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CONTEXTUAL KNOWLEDGE FOR AVAILABILITY ASSESSMENT IN MECHANICAL PRODUCT DESIGN

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Abstract
Product availability is rarely taken in to account format early design stage. In this work we aim to provide an approach for availability assessment at early stage of a new product design taking into account contextual knowledge. The approach assumes that there is a hierarchical dependency between availability and its three components: maintainability, reliability and safety. This paper presents in the first section the definition of the availability and the relationships between maintainability, reliability and safety. In the second section we point out the knowledge required for availability assessment taking into account contextual criteria related to product utilization environment, working conditions and enterprise organization and procedures. In the third section, we identify contextual factors and propose a solution to estimate contextual maintainability, reliability, safety and availability. In section five, we propose an implantation of our approach in a CAD system. In the last section, we describe the required simulation data file format.

Keywords: Product performance, Knowledge, Availability, Reliability, Maintainability, Safety.

1 INTRODUCTION
Availability represents the probability that a product or a system is in the operational status at an instant *t*. It is one of the crucial characteristics that strongly influence customers' final choice decision between concurrent products. Evaluating availability performance at early design stage is of great importance to ensure the new product commercial success. Actually, availability is determined using statistical technical data for existing products and from technical point of view. Actually, availability is obtained from only reliability (λ) and maintainability (μ) estimation in design phase as detailed in the section 2.
However, some approaches are proposed in the literature to predict products reliability, maintainability [2] but most of them are statistical methods that are not suitable for new products design. There is a lack of tools for behavioural performance evaluation for domains like availability and its components, which are semantically specified and need formal knowledge to be assessed. The availability is increased by a redundancy system. For example, redundancy allocation problem of a series-parallel system is traditionally resolved by experienced system designers [12].
A system availability optimization is classically based on quantifying the effects that design choices, testing and maintenance activities have on reliability and maintainability attributes [14]. In [13] Marseguerra et al proposed a multi-objective optimization problem and used genetic algorithms to solve it for reliability, availability, maintainability and safety optimization. Human intervention on system is necessary in operation, setting-up, maintenance, phases. Respecting safety standards contributed to decrease the number of accidents arisen during the use of a product. But, in spite of the considerable consideration of safety in design, there are always:
- accidents with an increasing gravity [6],
- some gaps between what is imagined in design and what is lived during using phase [8].
In fact, designer always focuses on the design of a functional, reliable product and under a certain budget. Once the functional reliable system is designed, designer adds safety measures to respect standard. This complicates the product by adding barriers, sensors, etc. which disturb the user. These

last equipments will proceed often to neutralize safety measures. Also, using conditions are not or poorly taken in to account during the design phase.

2 AVAILABILITY ASSESSMENT

Traditionally, two levels of availability assessment are considered: intrinsic and operational availability. Firstly, we recall those two levels then we propose an approach to take into account user safety to determine a safety-based operational availability.

2.1 Intrinsic Availability

The intrinsic availability (A_{in}) is calculated as a function of the Mean Time To Repair (*MTTR*), and the Mean Time Between Failure (*MTBF*), [4].

$$A_{in} = \frac{MTBF}{MTBF + MTTR} \qquad \text{(Eq. 1)}$$

It can be, also, expressed by the rate of failure $\lambda = 1/MTBF$ and the rate of repair $\mu = 1/MTTR$ where:
- λ and μ are constants
- the probability distribution follows an exponential low.

The *MTBF*, mainly depends on the product structural architecture and components reliability. This is considered in our previous works [5] where $MTTR_i$ are determined from a semantic matrix and the disassembly sequence for component *i* and by considering the maintainability intrinsic criteria.

2.2 Operational Availability

Traditionally, the operational availability (A_{op}) takes into account the Time for Administrative Procedures (*TAP*) [17] and is defined as:

$$A_{op} = \frac{MTBF}{MTBF + MTTR + TAP} \qquad \text{(Eq. 2)}$$

The *TAP* depends on the enterprise maintenance organisation policies and the procedures to be performed like ISO-900x constraints. Such information is not often available at design stage.

2.3 Availability Analysis

Here, we analyse availability as shown in figure 1. The product lifecycle begins from design to destruction and includes utilization period with operational and failure states.

