Global Efficiency Assessment based on Component Composition of OEE Using AltaRica Data-Flow Language

T. Kombe, E. Niel*, L. Pietrac*, A. Rauzy***
**Laboratoire Ampere, Universite de Lyon, INSA de Lyon St Exupery,*
25 avenue Jean Capelle 69621 Villeurbanne Cedex France
surname.firstname@insa-lyon.fr
*** Dassault Systemes SA*
9, quai Marcel Dassault
92150 Suresnes - France
Antoine.RAUZY@3ds.com

Abstract: We present in this article a method to assess a system efficiency based on modelling of the temporal and stochastic spread of faults. The OEE (Overall Equipment Effectiveness) has become through the NF E60-182 standard one of the major indicators of the effectiveness in piloting production systems. It includes 3 main concepts (Quality, Performance and Availability). If its evaluation can be easy for a single system, the modelling of its components for the global efficiency assessment is much more difficult (taking into account redundancies, temporal scale factors …). In order to take in account the local contribution of each component of a complex system, a notion of OTE (Overall Throughput Effectiveness) is developed. The purpose of OTE is twofold: it measures factory-level performance and factory-level diagnostics such as bottleneck detection. The expected result gives a formal contribution to the establishment a methodology for analysis, design, and decision-making. The results are discussed using a demonstrator based on AltaRica Data-Flow, language in both formal and graphic and real tool modelling / simulation.

Keywords: Efficiency, Production systems, NFE 60-182 Standard, OEE, AltaRica Data-Flow.

1. INTRODUCTION

Efficiency is about getting any given results with the smallest possible inputs, or getting the maximum possible output from given resources. The efficiency of an entity of production is an indicator of global and local performance that can be calculated for any level of decomposition (system or subsystem). The main purpose of calculating efficiency is to enable close link between maintenance and production service in a company. System performance assessment is an arduous problem that requires taking into account its different constituting parts (human, organizational, technical). Such way contributes manner differentiated to its global performance (Innal and Dutuit (2006)). With the increasing complexity of the industrial system structure and the importance that one associates to their capacity to work correctly, the need of modelling faithfully their functional and dysfunctional behaviour and, then, to value their global performance, makes itself more and more pressing. Various indicators of performances and assessment methodologies are already been used commonly. Beyond conventional concepts of reliability,
instantaneous availability, Petri nets, and GRAI (Graph of Results and Inter bound Activities) methodology (Kromm et al. (2001)), other more global indicator out of binary behaviour like work or breakdown, have been defined these last decades. Among these indicators, OEE has become through the French standard NFE 60-182 one of the more readable efficiency indicators. In this paper to assess global efficiency, each OEE's component is modelled under three views: a model based on the modes (working (w), degraded working (w_d) and out of service (o*s*)) in which a system can stay, according to its OEE value, and therefore of its efficiency; a model of calculation that permits to count the time of stay in every mode, and therefore to follow the dynamic of OEE according to stop durations (T_S) (supposed known for functional stops, and uncertainly for failures) and of the Planned Production Time (PPT); and finally a model of sub components (Operator and Repair-Crew) respectively generator of functional stop events as well as discounts in service and repairs. These models automata are then translated in AltaRica Data-Flow language with formal description (Rauzy (2006)). AltaRica Data-flow language avoids combinative explosion problem thanks to its hierarchical ability. This paper is structured as follow: we first present OEE and NFE 60-182 standard, then we discuss on OEE assessment, third we present a single component's OEE as well as system (series and parallel) assessment. Models with AltaRica data-Flow language are illustrated.

