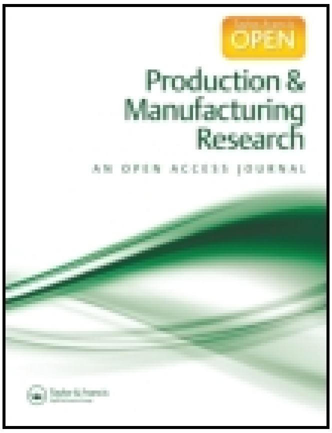

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Accelerated life tests as an integrated methodology for product design, qualification and production control: a case study in household appliances

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Accelerated life tests as an integrated methodology for product design, qualification and production control: a case study in household appliances

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Cost reduction and product quality are key factors in the present competitive market. Product reliability is strongly correlated with customer satisfaction. Accelerated life tests (ALTs) represent a methodology able to investigate product reliability performance in a short time with respect to the classical testing methods in the design. The aim of this paper is the proposal and development of an integrated procedure based on ALTs in order to evaluate the reliability performance of a new product; the use of such testing methods is useful to systematically support the design and qualification phases and to help the service demand forecasting before the product launch. The smart choice of the acceleration parameter and the knowledge developed during the upstream phase in the product lifecycle can be useful and cost effective for its utilization in the downstream lifecycle, as an acceptable substitute of specific advanced final inspection methodologies. The methodology has been tested during the development of a new model of washing machine. The application of ALTs was able to stress one of the most important failure modes of the product, returning important validation data for the design phase and qualification phase and giving good expectation for its fruitful utilization for final inspection in production.

Keywords: accelerated life test; reliability performance; product development; final inspection

1. Introduction and literature review

The household appliances market has reached a very high level of competitiveness. The main reasons can be identified as the increase in the number of companies operating in this business area and in the expansion of emerging countries. The concentration of all these companies in the same market sector leads them to invest a lot of resources and time in product research and development (R&D) in order to persuade customers to choose their products. Continuous technological development and increase of capital investments are key requirements to follow customer needs and to keep pace with competitors (Minderhoud, 1999). Because of the competition, companies try to develop products with increasing performance and new features. Moreover, they try to reduce the time to market, to introduce innovation and to avoid losing their competitive advantage over competitors. As customer satisfaction remains the key point for a successful product, one of the main issues of the R&D activities is to design products with a

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longer life far beyond the warranty expiration, ensuring long availability and proper functioning of the goods. Reliability and durability (Silvestri, Falcone, De Felice, & Di Bona, 2010) are important quality features of a new product which are, unlike static attributes, measurable on the bench with immediate results; they are dynamic and they must be estimated in two ways. The first approach is the reliability data analysis of similar products, applicable when there are similarities among them. For example, it is possible to estimate the assembly reliability using a reliability block diagram combined with a Weibull analysis (Kim, 2011; Zhai, Lu, Liu, Li, & Vachtsevanos, 2013).

The second way to evaluate reliability is through very long tests. New and innovative product reliability performances are commonly estimated through experimental tests, to simulate environmental life stress. Usually, such tests are time consuming and need dedicated resources. In the industrial setting, furthermore, the approach to these tests is not rigorous and scientifically robust. As a consequence, most of them don't provide the expected results and are not cost effective (O'Connor, 2001). Overlooked or poorly designed testing phases can lead to a product of poor quality, because some unapparent failure modes could go undetected (Yadav, Singh, & Goel, 2006).

In the household appliances field, and especially for washing machines, R&D achieved a very high level of reliability as the standard. Therefore, testing procedures of products have become very lengthy, since these are not prone to fail, while manufacturing companies need to estimate reliability performance more rapidly under the pressure of shorter time to market. Traditional reliability performance tests are no longer efficient enough and solutions are needed to accelerate them while not losing significance and correspondence with user experience. Already in the 70s, Nelson (1974) introduced the theory of accelerated life tests (ALTs) and showed its validity. ALTs are a category of test methodology able to assess reliability performance of a product or component in a short time, through the use of stress condition higher than the that in real time (Nelson, 2004). These tests are based on the hypothesis that there must be a relationship between the stress level and the product life. Hence, starting from a parametric form of this relation, a series of tests are performed to experimentally estimate it. Escobar and Meeker (2006) presented a review of ALTs and of their various applications. They are grouped based on: methods of acceleration, type and number of overstresses and life–stress relations. Several studies regarding different issues of ALTs are available in literature: Meeker (1984) compares compromise test plan and optimum test plan, Nelson (1980) used a step-stress procedure to further accelerate tests, while Fard and Li (2009) determined the optimum duration for each step. Yang (1994) deals with test durations using different censoring times for each level of overstress while Zhu and Elsayed (2013) propose an approach to ALT design with multiple stresses depending on different objectives and constraints. Yang and Zaghati (2006) increase the usage rate of a compact relay to accelerate its failure mechanism. ALTs can be used also to predict product field reliability using a relationship between ALT results and field returns as shown by Meeker, Escobar, and Hong (2008). There are also some ALTs' pitfalls, investigated by Meeker and Escobar (1998).