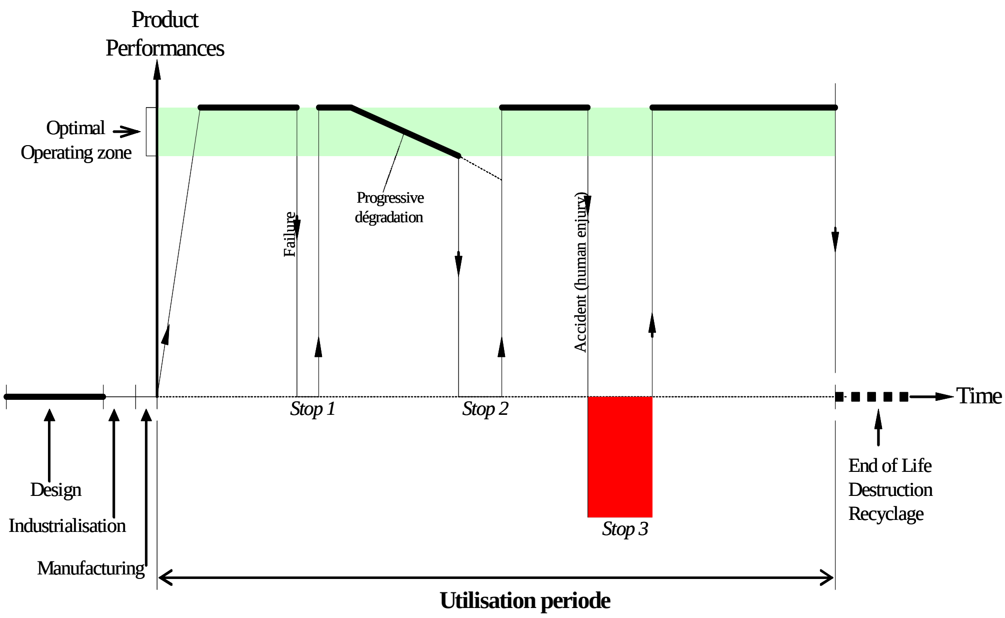


Figure 1: Product Lifecycle

Considering the product as a system consisting of a product and its working conditions, such system must be in one of the following two states: available and unavailable one as shown in Figure 2.

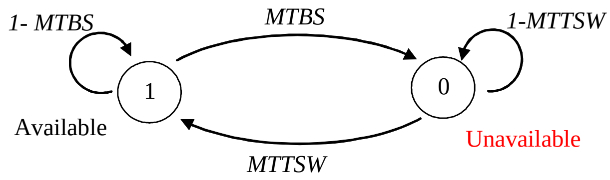


Figure 2: Markov chain of states

Where:

- *MTBS* is the Mean Time Between Stop. The Stop may be due either to a failure or to programmed preventive maintenance action or to an accident for its user during operating period.

- *MTTSW* is the Mean Time To Start Work. It is a time required to restart the work after a stop. It includes all the time duration in which the product is not available after a Stop occurred. It could be one or more of times illustrated in Figure 3.

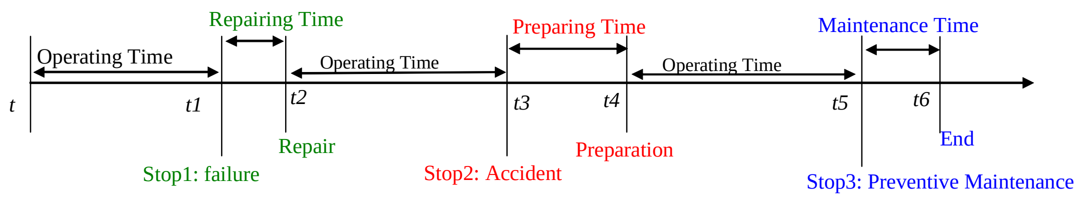


Figure 3. MTBS and MTTSW

Where:
- *Repairing Time* is the time required to restore the system after a breakdown classically represented by MTTR.
- *Preparing Time* is the time to prepare the system to the operating state after an accident or incident caused by the product itself. In this case, it is possible that the system, and because of the accident, could be hang out of order, so it needs time to evacuate the victim, to clean the system,… During an accident laps time, the product is not available and will require a certain time to be prepared. For example, if the product is a circular saw to cut wood, this saw, in case of an accident, cannot be used before the wounded person is evacuated and the saw is cleaned.
- *Preventive Maintenance Time* is the time necessary to perform the preventive maintenance, which is necessary to ensure the improve the product serviceability.
The consideration of working situation [18], in which the product will be used, is fundamental for a better availability evaluation. But in equations 1 and 2 user safety and using conditions are not taken into account to determinate the product availability.
In the next paragraph, we propose a concept of safety-based operational availability.