2. OEE AND THE NF E 60-182 STANDARD

AFNOR's (French Association of NORmalisation) standard NFE 60-182 defines the main productivity indicators. The most known is OEE. Standard applies in priority to machines or to machine nets. It can be easily spread, with profit, to

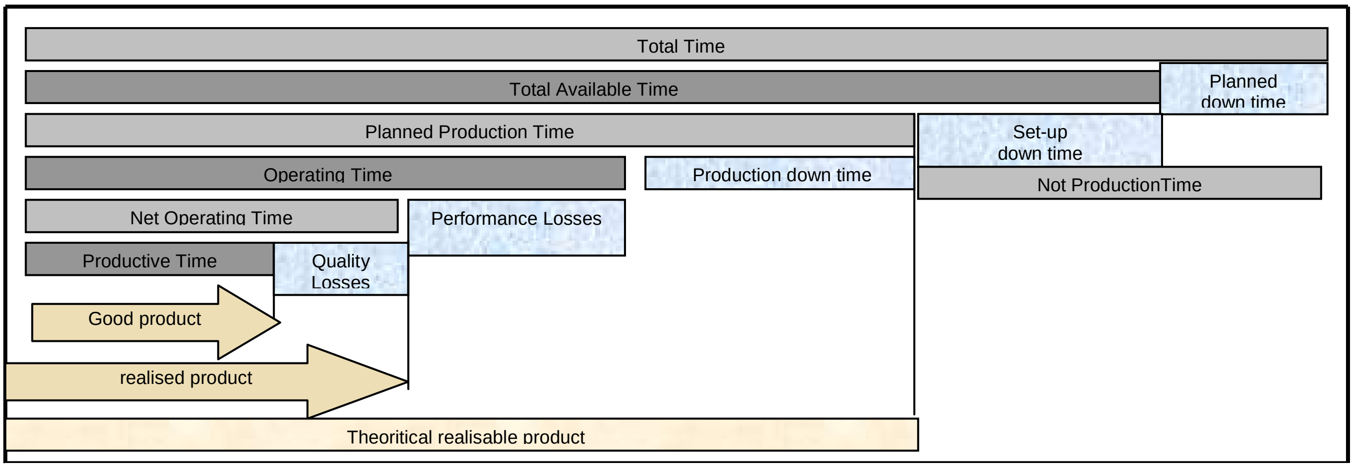

Figure 1: The times of state of a production means: The NFE 60-182 standard

manual manufactures or to process activities. OEE is the "temperature" of the production. But, to progress, to know is not sufficient, it is necessary to understand. That is why; one always associates value of OEE, a detailed and factual compilation of the reasons of none equipment effectiveness. The reasons will serve to determine the state duration that act as basis to the calculation of the indicators.

OEE is defined as a product of three factors that is: the Quality, the Performance and the Operational Availability (Ayel and Fontenelle (2003)).

$$OEE = Quality\ rate \times Performance\ rate \times Op.\ Availability \quad (1)$$

When taking into account the times of state of a production means defined according to the NFE 60-182 standard (figure 1), the components of the OEE are defined as follow:

2.1 Quality Rate (Q_R)

The quality rate can be expressed as the ratio of the productive time on the Net Operating Time.

$$Q_R = \frac{PT}{NOT} = \frac{NOT - t_{QL}}{NOT} \quad (2)$$

Where PT – Productive time
NOT – Net Operating time
t_{QL} – Lost time due to none quality

2.2 Performance Rate (P_R)

It is the ratio of Net Operating Time on the Operating time.

$$P_R = \frac{NOT}{OT} = \frac{OT - t_{SpL}}{OT} \quad (3)$$

Where OT – Operating time
NOT – Net Operating time
t_{SpL} – Lost time due to speed losses

2.3 Operational Availability (OA)

The Operational Availability integrates the planned production time (PPT) and the Operating time (OT).

$$OA = \frac{OT}{PPT} = \frac{PPT - t_{PS}}{PPT} \quad (4)$$

Where OT – Operating time
PPT – Planned production time
t_{PS} – Production stops

Putting formulas (2), (3) and (4) in formula (1), we finally obtain:

$$OEE = \frac{PT}{PPT} = \frac{PPT - T_S}{PPT} \quad (5)$$

Where PT – Productive Time
PPT – Planned Production Time
T_S - The stop duration that includes: induced, own and functional stops.

