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Controlling non-conformities propagation in manufacturing. Case study in an electromechanical assembly plant.

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Abstract - The purpose of this paper is to control the propagation of non-conformities. The control methods implemented to ensure the quality performance of a production system present weaknesses, inherent to their constitution, which can let non-conformities propagate along the value stream. This propagation cannot be avoided, but it can be mastered. This paper presents a method to master non-conformities propagation in a production system by building the associated control chart. In order to calibrate the proposition, a case study on non-conformities propagation in a low-volumes industry in the energy field is presented. The simulation of the proposed plan shows the benefits of controlling this indicator.

Keywords – Statistical quality control, Statistical process control, non-conformities propagation, layers of control

I. INTRODUCTION

This paper is interested in the quality control of manufacturing production. It proposes a methodology for controlling the propagation of defects in production systems.

Quality control systems during production are often grounded on expert knowledge and risk analyses. Many risk analysis techniques exist [1] and can be classified in two main categories:

1. Tree analyses (failures, root causes, butterfly), which start from a feared event to find causes and consequences.
2. Systematic analyses (FMEA, FMECA, HAZOP), which inventory possible failures of a system according to its constitution.

From these analyses, actions are undertaken, and layers of protection are set up. Layers of protection [2-7] illustrate the efforts to prevent failures' propagation and to stop them as close as possible from their origin in order to limit their impact at least in terms of costs. In the industrial quality field, these protection layers are, for example, control charts, preventive maintenances, acceptance tests, and inspections.

Even if exhaustiveness in risk analysis is intended, it cannot be ensured. Defects that have not been imagined can appear and meet only little resistance in the production system. These types of defects can then reoccur and reach a growing amount of products or at

least propagate for one product along the manufacturing process as illustrated on Fig. 1.

In addition, since the work by [8], detection speed (ARL_1) is a key performance indicator of detection means. The concept of permeability of a detection mean is then taken into account from its conception.

Thus control means implemented to ensure the quality performance of a production system present breaches inherent to their constitution. The occurrence of a defect and its propagation is a component of each production system, even of those with well-designed risk analyses and protection layers [9].

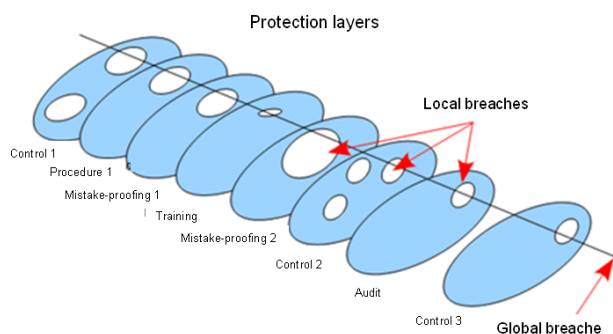


Figure 1 : Protection layers and breaches

Finally, the currently popular Lean Manufacturing concepts lead many companies to undertake rationalization of their production systems [10]. Controls viewed as unproductive are often pointed at by these refocusing policies. But this thinning down is sometimes destabilizing and can open the breaches even more.

The problem is then to control the inherent permeability of the protection system. This paper is grounded on the fact that the existence of propagation cannot be avoided, but its control can be organized. It presents a methodology to control the propagation distance of non-conformities along the value stream. The underlying hypothesis is that the average propagation distance is a relevant performance indicator of the global control system. Actually, defects that propagate highlight weaknesses in the protection layers' system. The propagation distance is closely linked to non-conformity costs through the increasing number of impacted products and/or amount of induced rework. The decrease of the defect propagation is coherent with Lean targets such as source control or auto-control.

The proposition is thus to monitor this propagation with a control chart. The remainder of the paper is organized as follows. The second section provides a literature review on process control, the third section introduces the control chart model, and the fourth section presents the case study. The simulation study along with discussion is given in section V. Our concluding remarks are given in the final section.

II. LITERATURE REVIEW

Process control crosses various disciplines to settle adapted layers of protection. This review is then structured around several aspects of process control activities: risk management, statistical process control, inspection allocation, and process control in various domains.

In order to detect process drifts of production systems, we looked at literature on statistical process control. An introductory and complete reference book is [11]. Several branches of this field provide adaptations regarding performance of control.

