An Operational Activity Analysis Using Analytic Hierarchy Process and Queuing Petri Net

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Abstract: We present in this paper an approach of constructing a model of diagnostic aid in order to analyze an operational activity. This approach combines the Monte Carlo simulation of Petri nets model with waiting queue QPN (Queuing Petri Nets) with a multi-criteria decision analysis method AHP (Analytic Hierarchy Process). The link between the simulation and the AHP method is to calculate a posteriori, by simulation, model of probability that describe causal relationships between process indicators and an global indicator of a delay in production.

Keywords: Failure analysis, process operation, analytic hierarchy process, cause-effect diagrams, Monte Carlo simulation

1 Introduction

Operational process of product systems are distinguished more by the complexity of their permanent structure and hence the analysis of these processes is facing a multi dimensional complexity due to the performance. In general, we are interested in the functioning of the process operation (process of production) and in particular to the elementary component, which is the activity. Specifically, the performance of an activity is subject to several sources of degradation which determines its level of operation, how can range for the perfect operation up to the totally faulty operation. The activity may, therefore, have levels of deteriorated functioning. In the area of reliability, the study of complex systems operating has long been carried out from the binary approach, where only two states are allowed: nominal operation (functioning) and complete failure, obscuring other intermediate states. Fortunately, recently published work in the literature, takes into account the different situations that may arise during system life span, and takes in considerations their multiple states. Such systems are called multi state systems (MSS). In [13], the authors consider that a system is a multi-state system, when it may have different levels of performance (including its components). Moreover, some type of MSS system may have several failure modes with different effects on their performance, as well as degradation. Several methods dealing with such systems exist in the literature, among them, we can mention, the stochastic processes method (mainly Markov and semi-Markov -

often applied to MSS small sizes); the Monte Carlo simulation model that permits a fairly realistic modelling of multi-state industrial systems with complex operations [20] and the universal generating function (UGF) approach that is generally used for its robustness. In addition, this method is based on the distribution of the performance of its components and is used to determine the distribution of overall performance of MSS [13]. These methods permit to measure one component reliability effect on the MSS global reliability. For this, it is important to know the role of each component, in order to determine their impact degrees on the global MSS performance. Therefore, these methods are interested to the different components of the system to identify the overall performance (on operational level), which can be reached finally by this later. However, the analysis and piloting of the processes and activities needs to inversely look at a global malfunctioning which is detected at the system output and trying to identify each component’s impact degree that has led to this result. This, is the foundation of this communication, even more, very little research is being conducted in this direction. We then call « dysfunction » of the process the drift situation compared to global objective previously established. Deficiencies may occur due to failures or bottlenecks in the operational resources (along the process). The objective is to be able to identify the root causes, from, (a posteriori) a proven global failure. More concretely, it is a question of establishing an effect and causes chain, which is measured by a relevant variable. In this context, we are generally interested in global functioning results (Overall performance) on the basis of relevant performance indicators.

In the industrial sector, performance indicators have been redefined in recent years as part of a process approach framework [3], [5], [6], in direct relation with the action variables [4]. In fact, the process approach puts forward a concept of objective in the chain activities and the aim of management and monitoring by process activities is to achieve operational excellence in the chain,. This issue has already been addressed in [11] by a characterization of the process as a state vector, whose components characterize the evolution in time of the activities involved. The ultimate goal is always to be able to localise the failure source and to take appropriate remedial measures by identifying effect / cause (s) between result indicator and process indicators [1]. If we draw a pie chart, the whole of the chart represents the goal of the decision problem. The pie is organized into wedges, where each wedge represents a cause contributing to the goal. Then AHP (Analytic Hierarchy Process) method [17] helps determine the relative importance of each wedge of the pie. Each wedge can then be further decomposed into smaller wedges representing sub-objectives, and so on. Finally, wedges corresponding to the lowest level sub-objectives are broken down into alternative wedges, where each alternative wedge represents how much the alternative contributes to that sub-objective. By adding up the priority for the wedges for the alternatives, we determine how much the alternatives contribute to the global objective. In this regard, we have chosen to measure the delay of an activity. Each activity is assigned a task with deadline where exceeding the deadline will be reported as a malfunction. First of all, we will describe the entity that is considered in this communication (operational activity) and its QPN (Queuing Petri Nets) model (section 2). Then from the activity-based operational model, we will identify a priori all of the possible causes of delay generators. Afterwards, we will set decomposition tree effect / case(s) where the outcome is of a qualitative nature (section 3). The quantification would be given by weight, using the AHP method [17] (section 4). This same method can then update a matrix whose elements measure the contribution of each case on the final effect found. The way to initialize the weight (value) falls within the expertise; it may use data field or simulation. Here, we choose the simulation. Section 5, explains how to use the activity simulation model by a network QPN (Queuing Petri Nets) [2]. We have already used this technique in the same context in [1], [12]. Finally, we will discuss the advantages of the methodology used (section 6), followed by conclusion in section 7.