2.4 World Class Performance

According to the world class performance all system is said efficient when it is characterized by an OEE ≥ 0.85. Thus, requirements to the three parameters are the following: quality rate must be $Q_R \geq 0.99$, performance rate $P_R \geq 0.95$ and operational availability OA ≥ 0.90 (Clemons (2000), Q-mation and Williamson (2006)). For modelling system efficiency, we will take into account these values. The determination of the working limits in each of the three admitted modes (working, degraded working and out of service) of each OEE's parameter can be made while solving the equations of the formulas (2), (3) and (4). The results are presented in table 1.

3. OEE ASSESSMENT

3.1 Temporal calculus

The determination of the working limits can be made while solving the equation of the formula (5).

$$OEE = \frac{PPT - T_S}{PPT} \Rightarrow O.85 = \frac{PPT - T_S}{PPT} \Rightarrow T_S = \frac{1}{7} PPT \quad (6)$$

Thus, all system remained so much efficient when the duration of its times of stops (including: fails, stops, loss of quality and loss of performance) is lower to 0.143 PPT.

Table 1: Different values of the OEE's parameters bound to the World Class Performance

OEE / Comp.	≥ 0.85 Working	0.85 < OEE > 0.25 degraded working	≤ 0.25 out of service
Q_R	≥ 0.99	0.99 < Q_R > 0.29	≤ 0.29
P_R	≥ 0.95	0.95 < P_R > 0.28	≤ 0.28
OA	≥ 0.90	0.90 < OA > 0.26	≤ 0.26

Now let's search for the limits of the "acceptable" working state i.e. the function $T_S = f(PPT)$. The results are represented in table 2.

Table 2: Value of OEE according to the Planned Production Time (PPT)

Ts	0	$\frac{1}{10}PPT$	$\frac{1}{7}PPT$	$\frac{1}{6}PPT$	$\frac{1}{2}PPT$	$\frac{3}{4}PPT$	PPT
OEE	1	0.90	0.85	0.83	0.50	0.25	0

The corresponding mode automaton to this temporal distribution of state duration and representing the efficiency view of the system is given in figure 2.

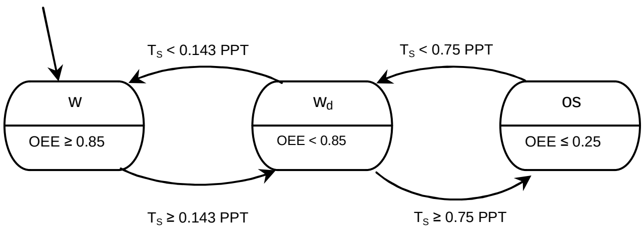

Figure 2: Mode automaton of the three states system representing its efficiency view

3.2 Generalized automaton mode

The temporal description of the behaviour of the system in each of the three modes is represented in the figure 2. It presents itself as follow:

Working mode (OEE ≥ 0.85): It is the initial state of the system. Its change of mode will depend on the value of OEE, that itself depends on the temporal variables, which are function of guards in transitions. The following situations (phases) can happen.

1. No stop is detected ($T_S = 0$) and the value of the OEE is maximal and equal to 1 (table 1);
2. A stop is detected ($T_S \neq 0$), the decrement of the OEE begins, and its value stretches toward 0.85;
3. If the factors having provoked the stop are mastered, the phase 1 will be restarted. If not, T_S increases continuously. As soon as the value of T_S reaches the seventh of PPT ($T_S = 0.143$ PPT), the value of OEE becomes less than 0.85, the system switches in degraded working mode.

Degraded working mode (OEE < 0.85): In this mode, the system continues to deliver a service even in case of quality or performance lost. The following phases can present themselves:

1. The system stays in this mode till that 0.85 < OEE > 0.25 that means 0.143 PPT < T_S > 0.75 PPT;
2. If the value of the stop duration (T_S) reaches three quarters of the Planned Production Time ($T_S \geq 0.75$ PPT), the system switches to the mode ‘’Out of Service".
3. If there is improvement of the stop duration, the system comes back to the mode "working ".

