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MODELLING AND CONTROL OF OPEN SYSTEMS

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MODELLING AND CONTROL OF OPEN SYSTEMS

ABSTRACT

A simple approach to Mathematical and Structural Modelling of Open Non Deterministic Systems is given. A methodology for constructing a set of Control Sensors is also outlined giving some examples of a process of control and improvement of system performance.

Keywords: control sensors; mathematical and structural modelling; open non-deterministic systems.

INTRODUCTION

The objective of an open system is measured by a performance criterion (or index) relating the output to the input. It is the goal of the system to optimize the output vis a vis the input, establishing a performance index in order to achieve this goal [1]-[2]. In this work, it is proposed to establish general guidelines to answer the following questions: given the objective and a performance index of a system, how to define the minimum internal structural differentiation able to pursue the optimization goal and, how to establish a proper control procedure, which is capable to keep the system in the right operational track [1]-[3].

The general methodology to be described is applicable to the modelling and control of large, complex and non-deterministic systems such as the operation of an Industrial Company, an Engineering Firm, a Transportation System, a Government Agency or whatever the system may be.

OBJECTIVE AND CONTROL

Transforming something into something else supposes the definition of a process. After the process has been selected, decision must be made with respect to the dimensions of the operation, compatible with the process itself and with any environmental restrictions. Walking over dry land, an animal cannot have an arbitrary weight because its body would not stand gravity. A popcorn factory producing thousands of tons of fresh popcorn per day would not find a market where to sell such product. An engineering firm producing systematically expensive and low-quality designs would not be viable.

The following scheme (Figure 1) shows a compact vision of an open-system. A Process Function $\underline{P}$ changes Input into Output variables. In order to do this, the control sub-system defines the levels of dimension (A_p) and operation (C_p) according to a standard reference value a performance index chosen to be $(R_p - C_p)/A_p$. The value of the total output of the system is initially estimated from estimated environmental requirements and Process Yield Potential. That is, the value of R_p depends on the Process, on A_p, on C_p and on the boundary interfacing of the System. The performance index

$$I = \frac{R_p - C_p}{A_p} = \frac{L_p}{A_p} \qquad (1)$$

is related to four types of functions:

R_p = Total Output = Revenue Function;

C_p = Operating Costs and Expenditures = Cost Function;

A_p = System Dimensions = Investment Function;

L_p = Net Output = Profit Function.