According to the presented studies, ALTs are typically implemented in the product lifecycle after the design phase and they integrate with the other production stages, as shown in Figure 1.

The diagram reported in Figure 1 shows the main stages that a new product goes through before it is put into production. ALTs are usually carried out after the final design step. The results of the experiments are mainly used for the finalization of the

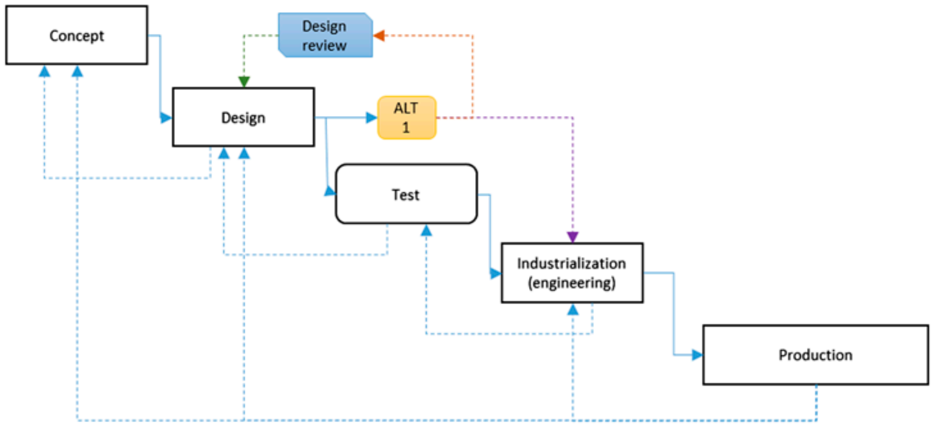

Figure 1. Integration of ALTs in the product design and development stages. The solid lines indicate a material flow, while the dashed lines represent the flow of information. ALT1 indicates the traditional application of accelerated testing.

design, highlighting the critical issues that the normal tests fail to reveal. The experimental evidence can also be useful in the production stage, going hand in hand with the usual tests on prototypes.

Although a lot has been written in literature on ALTs, at the moment they do not represent the standard test methodology when long-term product reliability must be investigated. Even though ALTs are more efficient than the traditional tests, they involve risks and technical difficulties. In fact, they need a lot of resources for design and implementation; this often worries the producer who sees in ALTs a risky methodology, also because of the high cost and for the chance of getting wrong results. Actually, to obtain correct and accurate results, the analyst must thoroughly investigate each interesting failure mode and pay attention on the sample size and on the number and type of overstresses applied. The bigger the sample size, the more accurate the results are. On the other hand, wider sample sizes would increase the costs, since more items and operators should be involved and the total test time will be greater.

The definition of the reliability performance must not be limited only to the design phase, but it should be updated even during production. In fact, during its life cycle, a product might be subjected to productive modifications (suppliers change, production layout modification, assembly sequence change, etc.). All these specific factors could bring the process out of control affecting product reliability. Thus they must be discovered, investigated and revised in order to elaborate corrective actions and to bring the process back under control. Some authors faced these problems: Meeker and Hamada (1995) presented in a tutorial the most suitable statistical tools for each phase of product lifecycle, pointing out how ALT is mainly suitable for the upstream phase (namely, concept, design, test and industrialization) and only for unavoidable degradation failures and known infant mortality, while other methodologies are able to capture unexpected infant mortality, known accidental failures or unexpected accidental failures. For the latter, the early field data and the warranty return data are obviously important, but if the company waits until the availability of these data, that means the economical and image damage was already done. Hobbs (2000) proposes an ad hoc methodology, the highly accelerated stress screens (HASS) just for such kind of failures both in the design and production phases.

Recently, Isaic-Maniu and VodĂ (2009) reviewed the reliability sampling plans to be used as final inspection of the production, developing some specific applications of ISO 2859 sampling plans to survival performance on items produced and inspected by means of accelerated tests. Hence, as far as we know, we can say that in the normal practice white goods industry does not employ such advanced methodologies.

With so much effort devoted to the development and tuning of the ALTs for a new product, it appears convenient to try to extend their deployment also to the control of the production process. Limiting their use only to the reliability performance assessment could be a mistake, while they could be suitable to make other kind of defects emerge, such as production problems, defective quality controls and so on (O'Connor & Kleyner, 2011; Raheja & Gullo, 2012). To this extent, design ALTs are not the most appropriate tool in themselves, but they can become useful if the choice of the accelerated parameters is modified according to those employed in HASS (Hobbs, 2000): vibrations and temperature variations.

The aim of this study is to increase the efficiency of ALTs to support the production stage, choosing conveniently the accelerated parameters, so to produce vibrations and temperature increase. In this paper a new methodological approach to ALTs is proposed, which essentially consists of applying them to three steps of the product life: testing, engineering and production. In particular, ALTs will be used not only as presented in Figure 1 (where these tests are useful for a limited period of the product lifecycle) but also during production and even in the wider after-sale phase (service, warranty, warehouse management, etc.).

As a case study, the reliability performances of a domestic washing machine were investigated using ALTs during the production phase.