2.4 Safety-based Operational Availability

We define here a safety-based operational availability that the product may be unavailable during a stop due to an accident or an incident. In this approach, we consider additional actions required to allow the resumption of work after an accident/incident: medical assistance of victims, cleaning the product and replace the operator.
So, to integrate these safety aspects, we adapt the previous operational availability definition in (Eq. 2) to define a new expression shown below:

$$A_S = \frac{MTBS}{MTBS + MTTR + TAP + MTTP} \qquad \text{(Eq. 3)}$$

In equations 1 and 2 the Stop is due to a failure while in the Eq.3 the Stop is assumed to be due to an accident/incident or to a failure or to a preventive maintenance operation. Then an additional term, *MTTP*, is included to express the time required to prepare the system after an accident and before restarting the work. By regrouping in *MTTSW* all the time required to repair the system after a failure or to perform programmed preventive maintenance action and to prepare the system after an accident, A_s is expressed as:

$$A_S = \frac{MTBS}{MTBS + MTTSW} \qquad \text{(Eq. 4)}$$

So, for safety assessment, Houssin et al. [9] identified parameters where the "*Task*" is defined as a necessary concept to satisfy the functions by one or more technical solutions and/or one or more users. A task often requires tools and consumables. This requires determining task duration, intervention zone, components, etc. For each potential technical solution, we must identify the "dangerous phenomenon" concept or the hazard. This concept is defined is the Standard 292-1 [19] as any cause capable to cause an injury or damage to the health of the user during the working situation. Task could be done in a zone named dangerous zone from safety viewpoint and this zone must be accessible for maintenance operations.
Our previous works [3] proposed some indicators related to reliability, maintainability and user safety. They are helpful to compare alternative design solutions taking into account intrinsic and operational criteria. They did not take into account contextual criteria concerning the product environment (temperature, dust, moisture…), the working conditions (noise, lighting, human experience,…) and the enterprise specific organisation and procedures. It is commonly assumed that these contextual factors influence the product availability but they are not taken into account enough in the design process.

3 CONTEXTUAL KNOWLEDGE

A few works try to integrate contextual factors into availability assessment. [11] defined the rate of failure as per million hours for existing electronic components.

$$\lambda = \pi_L \, \pi_Q \, (C_1 \, \pi_T + C_2 \, \pi_E) \, \pi_P \; .$$

Where notation are given below in Figure 4:

Notation	Meaning	Notation	Meaning
π_L	Learning factor	π_E	Environment factor
π_Q	Quality factor	π_P	Pin factor
π_T	Temperature factor	C_1, C_2	Complexity factor
λ	Failure rate	μ	Repair rate

Figure 4 : Contextual Failure rate estimation

In this expression, the failure rate depends on intrinsic factors (π_Q, π_P, C1, C2, μ) and on contextual factors including human operator's competence (π_L) and environmental factors (π_E, π_T).
Hyunki's expression of the failure λ is limited to reliability but does not include maintainability and safety aspects as we mentioned before.
In the next section we identify contextual criteria then we analyze their influence on reliability, maintainability and safety. Then we attempt to assess contextual availability.

3.1 Contextual factors

The product utilisation context concern as well as aspects related to its functioning, to maintenance operations and its interaction with human operators or users and in a wide extend the context includes environmental impacts.
We classify contextual factors into:
- Maintenance Tooling aspects: that includes *keys, screw drivers, handling equipments, etc.;*
- Logistics aspects: *maintenance subcontractors, Spare parts availability, transportation*