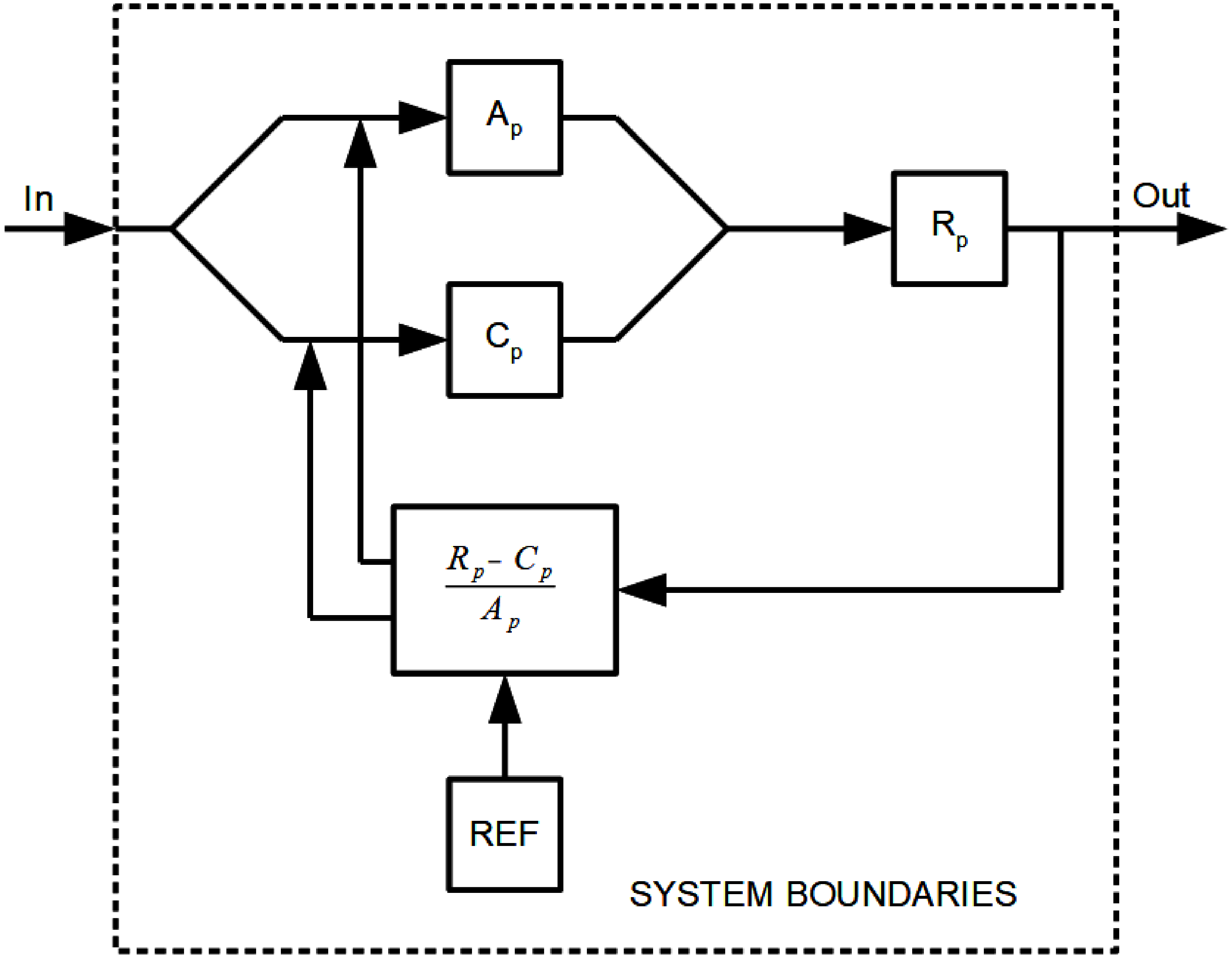

Figure 1. Compact vision of an open-system.

Such index has been chosen due to its wide applicability to open systems [4]-[5], although may not be better than any other one. It serves the purpose of developing this work based on real examples. Alternative evaluation indices are described, among other authors, by Camargo [6] and Brito [7] although referring to Investments and Capital Control. The importance of capital control, the decision on the right dimension of this element of the performance index defined by Eq. (1), one of the main task of a company high administration is widely discussed by [8].

The input variables are measured by A_p and C_p. Not all of them are supposed to be controllable neither independent. As mentioned above, it is assumed that the performance index has to be maximized. For an optimal operation procedure, the value of A_p corresponds to the transfer energy which has to be minimum with respect to a given transfer value L_p. Or, which is the same, the transfer value L_p of the process has to be maximum with respect to a given value of the transfer energy.

If the system is completely deterministic, to a given process P there correspond precise values of A_p, R_p and C_p, within tolerance levels which are compatible with the precision of the process. For instance, considering a Diesel Engine transforming fuel into motion, the value of A_p (Engine Total Weight corresponding to a given design and dimension), of C_p (Engine Power Loss due to internal friction, heat loss, partial combustion etc.) and of R_p (Engine Total Power Output including losses) can be established within very narrow numerical values.

If the system is non deterministic, to a given process P there correspond a large option of variable values of Ap, Rp and Cp.

For instance, factory producing automobiles from steel plates and all sorts of mechanical and electrical parts and accessories will differ substantially from another factory doing the same thing by essentially the same process. This is due to the fact that the entire company operation, which includes the unpredictable action of humans, is a complex, non-deterministic system. This is the basic reason behind the historical difficulty of defining a clear and rigorous theory and methodology toward the optimal operation of an enterprise [9]-[10].