Out of Service mode (OEE ≤ 0.25): It is one mode judged unacceptable in exploitation. The OEE's value proves that to the less one of its parameters (Quality, Performance or Availability) reached a critical threshold for which it is better to put it out of service rather than to continue to exploit it.

4. SINGLE COMPONENT OEE ASSESSMENT

4.1 AltaRica Data-Flow language

For modelling, we opted for an Architecture Description Language: AltaRica Data-Flow. The reasons of our choice are multiple:

1. AltaRica Data-Flow is a high level formal description language dedicated to reliability and dependability studies. It relies on the notion of mode automata.
2. AltaRica Data-Flow integrates links of flows in the input and output of the sub-systems, defining thus the notion of flow propagation, it allows to define a "vector of synchronization" capable to provoke a simultaneous state change on two or several objects. AltaRica Data-Flow permits to take into account the behaviours of the Operator and the Repair-Crew. This is not the case when using others software as DT Analyst 2.0 (Wonderware (2007)). They only limit themselves to the simple calculation of OEE.

4.2. Operational Availability Efficiency (OAE)

While talking about OAE, the system can stay in one of the following states: *Working*, *Failed*, *Stopped* or *Out of service*. The mode automaton of this behaviour is given in figure 3. Two types of transitions are shown here: probabilistic transitions which events are characterised by constant value of failure rate λ, as well as repair rate μ. Conventionally, they are defined by exponential laws. This concern the events *fail* and *repair*. Deterministic transitions which guards are defined by constant time values. This concern for example the events *stopDetected*, *restart*, *prolongedFail*… These events are characterised by Dirac functions. The event features bound to transitions are represented in table 4. An example of the AltaRica Data-Flow is given in figure 4. To illustrate this model, we will take the benchmark studied in Vorne (2008) who's associated data are given in table 3. The results of the stochastic simulation give an OAE = 0.999262. This value gives satisfaction according to the World Class Performance.

Table 3: Given data of the case study of the time of state of a production mean (from Vorne 2008)

Time of state of production means	Data
Planned Production Time	420 min
Operating Time	373 min
Net Operating Time	321.183 min
Productive Time	314 min

4.3 Quality and Performance Efficiencies

The level-headedness of quality and performance efficiencies are given in table 1. Their associated mode automata are identical as shown in figure 5. The events bound to the transitions of these mode automata are two types: exponential and Dirac.