Varying sampling interval, sampling frequency, re-controlling, or changing of control limits are common actions taken as data are collected. The investigation of this subject began with the publication of [12]. They demonstrate that having two levels of controls (sampling size, frequency, limits) is the optimal solution to control and detect issues faster while minimizing the cost of errors. Adaptive process control has been reviewed by [13]. More recently, [14] also presents a very clear overview of these techniques, providing a key paper in this field. Very recent literature focuses on the design of control charts for non-normal distributions [15] or correlated data [16].

The economic design of control charts is very interesting because it raises the question of control efficiency and its measurement. A key parameter of this measurement is detection speed. Actually, because of the statistical sampling, a process deviation can occur without being detected. This time is introduced under the names ATS_1 (Average Time to Signal) or ARL_1 (Average Run Length) [8], [11], [16], referring respectively to the average time to obtain a detection signal and to the average number of manufactured products before receiving a detection signal. These two parameters are included in the economic design of the control chart and in the performance evaluation of the control plan. For low-volumes and high-costs productions (aeronautics, healthcare, aerospace, dam industry), the global detection costs question is outclassed by detection speed. Actually, an ARL_1 of the same order of magnitude as the lead time can disturb the resilience of the production system. Thus, the decrease of impacted products (or at least potentially impacted) by the deviation is a key element that seems unaddressed by current work.

Several studies couple the economic design approach with the adaptive control one. Reference [17] presents an

integrated statistical and economical design of an adaptive control chart with variable sampling size and interval.

All adaptations are centered on the three following parameters: number of measured points (n), sampling frequency (f), and control limits (L). These methods are evaluated on costs and reactivity.

Works have been found on control charts adaptation based on learning and production volumes. Reference [18] has been a pioneer in this field, proposing a link between operational management and learning from the control charts. Based on an economic model, which takes into account the reuse of SPC data during yield and scraps investigations, [19] presents how quality controls can be released due to learning curves. Industrial testimonies show control plan adaptations based on “production maturity” [20]. These works point out a possible adaptation of control plans using parameters external from the detection. These works build on control plan adaptations based on learning levels (maturity milestones, learning curves). Very few do that in real-time.

To conclude, this literature review has found a performance indicator for evaluation of control plans (ATS_1 or ARL_1), which is interesting for the formulation of the detection problem for low-volumes and high-investment (aeronautics, factory creation) or high-stakes (healthcare, nuclear, etc.) industries. Risk analyses cannot prove exhaustiveness, and classical detection tools cannot ensure in-control ARL. It is thus necessary to adapt them globally. However, no link has been found between control plan adaptation and failures that have crossed the detection system. The opportunity exists to develop a proposition to adapt the control plan according to its performance, measured by the failure crossing the control barriers.

III. MODEL

A. Propagation distances matrix

As presented above, non-conformities propagation can generate huge costs for companies. The target of the quality control system is to stop defects as early as possible, ideally where they have been generated. The propagation distance corresponds then to the number of process steps a defect went through before being detected. This distance can be visualized on a matrix crossing generation and detection locations (Table I).

The process is composed of N steps $\{Op1, \dots, OpN\}$. A defect NDE_1 generated at Step _{i} and detected at Step _{j} has gone through a distance of $d = i - j$ steps. This distance corresponds to the distance to the diagonal of the matrix. In the worst case, a non-conformity issued in the first process step is detected at the last step (NDE_2 on Table I). As a defect cannot be detected before being generated, the below-diagonal part of the matrix is greyed.

TABLE I
PROPAGATION MATRIX

		Non-conformities detection location					
		Step ₁			Step _i		Step _N
Non-conformities generation location	Step ₁						NDE ₂
	Step _j				NDE ₁		
	Step _N						

This matrix has a double reading. At the event level, it allows a visualization of a defect's propagation, while at the system level, the average propagation distance illustrates the performance of the global control system. This average distance is set as a performance indicator:

$$\bar{D} = \frac{1}{K} \sum_{k=1}^K d_k = \frac{1}{K} \sum_{k=1}^K i_k - j_k \quad (1)$$

\bar{D} : average propagation distance
 K : number of registered defects
 d_k : propagation distance of the k^{th} defect
 i_k : generation location of the k^{th} defect
 j_k : detection location of the k^{th} defect

The goal of the control system is to reduce the defects' propagation and thus the average diagonal distance in order to have a matrix as diagonal as possible.

B. Modeling assumptions

Assumption 1: The defect concept is not linked to a particular failure mode, but to any potentially harmful event that can alter the product's performance.