For instance, considering an Industrial Company utilizing a specified production process, the value of A_p (Total Operating Assets), of C_p (Total Operating Costs and Expenses) and of R_p (Total Revenues from Products and Services) cannot be clearly defined "on paper" unless one actually has the Company running for real [11].

Having defined the Performance Index, the question arises on how to establish a structural internal model for the system and a compatible number of measuring devices to be used by the control group. This last question will be tackled first.

By writing

$$I = \frac{R_p - C_p}{A_p} = \frac{R_p - C_p}{R_p} \cdot \frac{R_p}{A_p} \qquad (2)$$

one finds

$$I = \left(1 - \frac{C_p}{R_p}\right) \cdot \left(\frac{R_p}{A_p}\right) = I_M \cdot I_R \qquad (3)$$

The Performance Index splits into two essentially different partial performance indices [10]. The index $I_M = 1 - C_p/R_p$ is called the Margin Index (Profitability) and is mostly related to the ability of transforming total output R_p into system net result (sales into profit) and depends critically on the ability of controlling the value of the Cost Function C_p.

The index $I_R = R_p/A_p$ is called the Rotation (turn over) Index and is mostly related to the ability of utilization of the physical structure and dimensions of the system and its operating expenditures to achieve the maximum total output.

Therefore, Margin is the result of a proper control of the system and its environmental interfacing, while Rotation is the result of the quality of the transformation process, that is, of the available technology.

A lower level of sensors for the control group are necessary to perform a detailed trend analysis on the evolution, over time, of the performance index defined by Eq. (1). Correct definition of such sensors, or financial indices, is essential to obtain a correct evaluation of such evolution [12].

The Cost Function C_p can be usually split into several Cost Components

$$C_p = \sum_i C_i \qquad (4)$$

and the same can be done with the assets Function Ap, that is,

$$A_p = \sum_j A_j \qquad (5)$$

The partial functions C_i and A_j are defined by, and related to, the process and the intangible elements of the system (as, for instance, people).

One has two sub-sets of Performance Indices $I_{C_i} = C_i / R_p$, which must be minimized, and $I_{A_j} = R_p / A_j$ which must be maximized.

For any two successive samples at times t_k and $t_{k+1} > t_k$, the goal of the system is to achieve

$$I_{C_i}(t_{k+1}) \leq I_{C_i}(t_k) \tag{6}$$

and

$$I_{A_j}(t_{k+1}) \geq I_{A_j}(t_k) \tag{7}$$

The Control Group of the system shall need direct communication to the performance sensors shown in the following tree (Figure 2).