2 Industrial Process Model

2.1 Considered Entities

An Activity object (Figure 1) is an organizational object that corresponds to a task to perform. It is initialized by the global process management level. This activity is based on the resources (machinery, competence). It needs, to be executed, to process (transform /assemble) a physical flow (material / components) that comes from upstream activities (An-1 activity and / or external suppliers). A complete operational process can be modelled as a series and / or parallel objects of this type. A resource correspond to know-how which it can be applied to concurrently with other activities belonging to other ongoing processes. As the resource (human machine) is limited, activities may be placed on wait.

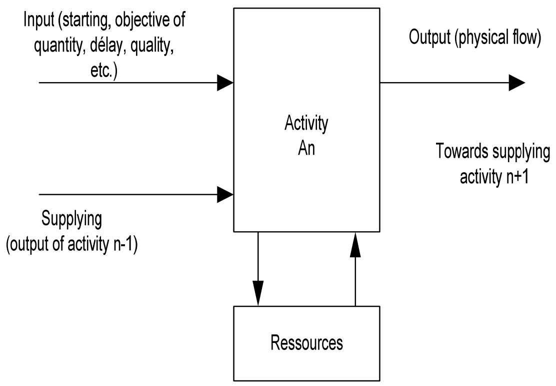


Fig. 1. Elements constituting an activity

2.2 QPN Activity-Based Model

To take into account both the aspects of flow synchronization and "put on wait" implied to access resources, we advocate the use of Petri nets with the waiting queue (QPN Queueing Petri Nets). These, were used to model the computer systems and measure their performance [10], but they are well adapted to model operational systems as well.

The place P1 contains tokens corresponding to a specific activity to be performed. The place P2 contains tokens corresponding to a quantity of material / components to be addressed. The transition T1 is fired when the work required can be performed. It corresponds to the removal of a stock in an amount corresponding to manufacturing Nomenclature. The P3 place is a queuing place. It is divided into a left and a right side. The token, which fired the transition T1, is put on hold (left side). It will come out of the queue to perform a service. The tokens in the right part are the tokens that have performed the service and have not yet fired the transition T2 (to the next activity).

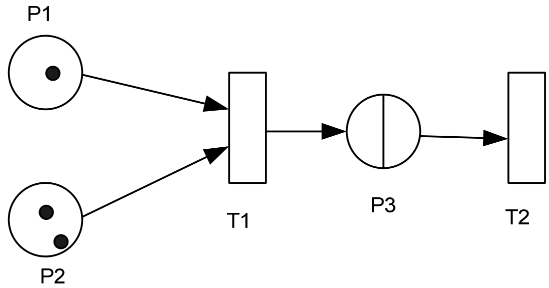


Fig. 2. Representation of an activity by QPN

The right side is managed as a place of an ordinary RDP. A queuing place is a place that contains tokens which have already executed a prior service (Figure 3). This service is characterized by a time unit execution, which can be fixed or random.

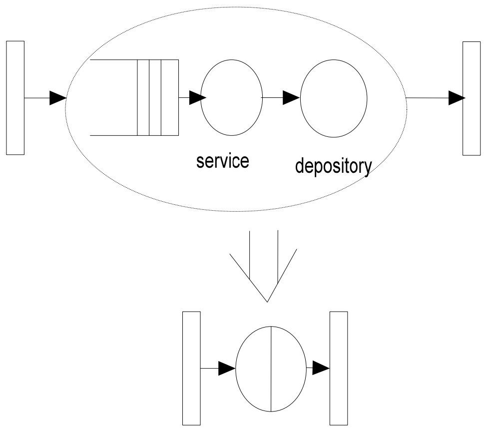


Fig. 3. Queuing place model

It is clear that any deadlock in resources will fill the waiting queue. Compared to the QPN representation that we have made, this means that we must introduce a conditional entry-level service. The QPN are very suitable for the performance measurement, if and only if we suppose that the service can always be executed (i.e. the Fault does not exist). In Figure 4, this concept is taken into account. The place 4 represents the "operational" state. The transition T3 is fired (after a time that can be random) when the "non-operational" event appeared. P5 represents the "non-operational resource" state. After a period that can also be unpredictable, the transition T4 is fired and the service becomes operational.

