-sigma framework are cost-benefit analysis, cause and effect matrix, and Pareto analysis. Other methods and tools used to a lesser degree are non-numeric methods, Practical Process Improvement (PPI), Theory of Constraints (TOC), unweighted scoring models, and Analytic Hierarchy Process (AHP) [4]. However, none of these methods are linked to the output side of the improvement projects, i.e. how to achieve the desired performance gains.

On the other hand, without quantitative analysis many organisations working on process improvement projects first look for the ‘low hanging fruit’ [5]. These ideas of considering low hanging fruit started by initially set priorities on fifty suggestions that provided the most benefit for the least effort expended and presenting a subset of this list as the most important [6]. Grant [7] suggested selecting projects that are significant and urgent to the business and which can be analysed simply allowing staff to be trained in and use simpler analysis tools to perform the analysis themselves. However, these methods are too superficial and the degree of success varies.

B. Decision Support Tools

The concept of analysing and making project ranking decisions based on difficulty of process improvement projects is ingrained in several decision support methodologies. The difficulty-impact grid problem solving tool provides support to continuous process improvement teams [8]. Benefit and Effort (B&E) Analysis [9] is a tool used to prioritise manufacturing system improvement projects that can be used for simple prioritisation problems or upscaled to include a more detailed benefit and effort estimation for each project or action based on a weighted sum of factors considered relevant to the organisation. Reyes *et al* [10] investigated optimisation of software development using a genetic

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algorithm to propose a cost effective investment of project resources to improve the probability of project success. The success probability output of a prediction model is maximised relative to cost. The complexity of this method may preclude its use in evaluating prospects of optimization.

C. Criteria for Project Prioritization

Antony *et al.* [11] suggested when selecting process improvement projects care should be taken to prioritise projects with a high probability of success. Clearly if probability of success is to be used as the single prioritisation criteria or alternatively one of several prioritisation criteria a method is required to estimate it. Methods to improve the probability of success of manufacturing improvement projects can be divided into those that:

a) Attempt to estimate probability of success in either qualitative or;
b) Quantitative terms [12] and;
c) Those that do not specifically estimate probability of success but which attempt to address and reduce failure risk factors or use multiple analysis tools in combination to improve the probability of success [13].

Alternatively a user is encouraged to associate probability of success values based on their personal experience. A weakness with this method is only relative probability of success are considered with no estimate in terms of quantitative odds of success.

The method described in this paper fills this gap by providing a means to quantify the level of effort required for particular process improvement projects so that the decision maker can make a judgment on whether the organization has the ability to carry out the optimisation process.

III Methodology

The performance effectiveness k_P is a measure of the effort to overcome the difficulty of successfully implementing a manufacturing improvement project and thereby moving from the current performance gain P_0 to an improved level of performance $P_{>0}$. In Fig. 1, the P^*/k_P function allows for a non-linear mapping between the effort required for PI project success and the subsequent performance gain in relative or actual units. As can be seen in Fig. 1, for a given relative performance gain P_1^* the range of effort required for projects A to D varies greatly from a negligible effort for project D to a considerable effort for project A. The introduction of the P^*/k_P function provides a potential solution to the above mentioned weakness in the risk assessment method. The focus of this paper is to propose a suitable method to determine the term P^*/k_P or the relation between relative performance gain P^* and performance effectiveness k_P for any specific process improvement project.

A productivity analysis of a manufacturing process or system is a tool to estimate the theoretical maximum performance level P_{th} [14]. Assuming P_{th} is estimated adequately this performance level is only attainable if the organisational capability to execute and implement process improvement is perfect.

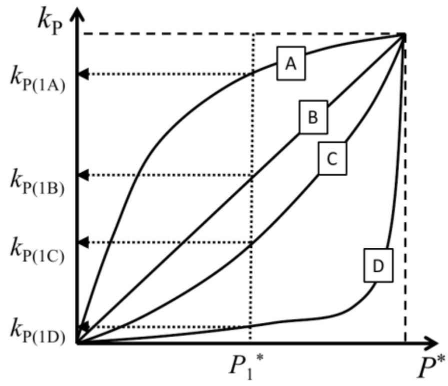

Figure 1. Varying effort k_P to achieve a relative performance gain P_1^* in diverse process improvement projects

The current performance level is designated P_0 or performance at time t_0. This occurs either when no action is taken and subsequently the system maintains the status quo performance level at P_0 or when action is taken and subsequently performance improvement achieved dissipates over time back to the level P_0. Assuming the aim of a process optimization project is to improve performance then an upward movement in performance is required somewhere between P_0 and P_{th}.