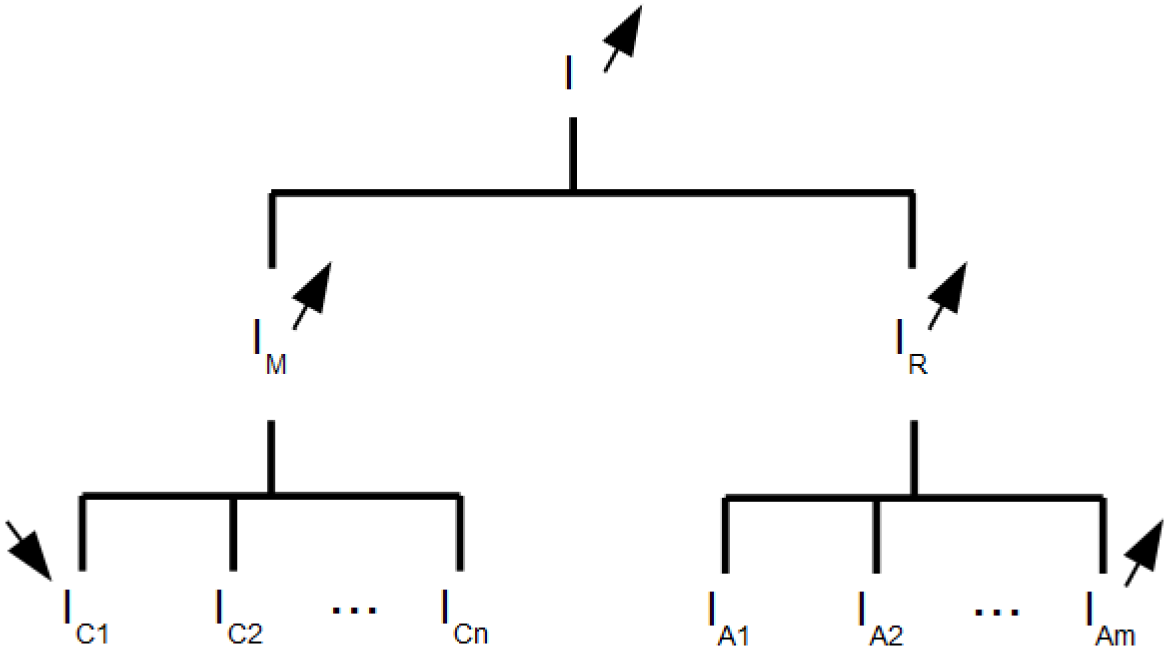

Figure 2. Hierarchy tree of a control group.

The arrows indicate the time trend to be expected and enforced by the Control Group, if the Performance Index has to be maximized.

Consider, again, the example of an Industrial Company. The Control Sensors most commonly used [5] are given as showed in Figure 3, where OP = Operating Profit, Re = Revenues from Products & Services, OA = Operating Assets, F.Exp = Fixed Expenditures, P.Exp = Proportional Expenditures, CA = Capital Assets, Prop. = Properties, MP = Manpower, Rec = Receivables, etc.

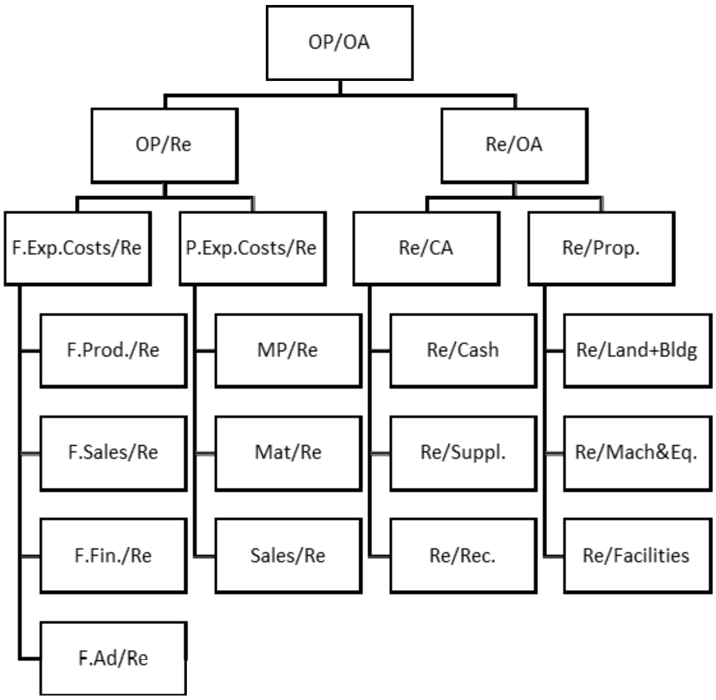

Figure 3. Control sensors tree for an industrial company.

For an Engine one may consider, in a similar way, the following Control sensors, Figure 4, where UP = usable power (excluding cost of operation); TP = total power; EV = Engine value, etc.