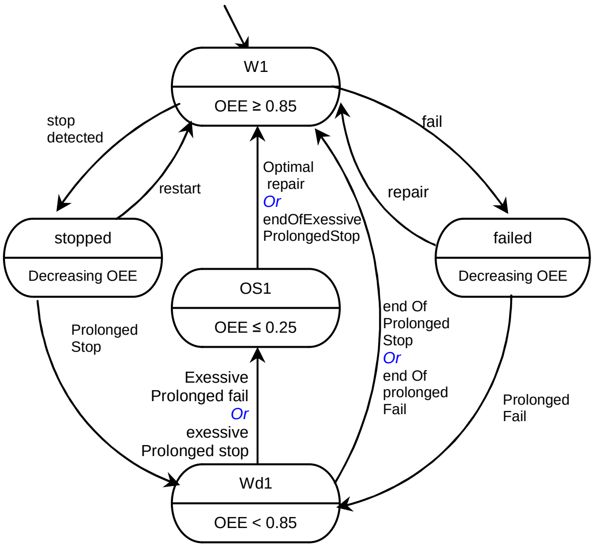

Figure 3: Mode automaton of a system for the Operational Availability Efficiency

```
node  Unit1
state  s                          :{working, failed, Wd};

      dateOfFail                  : float;
      timeOfFail                  : float;
      timeOfProlongedFail         : float;
      dateOfProlongedFail         : float;
      timeOfUnitFail              : float;
      PPT                         : int;
event  fail,  repair,  prolongedFail, endOfProlongedFail, end;
init   s                          := working;
      dateOfFail                  := 0;
      timeOfFail                  := 0;
      timeOfProlongedFail         := 0;
      dateOfProlongedFail         := 0;
      timeOfUnitFail              := 0;
      PPT                         := 420;
trans
     (s = working)         |- fail                  -> s := failed,
          dateOfFail              := %date();
     (s = failed)          |- repair                -> s := working,
          timeOfFail              := timeOfFail + (%date() - dateOfFail);
     (s = failed)          |- prolongedFail         -> s := Wd,
          dateOfProlongedFail := %date();
     (s = Wd)              |- endOfProlongedFail   -> s := working,
          timeOfProlongedFail := timeOfProlongedFail + (%date() -
dateOfProlongedFail),
          timeOfUnitFail          := timeOfFail + timeOfProlongedFail;
true                       |- end  ->;
extern
      law <event fail>                       = exponential(lambda);
      law <event repair>                     = exponential(mu);
      law <event prolongedFail>              = Dirac(sigma);
      law <event endOfProlongedFail>         = Dirac(kappa);
      law <event end>                        = Dirac(tau);
      parameter lambda     = 0.0001;
      parameter mu         = 0.01;
      parameter sigma      = <term(timeOfUnitFail = 0.1*PPT)>;
      parameter kappa      = <term(timeOfUnitFail < 0.1*PPT)>;
      parameter tau        = 8760;
edon
```

Figure 4: The AltaRica Data-Flow model for the three states node Unit 1: working, failed, Wd

4.4 Stochastic and temporal modelling of OEE

The AltaRica temporal and stochastic modelling of OEE of a single repairable component includes sub systems of figures 3 and 5 as well as the corresponding figure of the Performance efficiency. It can be represented of two different manners: we first consider ideal case in which the behaviours of Repair-Crew and Operator are not taking into account. The results of the AltaRica stochastic simulation give the value of OEE = 0.950358.

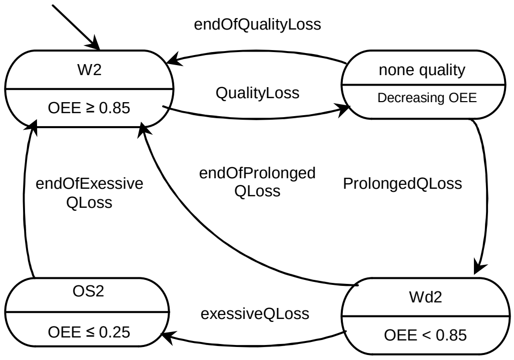

Figure 5: Mode automaton of a system for The Quality Efficiency

Table 4: features of the events bound to the transitions of the mode automaton of figure 3

Events	Param	Function	Value
fail	lambda	exponential	0,0001
repair	mu	exponential	0,01
stopDetected	pi	Dirac	6000
restart	phi	Dirac	5
prolongedFail	sigma	Dirac	timeOfUnitFail = 0.1 TR
endOfProlongedFail	kappa	Dirac	timeOfUnitFail < 0.1 TR
prolongedStop	sigma	Dirac	timeOfUnitStop = 0.1 TR
endOfProlonged Stop	kappa	Dirac	timeOfUnitStop < 0.1 TR
ExessiveStop	xi	Dirac	timeOfUnitStop = 0.74 TR
endOfExessiveStop	tha	Dirac	timeOfUnitStop < 0.74 TR
exessiveFail	nu	Dirac	timeOfUnitStop = 0.74 TR
optimalRepair	tho	exponential	$2{,}5.10^{-3}$

This value gives whole satisfaction because it corresponds well to the result that one could have gotten while using the formula (1) directly *i.e.* when making the product of OAE by QE and by PE obtained in the stochastic simulations of the precedents AltaRica models. In another case, the behaviours of Repair-Crew and Operator will be included in the AltaRica Data-Flow model. The mode automata describing these behaviours are given in figures 6 and 7.