From this point of view, we consider that an activity is put on wait when the service is operational, but not available. The delay of the activity is due to a call waiting too long or due to insufficient resource capacity or flow mismanagement.

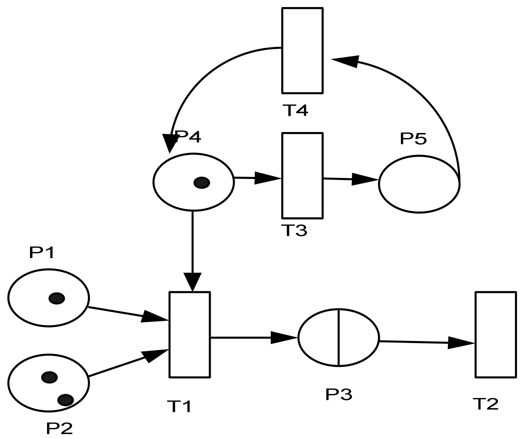


Fig. 4. The operational nature of the service

3 Relation of Effect / Cause(s) for an Operational Analysis

3.1 Effect / Cause(s) Decomposition

From Figure 1, we can establish a priori the hierarchical decomposition effect / causes, showing all local contributions witch probably cause a supplementary delay in the activity. Thus highlight the chains of cause and effect found witch are likely to explain performance (At run level). These concerns:

- Service
- The wait before service

More specifically the service is executable only when the requirements are fulfilled, namely:

- Resource is available
- The supply is available

If we extend this principle, one can lead to the type of cause / effect diagram (Causal Loop Diagram, CLDs) to conduct a qualitative analysis. The entities are measurable indicators. An arc represents a cause ->effect link. The signs + "-" respectively indicate that the effect and cause are changes in the same direction respectively opposite directions.

The causal model construction is based on the dynamicity of the QPN models of the system. Given a directed graph, G(t) = (v (t), x (t)), if there exists a mapping F(t): X(t) -> {-, +}, then G(t), together with the mapping F(t) is called causal loop diagram, denoted as D(t) = (V(t), X(t), F(t)), where V(t) is the elements set, while X(t) is the links set. By using CLDs, one can easily describe all kinds of causal relations. Figure 7 is a simple CLD, which illustrates hierarchical decomposition model and outlines the variable of process that we have chosen for analysis the potentials causes of activity delay.

In this diagram, we separate human and machine resources. The machine resources are subjected to faults or stops. Human resources are subjected to unavailability or stops. This diagram has a peak corresponding to the indicator reflecting the effect studied (delay of the activity).

The level of causality stops at the point where we can identify a variable of action and, thus, a mean of action. What is important to identify at this quality level, is the area of management (and of optimization) to which these variables belong. Figure 5 (diagram Ishikawa) represents a non-exhaustive list of resource factors unavailability, influencing a productive activity.

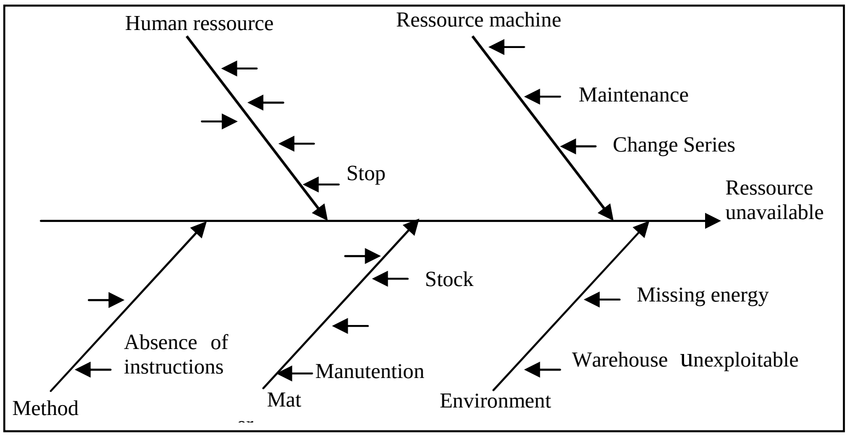


Fig. 5. Ishikawa diagram: classification of the causes of unavailability of a resource

We can clearly identify here:

- Maintenance management : engine failures, maintenance policy,
- Human resources management (or at least teams): stops, availability of people, skills management,

- Production management: batch size, machines resources capacity,
- Supply management: cycle management, suppliers.