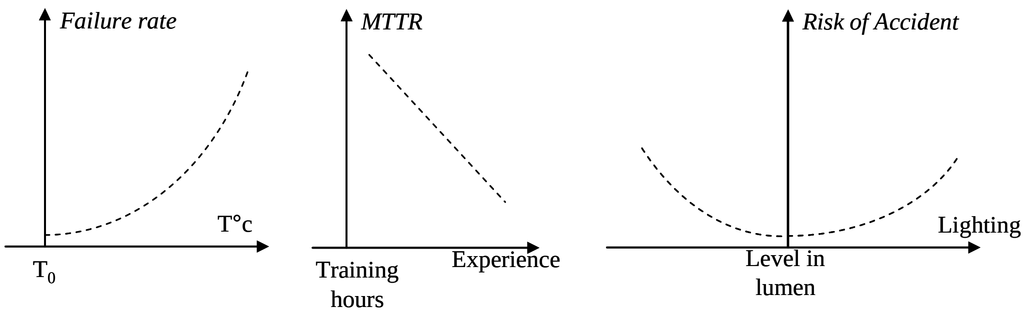
of technicians and spare parts etc.;
- Environment aspects: *temperature, humidity, corrosion, dust, lighting, noise*;
- Human aspects: *human labour competence, qualification,, etc. …*

We have identified some of contextual factors shown in Table 1. This list is not exhaustive but points out the qualitative influence of some usual contextual factors.
Then we classified these factors into subjective parameters (τ, φ, π) that depend on ergonomic considerations and organisational aspects and objective and measurable parameters (t, h, c, d, l, n). $M(\tau)$, $R(\tau)$, $S(\tau)$ and α_1 are respectively qualitative functions to evaluate tooling influence on the maintainability, reliability, safety and availability and so on for the other factors.

Table 1: Contextual factors and its influence

	Tooling $\tau\in[0,1]$	Logistics $\varphi\in[0,1]$	Competence $\pi\in[0,1]$	Temperature $t\in[0,1]$	Humidity $h\in[0,1]$	Corrosion $c\in[0,1]$	Dust $d\in[0,1]$	Lighting $l\in[0,1]$	Noise $n\in[0,1]$
Maintainability	$M(\tau)$	$M(\varphi)$	$M(\pi)$	M(t)	M(h)	M(c)	M(d)	M(l)	M(n)
Reliability	$R(\tau)$	$R(\varphi)$	$R(\pi)$	R(t)	R(h)	R(c)	R(d)	R(l)	R(n)
Safety	$S(\tau)$	$S(\varphi)$	$S(\pi)$	S(t)	S(h)	S(c)	S(d)	S(l)	S(n)
Availability	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	α_9

For example, the temperature level or the presence of dusts can decrease the reliability. A lack of sufficient lighting or a considerable noise may have an influence on user health and lead to the risk of accident increasing.
The military handbook [1] shows that the lack of appropriate tooling, the logistics strategy and maintenance operators competence directly influence on the maintenance operations duration.
Figure 5 (a, b, c) show some examples of qualitative influence of some factors: in (a) influence of the temperature on reliability (failure rate), in (b) relationship between the maintenance crew experience with the MTTR and in (c) the influence of lighting level on operators safety.



(**a**) *Reliability* (**b**) *Maintainability* (**c**) *Safety*

Figure 5: Qualitative evaluation of some contextual factors influences

We propose that T_0, H_0, C_0, D_0, L_0, and N_0, are the nominal contextual conditions, which indicate optimal values for measurable factors. Designers must estimate such values. In practice the product operating conditions is defined within a range around each nominal value related to technical system. Then the contextual influence is function of considered factors. Designer estimates degrading operating mode results from components failures but not those resulting from contextual factors changing.
In the following, we present how to evaluate Maintainability, Reliability and Safety taking into account contextual influences.

3.2 Contextual Maintainability Evaluation

Maintainability is mainly impacted by 4 contextual factors: Tooling M(τ), Logistics M(φ) Competence M(π), and Lighting M(l).
Then we express the global Maintainability Contextual Indicator by:

$$\mathrm{I}_{\mathrm{Mc}} = I_M * (1 + \frac{M(\tau) + M(\varphi) + M(\pi) + M(l)}{4}) \qquad \text{(Eq. 5)}$$

Where I_M is an intrinsic maintainability indicator that is the MTTR proposed in [17]. The contextual factors influences increase the MTTR.

3.3 Contextual Reliability Evaluation

We assume the product reliability to vary depending on operating conditions like temperature, humidity, corrosive and dusty atmosphere. Then we estimate the Contextual Reliability Indicator as follows:

$$\mathrm{I}_{\mathrm{Rc}} = \mathrm{I}_{\mathrm{R}} * (1 + \frac{R(t) + R(h) + R(c) + R(d)}{4}) \qquad \text{(Eq. 6)}$$

Where I_R is an intrinsic reliability indicator that is the MTBF [5]. The contextual factors influences decrease the I_R.