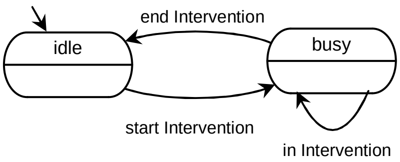

Figure 6: Mode Automaton of the Operator

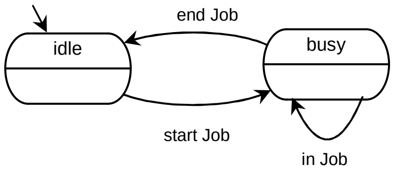

Figure 7: Mode Automaton of the Repair Crew

The event concordance between system working and Repair-Crew / Operator's behaviours is assured by synchronizations between the associated transitions. It is necessary to remark that in these models; we didn't take into account Repair-Crew or Operator's unavailability. One considers here that they intervene as soon as the fail or the stops are detected, what is not always true in practise. The results of the AltaRica stochastic simulation of the single repairable component with Operator and Repair-Crew behaviours give an OEE = 0.950358.

5. SYSTEM OEE ASSESSMENT

5.1 Series structure

When a system includes gone up in series *n* components, the global efficiency depends in whole on the individual behaviour of each component.

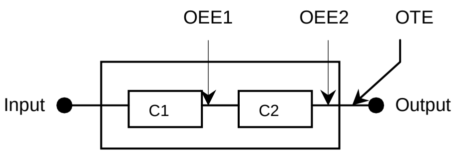

Figure 8: A two components system in series

According to formula (6), the individual OEE of each component in series is equal to:

$$OEE_i = \frac{PPT - T_{S_i}}{PPT} \qquad (7)$$

Where: PPT – Planned Production Time

T_{Si} –stop duration of the i[th] component

But in the subsystem with *n* components in series, OTE is equal to the product of local OEE_i.

$$OTE_{(series)} = \prod_{i=1}^{n} OEE_i \qquad (8)$$

Huang et al. (2003) had shown that, in the series system, the production is dominated by the slowest component, i.e. the component that has the highest loss time. Thus, the OTE is defined as follow.

$$OTE_{(series)} = \frac{PPT - \max(T_{Si})}{PPT} \qquad (9)$$

The results of the stochastic simulation of the AltaRica model of two single repairable components in series are given in figure 9. The value of OTE = 0.998515 obtained here is equal to OEE of the second component, i.e. the last one. This shows that, the efficiency of a system including *n* gone up components in series depends in general on the last component of the chain.

These results on efficiency could help the engineer charged of the implantation of the machines (know where to place the machine in weaker OEE in line of production, where to place intermediate stocks, what are intervention teams, curative, preventive, conditional maintenance policies…), what means to allow the operators to anticipate too frequent stops…).

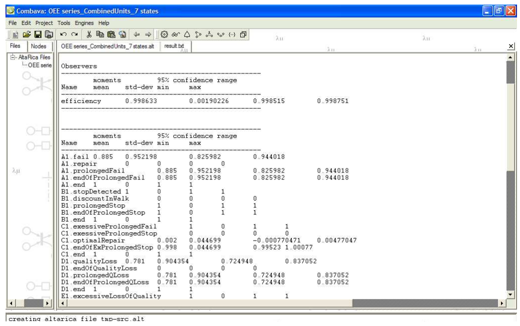

Figure 9: Results of the stochastic simulation of the AltaRica model of two single repairable components in series

5.2 Parallel structure

The expression of the efficiency including *n* components gone up in parallel depends on the type of redundancy. Two types of redundancies are met in practice: the hot redundancy, in which all components participate in the manufacture of a product and the cold redundancy in which it is necessary to put at least one component in an idle state. An example of a two component connected in parallel is given in figure 10.