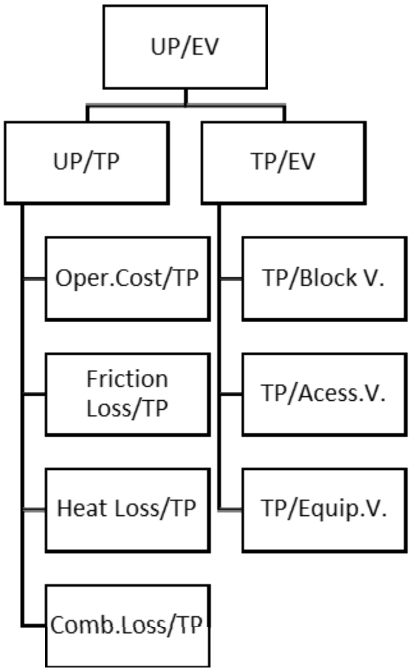

Figure 4. Control sensors tree for an engine.

MATHEMATICAL AND STRUCTURAL MODELS

The next task is to define a proper procedure for the modelling of the system. Following the definition of the production process one may always write

$$I = \frac{VR_u - \sum C_i}{\sum A_j} \tag{8}$$

where V stands for the total volume of production and R_u for the specific value of the output with respect to a unit value of V.

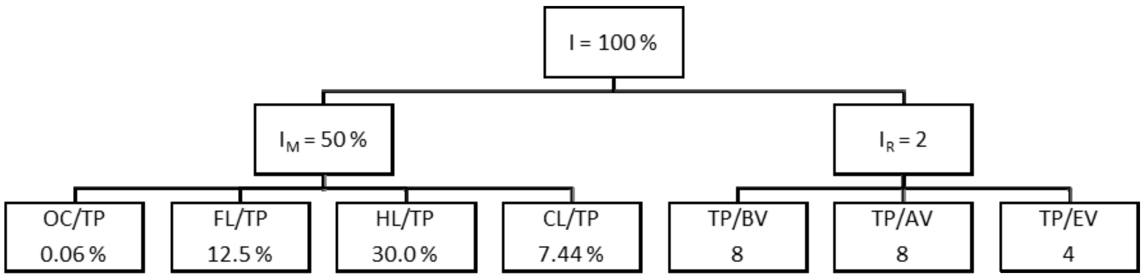

Figure 5. Hypothetical engine performance indices tree.

For the examples given, in the Engine one has that the total power output is the product of the torque (specific power) and the rotation of the shaft (total rotation angle output). In the Factory, the total volume is given by say, the number of pieces or tons sold, and the specific value of the output is the sale price per piece or ton. In these examples the meanings of C_i and A_j have already been discussed. The formula relating the performance index I to the input variables V and R_u is a simple but important mathematical model. The comprehension of this model gives a fundamental clue to the necessary internal structure of the system as shown in what follows.

The proper operation of the system will imply subsystems specializing in each component of the mathematical model, if the objective of the system, measured by the Performance Index, has to be properly pursued [13]. These sub-systems are given below:

(1) A sub-system that is responsible for the actual production of the volume V, that is, PRODUCTION sub-system.

(2) A sub-system that is responsible for the definition of R_u and part of the environment with which the system shall need to deal. This is a MARKETING sub-system.

(3) A sub-system collecting, evaluating, establishing, analysing and processing in many ways the values of the Cost Functions C_i. This is a COSTS sub-system.

(4) A sub-system granting the actual transfer of volume V, at the specified rate R_u, to the environment. This is a SALES sub-system.

(5) A sub-system defining the total value of A and the way of splitting this value into the components A_j. This is a CAPITAL sub-system.

(6) A sub-system defining the objective, the goals, the process, the dimension, the rules and reference standards of the system, also providing an efficient general control sub-systems. This is an ADMINISTRATION sub-system.

The six sub-systems defined above cover essentially any need of the system. Additional partition of the internal structure, meaning more complex internal differentiation, shall be at a lower level of hierarchy.

Following, a map giving these sub-systems for an Industrial Company and for an Engine (with some necessary attachments!) is presented n Table 1.

Table 1. A map giving sub-systems for an Industrial Company and for an Engine.