To determine the intermediate points of the $k_P = f(P)$ function, we assume:

a) Each individual performance outcome if satisfactorily implemented contributes an equal unit of performance gain,
b) The current performance level P_0 is known from measurement or estimation, and
c) The maximum theoretical level of performance P_{th} has been estimated as a result of for example a productivity analysis.

TABLE I. Scale of Degree of Effort Required

Intensity of Effort	Definition
1	None
2	*Compromise between levels 1 and 3*
3	Small
4	*Compromise between levels 3 and 5*
5	Moderate
6	*Compromise between levels 5 and 7*
7	Large
8	*Compromise between levels 7 and 9*
9	Very large

The maximum performance gain = (P_{th} – P_0) can be divided into n performance outcome intervals. The performance gain attributed to each performance outcome interval is therefore $(P_{th}-P_0)/n$.

The difficulty (and hence effort level) for achieving different performance outcome interval can be estimated by human expert using the Analytic Hierarchy Process (AHP) [15], [16]. A scale ranging from 1 to 9 as shown in

Table I is used for quantifying the relative significance of effort required for project success.

The proposed method compares the intensity of effort to move between defined discrete levels of performance, in particular from discrete levels of performance P_j to performance level P_i. To determine relationship between performance effectiveness factor and performance level, the AHP is applied to consolidate the Vector of Priority (VP) over the range of P_0 to P_n. The pairwise comparison judgements θ_{ij} in Table II use the 1 to 9 scale from Table I. This step produces the weights that reflect the level of difficulty to achieve certain level of performance.

TABLE II. PAIRWISE COMPARISON JUDGEMENT MATRIX FOR K_P

Intensity of Effort		P_j						VP
		P_n	P_{n-1}	…	P_2	P_1	P_0	
P_i	P_n	1	$\theta_{n,n-1}$	…	$\theta_{n,2}$	$\theta_{n,1}$	$\theta_{n,0}$	w_n
	P_{n-1}	$1/\theta_{n,n-1}$	1	…	$\theta_{n-1,2}$	$\theta_{n-1,1}$	$\theta_{n-1,0}$	w_{n-1}
	…	…	…	1	…	…	…	...
	P_2	$1/\theta_{n,2}$	$1/\theta_{n-1,2}$	…	1	$\theta_{2,1}$	$\theta_{2,0}$	w_2
	P_1	$1/\theta_{n,1}$	$1/\theta_{n-1,1}$	…	$1/\theta_{2,1}$	1	$\theta_{1,0}$	w_1
	P_0	$1/\theta_{n,0}$	$1/\theta_{n-1,0}$	…	$1/\theta_{2,0}$	$1/\theta_{1,0}$	1	w_0

The performance effectiveness factor k_{Pi} is then obtained over the range 0 to 1 from Equation (1) where n is the total number of performance outcomes.

$$k_{Pi} = \left(\frac{\theta_{n0} - 1}{8}\right)\left(\frac{w_i}{w_n}\right) \qquad i = 1, 2, ..., n \tag{1}$$

The boundary values of k_{Pi} are represented by the two extreme values 0 and 1 as shown in Equations (2) and (3).

$$k_{P0} = 0 \tag{2}$$

$$k_{P(n+1)} = k_{Pth} = 1 \tag{3}$$

TABLE III. PERFORMANCE EFFECTIVENESS FUNCTION DATA TABLE

i	P_i	P_i^*
0	P_0	$P_0^* = \frac{P_0 - P_0}{P_n - P_0} = 0$
1	P_1	$P_1^* = \frac{P_1 - P_0}{P_n - P_0}$
2	P_2	$P_2^* = \frac{P_2 - P_0}{P_n - P_0}$
…	…	…
n-1	P_{n-1}	$P_{n-1}^* = \frac{P_{n-1} - P_0}{P_n - P_0}$
n	$P_n = P_{th}$	$P_n^* = \frac{P_n - P_0}{P_n - P_0} = 1$

Relative performance P_i^* over the range 0 to 1 is calculated in Table III using Equations (4) and (5).

$$P_i^* = \frac{P_i - P_0}{P_n - P_0} \qquad i = 0, 1, 2, ..., n \tag{4}$$

$$P_{n+1}^* = P_{th}^* = 1 \tag{5}$$

The method is illustrated using an example to further illustrate the general principles. The performance measure has been divided into n = 5 segments. The current level of performance is known P_0 = 35. The theoretical maximum level of performance P_{th} = 100. The main area of interest is in the target area P_{targ} = 90 and as a result the performance parameters P_i are clustered in this area.