Assumption 2: The notation implies that every detection operation is included in a production step and that every production step can include a detection operation. This assumption allows the use of a square matrix.

Assumption 3: The chosen distance unit is the number of steps in the production process. This unit has been chosen in order to be coherent with the production system notion.

Assumption 4: The average defects' propagation distance is a performance indicator of the control system.

Assumption 5: For a given production system, the propagation distance follows a normal distribution.

C. Propagation control chart

The proposition is centered on an improvement strategy based on the minimization of this metric. One suggestion for its improvement is monitoring it with

individuals and moving range control charts. The idea is to follow the individual measured distances for each defect and the difference from one point to the next (moving range) over a given timeframe and to set an upper control limits (UCL) over which an alarm is triggered and an improvement action is taken. These upper control limits are defined in accordance with [11].

$$UCL_D = \bar{D} + \frac{3}{d_2} * \overline{MR} \quad (2)$$

$$UCL_{MR} = D_4 * \overline{MR}$$

\bar{D} : average propagation distance

\overline{MR} : mean of the moving ranges

d_2 : anti-biasing constant for n=2 [11]

D_4 : anti-biasing constant for n=2 [11]

IV. CASE STUDY

The field study was carried out within an assembly plant of a global powerhouse in electronics and electrical systems. The plant engineers to order customised equipments. The study is interested in one of the three manufactured products of the plant. This production line employs 40 operators and assembles around 200 products per year with a 10 days lead-time. The assembly and process plan is made of 15 major operations (N). The analysis is based on non-conformity reports issued over one year from different sources like factory and installation quality reports, quality meetings, and quality campaign for the operators. Forty-one defects were recorded in a 15x15 matrix as the one presented in section III. A.

The analysis enabled us to draw the following control charts of the propagation distance and the associated moving range (Fig. 2).

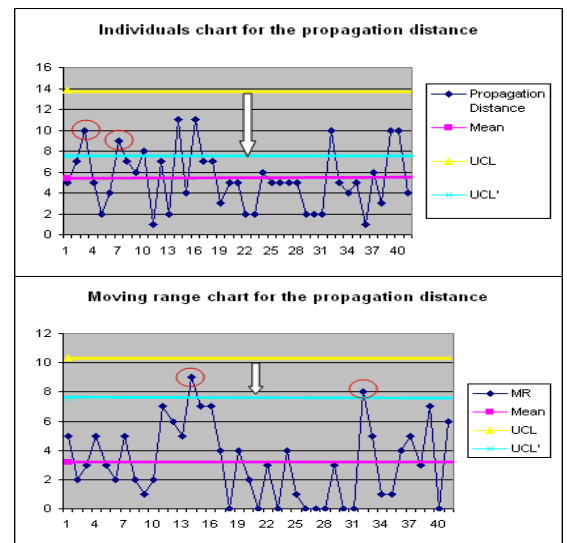


Figure 2: Individuals and moving range charts for the propagation distance

The limits defined in Equation 2 do not lead to any detection and are unsatisfactory in our industrial context (low volumes, high customization, and long lead times). Actually UCL_D is close to the number of process steps (15), meaning that the detection system lets nonconformities propagate along the whole process, leading to huge costs for the firm. This is not acceptable that why the limits should be revised downward. They could be set at $UCL' = N/2$ (half of the total process steps). Alarm examples with these new limits are visualized by red circles (Fig 2).

The analysis of the distance distribution with a Q-Q plot method shows that we can assume that the propagation distance is close to a normal distribution.

TABLE II
Q-Q PLOT REGRESSION COEFFICIENTS

a	0,3077703
b	-1,45316692
r^2	0,99219039

The r^2 coefficient close to “1” confirms this hypothesis. However, the little alignment default is probably due to the small amount of measures. Data containing forty-one measures are actually enough to run a normality test but is quite low to obtain a good approximation.

Data show that the UCL' defined at $N/2$ would have triggered seven alarms and so many improvement actions of the control system. Today the company does not measure the defect propagation. The next section illustrates through a simulation the improvement potential when monitoring this distance and reacting to a threshold overrun.