SUB-SYSTEM	**INDUSTRIAL COMPANY**	**ENGINE**
PRODUCTION	FACTORY	ENGINE BLOCK AND PISTONS
MARKETING	MARKETING	CARBURATOR
SALES	SALES	TRANSMISSION AND WHEELS
COSTS	COSTS ACCOUNTING	CONTROL INSTRUMENTATION
CAPITAL	FINANCE AND GENERAL ACCOUNTING	DISTRIBUTOR
ADMINISTRATION	MANAGEMENT	COMMAND EQUIPMENT
INPUT	RAW MATERIAL, ACCESSORIES, ENERGY, MANPOWER, TECHNOLOGY	FUEL, LUBRICANT, WATER, ELECTRICAL SOURCE
OUTPUT	PRODUCTS AND SERVICES	MOTION AND TRANSPORTATION

SENSITIVITY FACTORS OF PERFORMANCE

The Administration has to collect all values of V, R_u, C_i and A_j and modify them in such a way as to keep the increasing (or non-decreasing) trend of the Performance Index. The Cost Indices must not increase while the Rotation Indices must not decrease. In the best case they should decrease and increase, respectively.

For a system, in general, there will be no exact and defined functional dependence among the input variables C_i and Aj and the output variables V and R_u. This is only true in a completely deterministic system. Also, not every input variable can be controlled. Some are completely out of control (inflation rate, water boiling point) others are only partially controllable (raw material costs, fuel octhane containt) and others can be kept well under control (production process, compression rate). The simultaneous change of input variables, in order to improve the performance index, is simple when one has a deterministic system and when the mutual dependence is well known. In all other situations one has to rely on the experience or the past history of the system and its environment in order to propose a consistent plan of action.

Despite all difficulties involved, one can, for any particular system, define a set of numbers representing, within a good approximation, the expected influence of any change of the input variables on the performance index [14]. From the mathematical definition

$$I = \frac{VR_u - \sum C_i}{\sum A_j} \tag{9}$$

one finds that

$$\begin{aligned} 100 \cdot \frac{\Delta I}{I} &= S_V \cdot \left(100 \cdot \frac{\Delta V}{V}\right) + S_{R_u} \cdot \left(100 \cdot \frac{\Delta R_u}{R_u}\right) + \\ &+ \sum S_{C_i} \cdot \left(100 \cdot \frac{\Delta C_i}{C_i}\right) + \sum S_{A_j} \cdot \left(100 \cdot \frac{\Delta A_j}{A_j}\right) \end{aligned} \tag{10}$$

where the sensitivity factors S are given by

$$S_k = \frac{\partial(\ln I)}{\partial(\ln X_k)} \tag{11}$$

where X_k is anyone of the variables defining the performance index I.

The percentual change of this index is simply related to the percentual changes of the input and output variables, provided such changes are consistent with the afore mentioned dependences among them, either in explicit mathematical form or given by the numerical history of the system.

The explicit values of the sensitivity factors are given by

$$S_V = S_{R_u} = (I_M)^{-1}, \quad (12)$$

$$S_{C_i} = -\frac{C_i}{R_p - C_p}, \text{ and} \quad (13)$$

$$S_{A_j} = -\frac{A_j}{A_p}. \quad (14)$$

As an example, consider a Company with the following results obtained from two account reports (Table 2).

Table 2. Sensitivity factors.

Item	**2012**	**2013**
Cash	0.020	0.026
Accounts Receivables	0.230	0.200
Supply Inventory	0.053	0.051
Long Term Credits	0.0003	0.0000
Other Assets	0.068	0.069
Properties, Plant & Equipment	0.63	0.65
Job Cost and Expenses	32.12	47.67
Materials	23.76	26.40
Manpower + Social Benefits	5.04	5.46
Energy & Fuels	1.01	1.67
Proportional Job Costs and Exp.	29.84	43.55
Overhead MP + Soc. Ben	1.44	2.65
Depreciation	0.19	0.37
Sales Expenses	8.30	14.27
Administration Expenses	2.50	7.68
Interest Expenses	1.93	2.99
Sales Price	45.97	73.97

Item	2012	2013
Sales Volume	45.97	73.97
Total Sales Value	1.00	1.00
Total Operating Assets	1.00	1.00

Also, are given the following values [10^3\$] in Table 3.