3.4 Contextual Safety Evaluation

We assume the risk of accident to be related to 3 operating conditions: operator experience, noise and lighting. Then the Contextual Safety Indicator is expressed as follows:

$$\mathrm{I}_{\mathrm{Sc}} = \mathrm{I}_{\mathrm{S}} * (1 + \frac{S(\pi) + S(n) + S(l))}{3}) \qquad \text{(Eq. 7)}$$

Where I_S is an intrinsic safety indicator that is the risk of accident which increases with contextual factors influences [10].

3.5 Contextual Availability Evaluation

After contextual factors influences on maintainability, reliability and safety are estimated, the contextual availability is determined using Eq.4 where:
- as explained in [3], I_{Sc} must be as smaller as possible, so we express the *MTBS* as it follows:

$$MTBS = \mathrm{I}_{\mathrm{Rc}} / (1 + \mathrm{I}_{\mathrm{Sc}}.) \qquad \text{(Eq. 8)}$$

- the *MTTSW* is expressed by:

$$MTTSW = \mathrm{I}_{\mathrm{Mc}} + TAP + MTTP \qquad \text{(Eq. 9)}$$

- and we are working on how to estimate *MTTP* from user sites by measuring the time required to prepare the system after an accident and before restarting the work. In reality, this time has the same nature as like as the *MTTR*. So we can use the same technique to evaluate it.
In the next section, we outline some existing tools aimed to estimate *MTBS* and *MTTRW* and we propose a software module to integrate this evaluation into a CAD system.

4 EVALUATION TOOLS

In this section, we recall some existing software tools for availability components evaluation: MTBF and MTTR. Then we propose a software architecture to implement our approach.

4.1 Statistical tools and software packages

Traditionally, intrinsic characteristics *MTBF* and *MTTR* values are statistic data collected during the product usage for existing products. Such data are not available in the case of new product design.
Different software tools are used to predict maintainability and to evaluate safety aspects at design stage.

Relex and Item software [20] is widely used in various industrial domains for Reliability and Maintainability prediction. But such software gives good results for standard product components covered by MIL-HDBK-472, Procedures 2, 5A and 5B.

During these last ten years, Virtual Reality software are used in case of innovative design. Those tools are mainly intended for maintenance operations, ergonomic study and human trajectory presentation. It could be coupled with a dynamic simulation. Those techniques lead to natural user interactions with virtual environments. [16] used the virtual reality to propose a better integration of safety and health requirements in design. In addition, they are still expensive.

So, we propose software architecture to implement availability assessment. The CAD system is extended to allow availability assessment using three sources of data:
- Statistics databases on failure rates and accidents in case of routine design,
- Accelerated tests when prototypes are available;
- Simulation tools such as Finite Elements Analysis Method (FEAM) for new components.

4.2 Implementation in CAD Systems

Figure 6 shows software architecture we proposed in our previous works to assess behavioural performance indicator [17]. Here contextual information for availability estimation are added as external databases. The solution consists of implementing a Knowledge-Based module that describes and manage contextual information in collaboration with a CAD system.

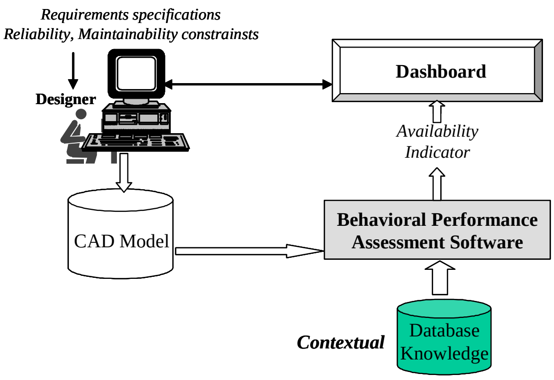


Figure 6: Software architecture

In our current work we use SolidWorks CAD software to provide information related to the influence of contextual factors. This software implements some functionalities for capturing components properties and an API (Application Programming Interface) toolbox that is easy to connect external programs and databases. Here we use Java programming language and a MySQL database. The product CAD model is enriched as follows:

- While modelling each component the Environmental conditions are considered in terms of penalties in case of negative utilization conditions. For example, we capture information about excessive cold/hot temperature, about the presence of dust or about corrosive atmosphere.
These contextual information are stored in a MySQL database.