TABLE IV. JUDGEMENT MATRIX

Intensity of effort		P_5	P_4	P_3	P_2	P_1	P_0	VP
		100	95	85	70	50	35	
P_5	100	1	2	3	5	6	8	0.385
P_4	95	1/2	1	2	4	7	7	0.273
P_3	85	1/3	1/2	1	3	5	6	0.181
P_2	70	1/5	1/4	1/3	1	2	3	0.079
P_1	50	1/6	1/7	1/5	1/2	1	2	0.049
P_0	35	1/8	1/7	1/6	1/3	1/2	1	0.033

The relative significance of intensity of effort to move between levels of performance is evaluated by pairwise judgement as shown in Table IV. The consistency ratio (CR) for the judgements is 0.03 which meets the Saaty criterion of CR $\leq$ 0.1 for acceptable consistency of judgements.

TABLE V. METHOD TO CALCULATE WEIGHT RATIO

	w_0	w_1	w_2	w_3	w_4	w_5
w_0	1					
w_1	1.41	1				
w_2	2.12	1.50	1			
w_3	4.87	3.45	2.30	1		
w_4	7.87	5.57	3.71	1.61	1	
w_5	11.64	8.24	5.48	2.39	1.48	1

TABLE VI. PERFORMANCE EFFECTIVENESS FUNCTION DATA TABLE

i	P_i	VP	P_i^*	k_{Pi}
0	35	0.033	0	0
1	50	0.049	0.231	0.111
2	70	0.079	0.538	0.180
3	85	0.181	0.769	0.412
4	95	0.273	0.923	0.619
5	100	0.385	1.000	0.875
th	100	…	1	1

The ratios w_i/w_j between the VP weights from Table V are calculated as an intermediate step.

The next step is to calculate k_P from Equation (1). Ratios using the term w_0 are not required as k_{P0} is defined to be zero in Equation (2) as zero additional effort towards improvement is required to maintain the *status quo* performance P_0.

The performance effectiveness is calculated using Equations (1) to (3) and the relative performance P^* using Equations (4) and (5). The calculations are summarised in Table VI.

The corresponding performance effectiveness function can then be plotted as shown in Fig. 2.

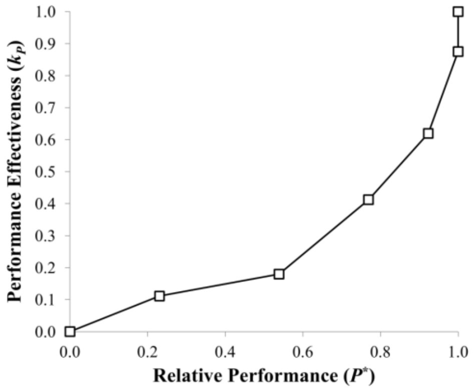

Figure 2. Example performance effectiveness function

The method uses Delphi based decision making in the methodology. In practice, the values θ_{ij} are determined by a survey of experts and experienced stakeholders of the manufacturing system. Decisions can be made by individuals but accuracy may be improved by the use of multiple expert opinions in a structured decision making methodology. Decisions are made on either or both relative intensity of effort and level of benefit depending on the method chosen. The method compares relative intensity of effort between items.

IV. Case Study

A. Background

The use of performance effectiveness function is illustrated by a case study based on a process optimization project conducted at the Australian branch of a global manufacturing organisation. The manufacturing company produces several main product families on a made-to-order basis including paint mixed and packaged to order. Customers are a mixture of local and overseas with a customer demand level exhibiting extreme variability.

Company management has noted an issue with inventory accuracy of raw materials and finished goods produced from the paint production section. This inventory data inaccuracy is responsible for a number of problems. The consequences are the inability to fulfill orders and the detrimental effect on confidence in the business from a customer perspective.

Management has specified a performance target of P_{targ} = 90% inventory accuracy in the belief achieving this level of inventory accuracy will reduce the aforementioned problems to an acceptable level. Before making changes to the current system, a snapshot was taken recording the types and frequency of stock errors between the data in the work planning system and actual stock on the shelves. Analysis of this data indicated the current inventory accuracy is in the order of P_0 = 35%. The theoretical maximum inventory accuracy is P_{th} = 100%.