V. SIMULATION AND DISCUSSION

Based on data collected from the field, a comparison between a situation where defect propagation is under control and one in which this distance is not followed is simulated. Defects and their propagation distance are randomly generated. The simulation is made of R runs with k defects in each run. For each run, the parameters μ_D and σ_D of the normal distribution are stable. The average distance and the average moving range are calculated for each run. That gives the UCL for the run. The parameters μ_D and σ_D are then adjusted for the next simulation run regarding the numbers of alarms and assuming an alarm leads to an improvement action. The assumptions of the simulation are the following:

1. The propagation distance follows a normal distribution $N(\mu_D; \sigma_D)$.
2. An improvement action will impact the parameter μ_D and σ_D of the distance distribution. This effect can be either positive or negative.

3. The effects of the improvement action on μ_D and σ_D are randomly distributed in $[P\mu_{\min}; P\mu_{\max}]$ and $[P\sigma_{\min}; P\sigma_{\max}]$.
4. The control process is supposed to be stable

The parameters of the simulation are the following:

R: Number of runs

K: Numbers of defects per run

μ_0 : initial mean of the propagation distance

σ_0 : initial standard deviation of the propagation distance

$[P\mu_{\min}; P\mu_{\max}]$: Performance of the improvement action on the mean of the propagation distance

$[P\sigma_{\min}; P\sigma_{\max}]$: Performance of the improvement action on the standard deviation of the propagation distance

The simulation has been initialized with the empirical mean and standard deviation of the propagation distance calculated on the forty-one observations. The performance of the improvement actions on the distance mean and standard deviation is randomly distributed in the interval $[-1\% ; +5\%]$. This hypothesis is called pessimistic by the company.

TABLE III
SIMULATION RESULTS

Defect	Run1	Run2	Run3	Run4	...	Run50
1	3	2	8	5		7
2	4	6	7	7		2
3	9	4	0	2		4
4	11	8	11	9		3
5	4	5	3	1		4
6	5	8	7	6		1
7	8	6	2	5		7
8	2	6	10	7		3
9	9	2	9	8		4
10	6	6	2	5		2
\bar{D}	6,10	5,30	5,90	5,50		3,70
\overline{MR}	2,46	1,46	3,46	2,06		1,30
UCL_d	12,63	9,17	15,09	10,97		7,16
UCL_{Mr}	8,02	4,76	11,29	6,72		4,25
μ_D	5,60	5,60	5,60	5,60		3,17
σ_D	2,80	2,80	2,80	2,80		1,70
Alarms ($d > Ucl_d$)	0,00	0,00	0,00	0,00		0,00
Alarms ($Mr > Ucl_{Mr}$)	0,00	0,00	0,00	2,00		2,00
Improvement						
μ_D Improvement	1,00	1,00	1,00	0,95		0,99
σ_D	1,00	1,00	1,00	1,00		0,98

Table III shows the simulation results. After fifty runs of 10 defects, the propagation distance mean has decreased of 43%, the standard deviation of 39%. The control of the propagation distance and the implementation of the associated improvement actions in case of alarm seem to be profitable. Following the distance can be a decision aid tool for implementation of improvement actions. Quality tools and working groups are actually implemented for major defects. This qualification is however quite arbitrary. The presented tool could thus be a more realistic trigger to start improvement action.

This informative simulation demonstrates that the propagation can be mastered even if improvement actions present major weaknesses. In order to fully validate the results, an industrial scale-1 test has to be implemented. The currently running industrial application of the method already proved operational utility in pointing out weaknesses of the control plan.

The proposed model however presents limits. It is grounded on simplifying assumptions, in particular the use of a normal distribution for the propagation distance. The detection of deviations is moreover not automated, but relies on humans. It means that the ATS is not mastered. In order to refine the model, the detection speed and the type I and type II errors have to be investigated.

VI. CONCLUSION

Industrial companies set up mechanisms to protect themselves against non-conformities: on the one hand, risk analyses to prevent defects and, on the other hand, detection systems in order to detect them as soon as they occur. These measures can however present breaches and let some defects run through and propagate. This propagation induces huge costs for companies because it causes scrap, rework, and delays and can potentially impact customer satisfaction.

This paper is thus interested in controlling this propagation, which reflects the global performance of the control system. It proposes to create a propagation control chart and to implement improvement actions as soon as a propagation threshold is overrun. The interest of this method is illustrated through a case study in a low-volumes industry and a simulation. Developments have to be conducted to refine this method and to evaluate more precisely the impact of the improvement actions on the control system. The applicability of this method in other industries should also be validated.

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