- Safety conditions are considered by using the working situation demonstrator tool developed in Microsoft/ACCESS Database Management System [9]. This tool allows designer to take into account safety parameters. It aims to capitalize and reuse knowledge concerning safety assessment during design phase and also allows to calculate the safety indicator I_s.
For existing product redesigning, we can find that information from the customers using similar products. But for a new product, we propose a structure for required simulation data file for availability assessment. Then considering a new product, we have to simulate its usage profile, define the associated preventive maintenance program and make some hypothesis on Failure Mode Effect and Criticism. In addition, we have to imagine accident occurrence during its utilisation using methods like failure tree, MAFERGO [22], etc.. These necessary statistical or simulation data may be registered using Table 2.
From this table we determine *MTBS* and *MTTSW*, and then the availability can be calculated.

Table 2: Simulation/ Statistical data

Time	**Events**	**Reasons for Events**			**Maintenance Actions**		**Medical assistance**	
		Failure	*Pm*	*Accident*	*Reparation (minutes)*	*Restart (minutes)*	*Assistance (minutes)*	*Restart (minutes)*
00:18:10	*Start*	0	1	0				
02:51:25	*Stop*	1	0	0	45	2	0	0
03:38:00	*Start*	1	0	0				
13:05:00	*Stop*	0	0	1	0	0	70	5
14:20:00	*Start*	0	0	1				
23:44:17	*Stop*	1	0	0	10	1	0	0

To show the principle of calculation procedure, we consider here a simplified situation where the observation period lies within the same day. So the time is given in *hh:mn:s*s format to indicate hours, minutes and seconds. In the general situation this format must include the date with the day, the month and the year. So the format is pressed as: *aaaa:mm:dd:hh:mn:ss*.
Figure 7 show the graphical chronogram of the product behaviour as monitored in Table 2. The events instants are marked by t_i, where I varies from 1 to the number of events *n*.
ΔT is the observations period.

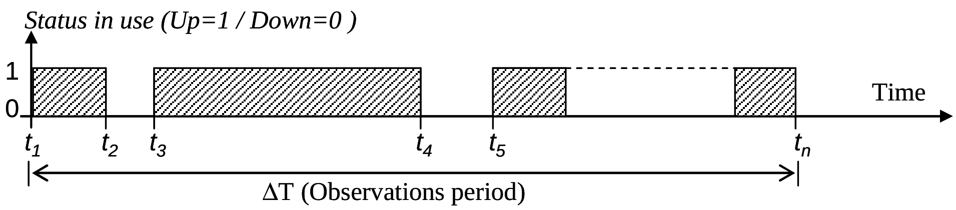


Figure 7: Simulated/ Statistical Behaviour chronogram

In the *MTTSW* and *MTBS* calculation algorithms proposed by Coulibaly [21] in Table 3:

Tsw is the total stops duration over a ΔT period;

Tbs is the total time duration between stop instants over ΔT;

t[i] stands for t_i;

I is the events counter and

k is the intervals counter.

Note that the observations period ΔT must be as long as possible in order to collect significant number of *start* and *stop* events.

The following algorithms to calculate *MTBS* and *MTTSW* require a precondition with $n \geq 4$.

Table 3: MTTSW and MTBS calculation algorithms

MTTSW	Tsw=0 k=0 For (i=3, I $\leq$ n, I = i+2) { k=k+1 Tsw = Tsw + (t[i] – t[i-1]) } MTTSW = Tsw / k
MTBS	Tbs=0 k=0 For (i=4, I $\leq$ n, I = i+2) { k=k+1 Tbs = Tbs + (t[i] – t[i-2]) } MTBS = Tbs / k

After *MTTSW* and *MTBS* are determined we calculate the contextual availability using Eq.4.

5 CONCLUSIONS

This paper outlines an approach to take into account environment and using conditions to predict product availability at design stage. We evaluate the contextual availability by firstly introducing safety dimension in the operational availability then by integrating contextual factors influence. In this approach we determine contextual indicators for the Maintainability, Reliability, Safety and Availability.

We are working to determinate the qualitative functions mentioned in table 1. We also work on gathering statistical data for the *MTTP* and *MTTSW* assessment. This will allow us to determine what of failures or accidents cause more stops during the product utilisation. Such information gives the designer an idea about how to improve the product availability performance.

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