TABLE VII. Proposed Improvements to Optimise the Stock Control System

No	Outcomes
A	*Layout changes*
A1	The packing area is removed from the production area.
A2	Local storage in the immediate vicinity of the paint production area is expanded to include all consumables and raw materials moving in to the area and finished goods moving out of the area.
B	*Personnel responsibility changes*
B1	Responsibility for packing of finished goods is transferred to dispatch personnel from production operators.
B2	Responsibility for transport of all materials to and from the warehouse area is transferred from production operators to warehouse and/or dispatch personnel.
B3	Responsibility for providing accurate and timely status information on the state of raw materials currently in the paint production machine tanks is to be formalised. Reporting frequency and required accuracy to be specified by management.
B4	A function/person in the organisation must be designated as responsible for the timely entry to the material planning system of the current state of raw materials in the paint production machine tanks.
C	*Process changes*
C1	Production operators are prohibited from access to the warehouse area except under special circumstances (defined by management).
C2	Once raw materials are transported from the warehouse to local production storage any unused portion is not returned to the warehouse.
C3	Management put in place routines to replenish raw materials and consumables to the production local storage.

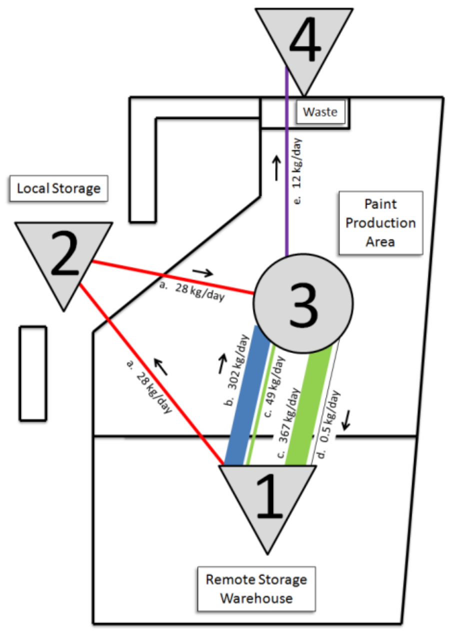

Figure 3. Current material flow diagram

A productivity analysis was performed using a simplified version of the systematic handling analysis by

Müther and Hagan's [17] involving study of the materials flows though the production and warehouse areas. An analysis of the data resulted in recommendation of a number of improvements (Table VII). The question to be answered: What is the probability of success of meeting the 90% target if the recommended changes are implemented?

The aim of these improvements is to reduce the transport work performed by paint production operators. As seen from Fig. 3, the current transport work for production operators is estimated at 12,300 kg-metres/day. After the systematic handling analysis, Fig. 4 should that the transport work can be reduced to 4,000 kg-metres/day. This is equivalent to a 67 percent reduction.

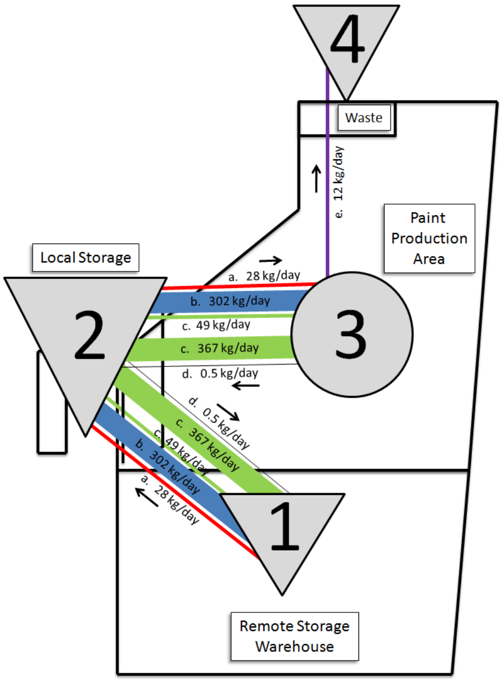

Figure 4. Proposed material flow diagram

The primary purpose of material flow process re-engineering is to improve inventory accuracy. In line with the carefully planned transport system, the operators will be given the responsibility to ensure correct placement of goods at specific locations. This leads to the measurement of k_p using inventory accuracy as the key performance indicator.

B. Estimate of the Function $P = f(k_P)$

An analysis of the inventory accuracy problem produced a set of process improvement outcomes the organisation is required to achieve to improve the inventory accuracy performance measure. It is assumed that the set of outcomes is sufficiently complete that if they are implemented perfectly the resulting inventory accuracy will be perfect i.e. 100 percent inventory accuracy. In practice perfection is impossible and some degree of error will be retained after the process improvement implementation. The question is what level of performance will likely be achieved?