4 AHP Method

The Analytic Hierarchy Process or AHP, developed at the Wharton School of Business at the University of Pennsylvania [15], allows decision makers to model a complex problem in a hierarchical structure showing the relationships of the goal, objectives (criteria), sub-objectives, and alternatives. Uncertainties and other influencing factors can also be included. AHP enables decision-makers to derive ratio scale priorities or weights as opposed to arbitrarily assigning them. In so doing, AHP not only supports decision-makers by enabling them to structure complexity and exercise judgment, but allows them to incorporate both objective and subjective considerations in the decision process. The AHP method was implemented in many decision support systems. The AHP method has already been used as a method of risk assessment [9]. It has been extended to the ANP method (Analytic Network Process) [17] to take into account closures (backward arcs) between cause and effect. The ANP method has been proposed in the management of the Supply Chain (SCM) [14], the decision analysis [19] for a textile company.

The AHP method is based on three basic principles: decomposition, comparative judgments, and hierarchic composition or synthesis of priorities. It provides, "to identify, understand and evaluate the interactions of a system considered globally" [16]. This approach also strives to ensure consistency and relevance of the groups, as well as the proportionate relationship between the parameters of significance during construction and structuring hierarchy of priorities.

Table 1. Relative importance scale of AHP method

Intensity of Importance	Verbal scale	Description
1	Equal Importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgement slightly favour one activity over another
5	Essential or strong importance	Experience and judgement strongly favour one activity over another
7	Demonstrated importance	An activity is strongly favoured and its dominance demonstrated in practice
9	Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgements	When compromise is needed

The decomposition principle is applied to structure a complex problem into a hierarchy of clusters, sub-clusters, sub-sub clusters and so on.

The principle of comparative judgments is applied to construct pairwise comparisons (used to set priorities/preference) of all combinations of elements in a cluster with respect to the parent of the cluster. These pairwise comparisons are used to derive 'local' priorities of the elements in a cluster with respect to their parent.

The principle of hierarchic composition or synthesis is applied to multiply the local priorities of elements in a cluster by the 'global' priority of the parent element, producing global priorities throughout the hierarchy and then adding the global priorities for the lowest level elements (the alternatives).

Table 1, provides an initial numerical scale proposed by [16]. Usually, an expert emits for each pairwise of elements his preference intensity for one over the other. In this communication, to deal with the subjective nature of this method, we use the results of the simulation to assign these weights (see section 5-2). This comparison is applied at all levels of the hierarchy. The relative importance of the criteria thus obtained is aggregated according to a bottom-up approach to achieve a single criteria synthesis root of the tree.

Problem Decomposition and Estimation of the Relative Importance of the Criteria (RIC)

The first phase of the AHP method is to analyse the problem in order to identify the various aspects and characteristics that may be involved in the resolution and particularly in the extraction of the goal (or target), the objectives and the overall potential actions. Once identified, these elements are relatively located to each other in homogeneous levels according to the principle of hierarchy.

The hierarchy being established, the second phase of the method is to quantify the intensity of preference between the components of the same level. In other words, it involves, which is better, for determining inter-criteria information preferential for determining the exact relative position of each element in each level. The estimation of the relative importance of the criteria is composed of three steps: setting priorities, summary of findings and consistency calculation.

In the first stage: Criteria for the same level are compared with parent criteria of the test level relatively. The comparisons of pairs (g_i, g_j) of criteria are made using a scale semantics which is associated with a numerical scale [7]. The scale reflects semantic in nature and intensity of the partial term preference between each criteria. The initial numerical scale proposed in [15] is a measurement scale up to 9 times (Table 1). Comparisons pair are presented in a square matrix, reciprocal, N-dimensional, note that: $M = (m_{i,j})$ where $m_{i,j}$: represents the importance of g_i on g_j relative to g_A, such as: $m_{i,j} > 0$, $m_{i,j} = 1$ and $m_{i,j} = 1/m_{j,i}$, with $i, j = 1,...,n$.