Table 3. Values for example proposed [10^3\$]

	2012	2013
Operating Assets	8,161,934	6,853,112
Operating Profit	220,794	112,908
Revenues	10,148,804	8,318,692
Operating Costs	9,928,010	8,205,784

From this information, one can already draw some conclusions. For instance:

(1) The items that are most affecting the Return on Investment Rate (I = Operating Profits/Operating Assets) are, in this order: Sales Price and Volume, Job Costs and Expenses, Proportional Job Expenses and Costs, Materials, Sales Expenses, Administration Expenses, Direct Man-power, Interest Expenses and Overhead.

It follows that a closer control should be kept in Departments that are in charge of such activities.

(2) From 2012 through 2013 there has been a considerable change in the company. Most of all:

The dependence from major items like Job Costs, Materials, Proportional Costs, Sales Expenses, Administration Expenses, Price and Volume has decreased by a large percentage. This, of course, is a good indicator of improved administration.

(3) Supposing technical viability, the following plan would have an important result on the return of Investments (Table 4).

Table 4. Return of investment.

Item	Change	Sensitivity (2013)	Change in Return
Materials	- 3 %	- 23.76	+ 71.28 %
Sales Exp.	+ 5 %	- 8.30	- 41.50 %
Sale Price	- 2 %	+ 45.97	- 91.94 %
Sales Volume	+ 10 %	+ 45.97	+ 459.70

Item	Change	Sensitivity (2013)	Change in Return
Account Receivable	+ 10 %	- 0.23	- 2.3 %
Cash	+ 10 %	- 0.02	- 0.2 %
TOTAL			+ 395.04 %

Since the 2013 Rate of Return was 1.65 % the new expected rate of return will be 8.16 %. This, of course, has to be considered only an illustrative example.

As another example consider the performance index for an engine. For the performance indices given at page 8 suppose the following hypothetical values:

UP = 200 HP = \$ 2,000.00
EV = \$ 2,000.00
TP = 400 HP = \$ 4,000.00
Op. C./mile = \$ 2.50
Fric. L./mile = \$ 500.00
Heat L./mile = \$ 1,200.00
Combustion L./mile = \$ 297.50
Block Value = \$ 500.00
Acess. Value = \$ 500.00
Equip. Value =\$ 1,000.00

For this hypothetical engine one has a performance indices tree shown below. Any improvement of this engine should decrease the cost indices (on the left except I_M which should increase) and increase the rotation indices (on the right). The value of 100 % given to I is of no particular importance.

The Sensitivity Factors for each item are computed and given in Table 5.

Table 5. Sensitivity factors

Item	Sensitivity Factor
OC	- 0.00125
FL	- 0.25000
HL	- 0.60000
CL	- 0.14875
BV	- 0.12500
AV	- 0.12500

Item	Sensitivity Factor
EqV	- 0.50000
EV	- 1.00000
TP	+ 2.00000

Table 5 shows that efforts in improving this particular engine should be directed toward decreasing Heat Losses, decreasing equipment costs, decreasing Engine Price and increasing Total Power. It is also obvious that these changes cannot be considered independent. In any event one sees that an increase of 10 % in total power with following consequences:

OC +10 %

FL –

HL –

CL –

BV + 2 %

AV + 5 %

EqV –

EV + 5 %

shall produce an increase of 34.11 % in the performance index, giving a final value of 13.11 %.

CONCLUSION

Given the objective of a system and a performance index one can build a simple mathematical and structural model and a set of control sensors, which can be effectively used to improve the performance of the system.

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