The pairwise comparison judgements have been carried out with assistance from the Manufacturing Manager and Warehouse Supervisor of the company. The analysis indicates 72 percent of the effort to overcome difficulty is expected to originate from handling responsibility changes of personnel working in paint production and supporting services, 19 percent with managing process changes and 8 percent organising and implementing the necessary layout changes. The overall result is shown as a hierarchy in Fig. 5.

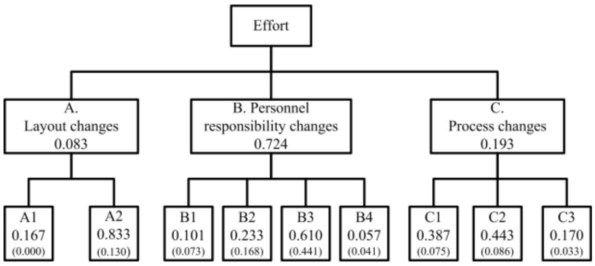

Figure 5. Process improvement outcomes hierarchy

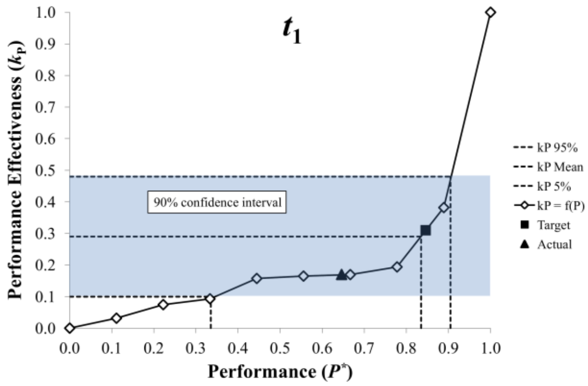

Figure 6. Case study: $k_P = f(P^*)$

The overall process improvement outcome weightings are obtained by rolling up the local weightings at levels 1 and 2. For example, the global VP for outcome 'B3' = VP_B x VP_{B3} = 0.724 x 0.610 = 0.441. The complete set of outcome weightings calculated in this manner is presented in Fig. 6.

The outcome weights are sorted in their order of increasing weight of effort to overcome difficulty. The actual project performance achieved immediately after implementation was less than the mean k_P but within the 90% confidence interval. The achieved result indicates the organisation applied less effort than may be considered usual given their current capability with corresponding results below target.

V. Conclusion

Organisations trying to optimize their manufacturing processes want a return on their investment in the form of increased performance in one or more areas. It is generally acknowledged in the literature the probability of not meeting performance target goals is unacceptably high. The availability and application of a quantitative assessment that provides insights into expected and range of performance results is a critical tool in this regard.

This paper presents a performance effectiveness function that links the level of effort (and hence the actions required) to the expected performance outcomes. The application of this k_P prediction interval to obtain a prediction interval on relative performance gain P^* and performance gain P at a future time t_1 is presented including the feedback of an actual case study result. Extending this function to evaluate the risk in planning system optimization or process improvement projects would provide organisations with insights on the level of risk they are facing and reinforce the need for constant focus if the target gains are to be achieved within an acceptable probability.

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Boyd A. Nicholds is a PhD student, School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Melbourne, Australia. He worked in Europe as a Quality Engineer in an industrial engineering company for 17 years and has a particular interest in process improvement. He has also worked in Australian Paper for 5 years before moving to Europe.
Boyd has a BEng (Electrical Engineering) and a MEng (Integrated Logistics Management). He has received an award from the Australian Mathematical Society and Australian Aerospace Association to study factors affecting manufacturing system improvements in the local industry.

John P. T. Mo is Professor of Manufacturing Engineering and former Head of Manufacturing and Materials Engineering at RMIT University, Australia, since 2007. He has been an active researcher in manufacturing and complex systems for over 35 years and worked for educational and scientific institutions in Hong Kong and Australia. From 1996, John was a Project Manager and Research Team Leader with Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) for 11 years leading a team of 15 research scientists.
John has a broad research interest and has received numerous industrial research grants. A few highlights of the projects include: signal diagnostics for plasma cutting machines, ANZAC ship alliance engineering analysis, optimisation of titanium machining for aerospace industry, critical infrastructure protection modelling and analysis, polycrystalline diamond cutting tools on multi-axes CNC machine, system analysis for support of complex engineering systems
John obtained his doctorate from Loughborough University, UK and is a Fellow of Institution of Mechanical Engineers (UK) and Institution of Engineers Australia.