Assessment synthesis stage allows evaluating the RIC from the assessments made during the Paired comparison process. RIC takes an eigenvector form $w = (w_1, w_2,..., w_n)$ obtained by solving the system $M.W = n.W$, w_i represents the relative importance of the g_i criteria in relation to its owned family. In other words, it approximates the average of n elements of the row i of the normalized matrix M'. So for each parent criteria g_A the table 2 is implemented.

In the end, the AHP method offers an index consistency (IC) which measures inconsistencies in judgments. According to Saaty, though the extent of this difference is less than 0.1, the assessments can be considered acceptable.

$IC = (\lambda_{\max} - n)/(n-1)$ with $\lambda_{\max}$ the maximum value of the priority matrix.

Table 2. Comparison (relatively to parent criteria g_A), and associated eigen vector

	$g_0 \cdots g_i \cdots g_n$			W
g_0	m_{00}	m_{0i}	m_{0n}	w_0
$\vdots$				$\vdots$
g_i	m_{i0}	m_{ij}	m_{nj}	w_i
$\vdots$				$\vdots$
g_n	m_{n0}	m_{nj}	m_{nn}	w_n

Single Criteria Evaluation

In order to quantify the causal relationships of our model with the AHP approach, a "super" final-matrix $W^f = (I - W)^{-1}$ is calculated. It contains the influence of each factor line compared to a single factor (prepared in column).

I : is the identity matrix

W : is the original matrix, it reflects the influence of variables arranged in line with those arranged in column. It contains, among other things, the eigenvectors of different RICs calculated at previous step.

Table 3. Matrix of relative importance vectors

	g_1	g_2	$\cdots$	g_j	$\cdots$	g_n
a_1	$w_{1,1}$	$w_{1,2}$	$\cdots$	$w_{1,j}$	$\cdots$	$w_{1,n}$
a_2	$w_{2,1}$	$w_{2,2}$	$\cdots$	$w_{2,j}$	$\cdots$	$w_{2,n}$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
a_i	$w_{i,1}$	$w_{i,2}$	$\cdots$	$w_{i,j}$	$\cdots$	$w_{i,n}$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
a_m	$w_{m,1}$	$w_{m,2}$	$\cdots$	$w_{m,j}$	$\cdots$	$w_{m,n}$

5 Application of the AHP Method on the Activity Component

5.1 Activity Hazard Model

The model simulation (Figure 6) allows to track the system evolution from a global time (delay) indicator and establishes the numerical scale priorities needed for the AHP method. For this, we calculate the coming probability of each hazard "m" as follows:

$$q_m = \frac{T_m}{\sum_{m=1}^{M} T_m} \qquad (1)$$

T_m : is the time spent in a state M. Then the contribution of each hazard operation is given by $d = q_m T_m$. These results are realized to establish the numerical scale of priorities.

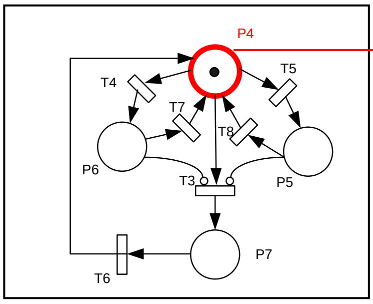
The QPN network and causal diagram that illustrate respectively, the links between the various state variables are presented in Figures 6-a, 6-b and 7. The place P4, correspond to the "operational" resource state: a token in this place means that resources (human and material) needed to carry out the activity are operational. Places P1 and P2 contain tokens that correspond to the activity to be performed and the amount of material to be processed. The P3 place is a queuing place. Places P5, P6, P7 correspond respectively to "non-operational staff", “preventive maintenance action” and “faulty machine" states.

Transitions T3, T4 and T5 respectively represent the cases of a machine breakdown, maintenance activity and personnel absence. Transitions laws are fish laws with parameters $(\lambda_1 = 1/10,\ \lambda_2 = 1/30,\ \lambda_3 = 1/15)$ respectively. Here the unit of time is the day. Transitions T6, T7 and T8 represent deterministic durations of each state (d6, d7 and d8 = 1).

The places P2, P8 and the transitions T9, T10 represent stock-out generator. It is assimilated here to a fault / repair model, namely: The place P2 represents "normal" state; instead P8 represents the state "break". The token of the place P2 can pass randomly to P8 and cannot come back to P2 until a specific slot time is reached, which represents the replenishment delay.