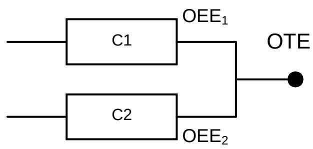

Figure 10 : A two components system in parallel

5.2.1 Parallel structure in hot redundancy

We consider for this application that the two components are identical and manufacture the same type of product. The number of total pieces is equal to the sum of the numbers of pieces achieved individually by every component. Since the two components have the same cadence, they will achieve each the half of the total pieces. Thus, in a system including several components gone up in parallel in hot redundancy, OTE of the system is equal to the sum of the local OEE_i.

$$OTE_{\left(\substack{parallel\\ hotredundancy}\right)} = \sum_{i=1}^{n} OEE_i = \frac{PPT - T_{S_1}}{PPT} + \frac{PPT - T_{S_2}}{PPT} + \cdots + \frac{PPT - T_{S_n}}{PPT}$$

$$OTE_{\left(\substack{parallel \\ hot\ redundancy}\right)} = \frac{n\ PPT - \sum_{i=1}^{n} T_{S_i}}{PPT} \qquad (10)$$

5.2.2 Parallel structure in cold redundancy

In the case of a system including several components gone up in parallel in cold redundancy, two cases can present themselves: either the system functions without restart of the components in stop, or it functions with restart. In the first case, OTE of the system is equal to the ratio of the sum of the Operating Times (OT) of all components minus the sum of the lost times due to none quality of the different elements (t_{QLi}) on the Planned Production Time (PPT).

$$OTE_{\left(\substack{cold\ redundancy \\ without\ restart}\right)} = \frac{\sum_{i=1}^{n} OT_i - \sum_{i=1}^{n} t_{QL_i}}{PPT} \qquad (11)$$

Where OT_i – Operating Time of the i^{th} component

PPT – Planned Production Time

t_{QLi} – Lost time due to none Quality of the i^{th} component

Let’s mention that the system doesn’t have Production stops ($t_{PS} = 0$). It operates so much as at least a component is available, and stops when all components are failed. For the same reasons, there’s no lost time due to speed losses ($t_{SpL} = 0$). The sum of the Operating Times of all the components must be lower or equal to the Planned Production Time.

$$\sum_{i=1}^{n} OT_i \le PPT$$

In the second case, global OTE is equal to the ratio of the sum of the Operating Times of all the components to every start minus the sum of the lost times due to none quality of the different components in the same starts, on the Planned Production Time.

$$OTE_{\left(\substack{cold\ redundancy \\ with\ restart}\right)} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{k} OT_{ij} - \sum_{i=1}^{n}\sum_{j=1}^{k} t_{QL_{ij}}}{PPT} \qquad (12)$$

i = 1, 2, …, n = number of the components

j = 1, 2, …, k = number of the restarts

The sum of the Operating Times of all the components to all the starts must be lower or equal to the Planned Production Time.

$$\sum_{i=1}^{n}\sum_{j=1}^{n} OT_{ij} \le PPT$$

The results of the stochastic simulation of the AltaRica Data-Flow model of two single repairable components in parallel using the formula (12) give an OTE = 0.999986. These results give whole satisfaction since a passive redundant system doesn't know any time of stops. Efficiency is maximal and stretches toward one. It perfectly shows the advantage that present such a system in relation to the systems in series.

6. CONCLUSION

In this paper, we developed a method of modelling and calculating the system Efficiency based on the temporal and stochastic approach of the OEE’s components. The integration of Operator and Repair-Crew behaviours in the assessment of the Efficiency is the major contribution. The use of mode automata represents more precisely the link not only between the different modes defined according to the OEE, but also between different flows of subsystems. It also establishes synchronization between different structures. The use of the AltaRica Data-Flow language allows managing easer different event laws associated to production and maintenance policy. We used the probabilistic laws and deterministic at a time. These works will go on in a perspective of assessment of critical systems efficiency.

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