The transition T1 (Figure 6.b) is fired :

- If there's an activity to be carried out (the presence of a token in P1),
- If there's a sufficient quantity of material, i.e. that there is no replenishment hazard (presence of a token on P2), and
- The necessary resources are available (with a token on P4).



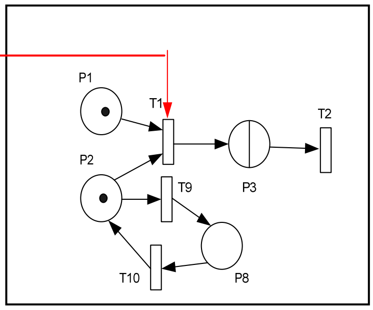


Fig. 6a. Hazard generator model

Fig. 6b. Activity model with uncertainties on the resources and supply state

5.2 Establishment of the Relative Importance of Criteria

The figure 7, illustrates the hierarchical decomposition of potential cause delays in the production activity.

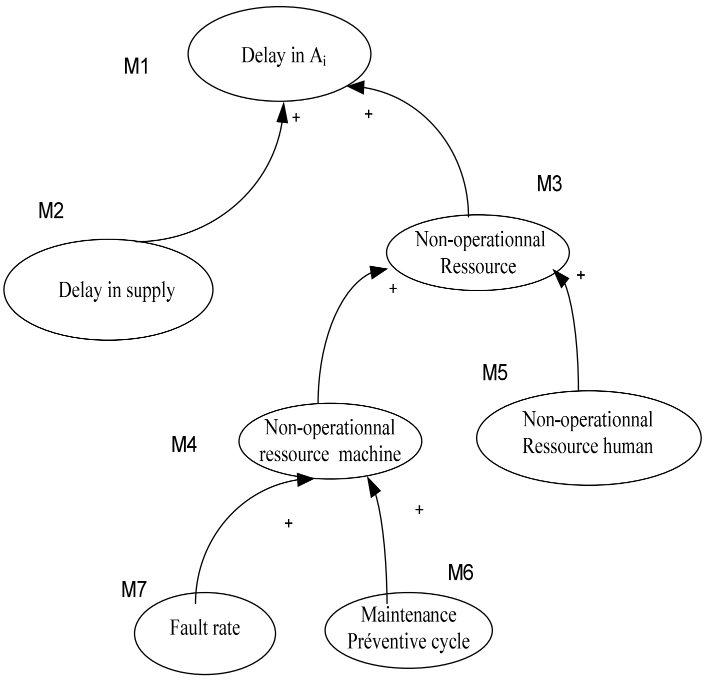


Fig. 7. Causes and effect diagram

We mentioned previously that the simulation results will be used as input of AHP method. This occurs while estimating the RIC.

The table 4 shows the probability of each state.

Table 4. Probability states

Mi	M2	M3	M4	M5	M6	M7
qm	0.333	0.666	0.555	0.111	0.222	0.333

The numerical scale of different comparisons is set up, from the simulation results (Table 4) and in accordance with the AHP method measuring scale (Table 1). For example, from Table 1 and the comparison between the two associated probabilities to M2 and M3, we are giving a preference ratio "3", between M2 and M3 in respect to M1.

The following AHP method steps application, will ultimately find the influence degree and priority of each state variable on the overall result. The transformation process is given in the following tables:

Table 5. Estimated weight compared to M1

M_1	M_2	M_3	W
M_2	1	1/3	0.250
M_3	3	1	0.750

Table 6. Estimated weight compared with M2

M_3	M_4	M_5	W
M_4	1	7	0.875
M_5	1/7	1	0.125

Table 7. Estimated weight compared to M3

M_4	M_6	M_7	W
M_6	1	2	0.666
M_7	1/2	1	0.333

Table 8. Super original matrix determined from a simulation

	M_1	M_2	M3	M4	M_5	M_6	M_7
M_1	0	0	0	0	0	0	0
M_2	0.250	0	0	0	0	0	0
M_3	0.750	0	0	0	0	0	0
M_4	0	0	0.875	0	0	0	0
M_5	0	0	0.125	0	0	0	0
M_6	0	0	0	0.666	0	0	0
M_7	0	0	0	0.333	0	0	0

The table 9 contains weights corresponding to the influence of each factor to another. For example, at line 7, and in column 1, M7 acts on (influence) M2 with a 0.219 factor.

Table 9. Final AHP super matrix W_f

	M_1	M_2	M3	M4	M_5	M_6	M_7
M_1	1	0	0	0	0	0	0
M_2	0.250	1	0	0	0	0	0
M_3	0.750	0	1	0	0	0	0
M_4	0.656	0	0.875	1	0	0	0
M_5	0.094	0	0.125	0	1	0	0
M_6	0.437	0	0.582	0.666	0	1	0
M_7	0.219	0	0.291	0.333	0	0	1

6 Discussion

The objective of the presented method is to define a hierarchical effect / cause(s) diagram. The presented example is not exhaustive in the sense that the decomposition could involve other causes criteria such as:

- The supply delay may be due to several factors such as suppliers non-reliability and the insufficient reliability of the management method,
- The human resource can be rendered inoperative for reasons of: absence (illness, vacation), training and assignment to another position (if it is versatile),
- Resource machine can be ineffective in the case of a tuning. In this case, the versatility test intervenes again. A multitalented versatile technician will put more time than a specialist technician. Flexibility helps to compensate for any absences but carries a profitability lower risk. In addition, batch sizes management are also at this level. Doing batch in larger amounts tends to reduce setup time.

The example that we have presented can be enriched. The disadvantage is purely computational because it increases the matrix size. The fundamental objective of this method is to target the areas where are localised the action variables (to be reused in an optimization process) and the action means (for the purpose of monitoring and correction): production, maintenance, teams and supplies management.

The method provides a hierarchical feature but interrelations may exist in the reality. We cited one: the technician versatility had a positive effect in reducing human resource inoperative time but it is negative in the sense that it increases the adjustment time. The method AHP assumes independency between criteria a priori which appear in separate branches of the causal tree. This method can be extended and the generalized ANP method can be applied for taking into account the dependency between criteria. The simulation has been used here as a learning method and is well positioned here as a way to support aid the expert work to fix the weight a priori. But in actual field data are quite usable as a result of the a posteriori knowledge of the process, the machines reliability, suppliers, rates absence of operators, etc.. This data is more or less accurate: reliability rate, the annual ratio, etc.. Diagrams treated with the AHP method (and ANP) such as the one in Figure 7 presents similarities with Forrester diagrams [8]. In fact, Forrester diagrams are dynamic, i.e. they believe that the characteristics of studied system evolve over time. Forrester pulling from these diagrams a “intégro-differentials” relations between the different variables. In fact, everything depends on the scale at which it is located. Plus it is at a "macro" level, the more we get to stationary conditions. On the contrary, more it will adopt a level close to the ground**,** particularly involving human activities, most of this stationery condition will be difficult to achieve. It is undoubtedly one of the advantages of reason in terms of probability. But in absolute terms, they are not always calculable. In fact, How to quantify a supplier or human reliability by probabilities? That is where we need undoubtedly suggest the fuzzy approach formulation as possible and also as a working perspective to represent data, which is poorly understood. The method, AHP / ANP has been enriched by a lot of work from the “fuzzy” community.

An approach based on Bayesian networks represents a known alternative to constitute and quantify the causes and effect diagrams. In fact, the Bayesian approach uses the probabilities language, witch are related to events or states. In the Saaty AHP / ANP method's, the variables are arbitrary and we are interested a priori only to influence relationships that we attempt to graduate in a relative way, etc.. But the goals are the same, and in both cases, the simulation can be used as a learning step to help the expert to give weight (to the arcs) in a causal relationships diagram.

7 Conclusion

In this paper, we have presented an a priori failure analysis method of an operational activity. We showed different entities in order to model the possible failure sources. Then we proposed the use of AHP method (Analytic Hierarchical Process) - usually used in decision field – witch is eligible here to constitute a cause(s) and effect diagram. The simulation has been used to quantify a priori established influence relations, but in practice there are field data available to enrich a diagram. The example is fairly generic to discuss the methodology but it can be detailed. The primary interest is to obtain a priori a measure of a particular variable influence on a global effect, as measured by a relevant indicator. One goal is to identify the critical variables (those that present the greatest risk) by field management and therefore optimization is possible.

The prospects of this approach are as follows:

- Generalize to a process,
- Integrate uncertain data ,
- Establish the similarities and differences with the Bayesian approach.

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