The remainder of the present paper is as follows: after a description of the methodology in the methods section, the following results section presents a brief introduction on the case study, the experimental procedure adopted and the experimental outcomes. The discussion section follows, analysing the main achievements and showing a further possible area for ALTs deployment. Finally, some conclusions and interesting future developments are shown with a suggestion of a new possible way to use ALTs together with final inspections for statistical quality control (SQC).

2. Methods

ALT is a methodology based on the assumption that there is a relationship between the stress level and product life. The modelling function depends on two main factors: the component type under analysis and the stress type. Typically, the lifetime of a mechanical component is affected by operating parameters such as temperature, vibrations, environmental conditions and load. Literature review suggests the 'Inverse Power Law' model as the most suitable and flexible model for mechanical components if the stress is non-thermal. Escobar and Meeker (2006), Yang (2007) indicate the Inverse Power Law as the most suitable relationship that describes the dependence of the washing machine life L on mechanical stress.

$$L = \frac{A}{S^B} \tag{1}$$

where L is the nominal life, S is the stress (in this case a mechanical load) while A and B are constants, dependent on material properties, product design, etc.

The independent variable chosen for the reliability model was the number of standard washing cycles, even if in the following formulas it is referred to as *t*, recalling its link to the lifetime. As it will be explained in the next section, the tests were 'Type I censoring' with a censoring time fixed at 500 cycles. The estimation of the reliability function at the user level, obtained from the overstress values, was carried out with the software ALTA© (ReliaSoft Corporation, Tucson, Arizona, USA). To assess the reliability of the machines at the user level (normal operating conditions), it was necessary to find the probability function that best represents the data collected at each level of overstress; in this case, a two-parameters Weibull function was chosen. The probability density function (p.d.f.) is shown in Equation (2):

$$f(t) = \frac{\beta}{\alpha^{\beta}} t^{\beta-1} e^{\left[\left(\frac{t}{\alpha}\right)^{\beta}\right]}, \quad t > 0 \tag{2}$$

where α is the scale parameter, also called characteristic life (it is the life at which 63.2% of the population will be failed) and β is the shape parameter. When $\beta > 1$ ($\beta < 1$), the distribution has an increasing (decreasing) hazard rate, while for $\beta = 1$ it has a constant hazard rate.

The probability that a washing machine will fail during an interval [0, *t*] is defined by the cumulative distribution function *F*(*t*). The latter is obtained by integrating the p.d.f. within the interval [0, *t*]:

$$F(t) = \int_0^t f(t)dt = 1 - e^{-\left[\left(\frac{t}{\alpha}\right)^{\beta}\right]} \tag{3}$$

As a consequence, the reliability function *R*(*t*), derived by the cumulative function, is given by:

$$R(t) = 1 - F(t) = e^{-\left[\left(\frac{t}{\alpha}\right)^{\beta}\right]} \tag{4}$$

In some cases, when performing ALTs, we can define a useful parameter called accelerating factor. It is defined as (5):

$$A_f = \frac{t_p}{t'_p} \tag{5}$$

where t_p is the 100th percentile of the life distribution at user stress level and t'_p is the 100th percentile of the life distribution at the overstress level. Using A_f ,it is possible to calculate user-level reliability performance like test hours (cycles), life percentiles, etc. from those obtained with higher stress levels. For example, known the test hours with high stress level, A_f can be used to obtain the equivalent test hours at the user stress level. The choice of an acceleration factor is based on the hypothesis that the reliability function for all stress levels has the same shape parameter; because we are using a Weibull function, it means that β must be the same for all the stress levels. As a consequence, once that β is calculated for a certain level of stress, the scale parameter of the Weibull function for each stress level is the only missing parameter to be estimated.

The two Weibull parameters (α and β) were calculated using the maximum likelihood estimation (MLE) as it is the most suitable method with several censored data (Nelson & Meeker, 1978). The chosen unilateral lower confidence interval is 97%.

The reliability function at user stress level was obtained using data from tests implemented with three different mechanical overstress levels. As previously stated, to find the relationship between life and stress, the Inverse Power Law correlation function (1) was used.

In this case, the acceleration factor between two stress levels is,

$$A_f = \left(\frac{S'}{S}\right)^B \tag{6}$$

where S' is the highest stress level.

3. Results

As already mentioned in the introduction, the aim of the present study is to show how ALTs can support the industrialization phase, providing useful information about the long-term product reliability. These results are critical, for example, for a more correct initial sizing of inventories, for the prediction of the extents of the after-sales service, for understanding the issue of service calls management under warranty. The possible representation of the interaction of ALTs with the life cycle of the product is shown in Figure 2.

Figure 2 shows how this new ALTs application allows to interact directly on the production process, as a feedback. The comparison between the results of ALT1 and ALT2 allows you to assess the long-term performance of production with those foreseen in the design. For any discrepancy, you will be able to undertake a control and corrective action.

In addition, the predictions of the ALT2 can be compared with the actual performance of the product, rising from the field. So you will be able to promptly detect abnormalities and you might intervene with measures at different levels: from design to engineering, even up to the redesign of ALTs, if problems arise in the experimental phase of the accelerated testing.

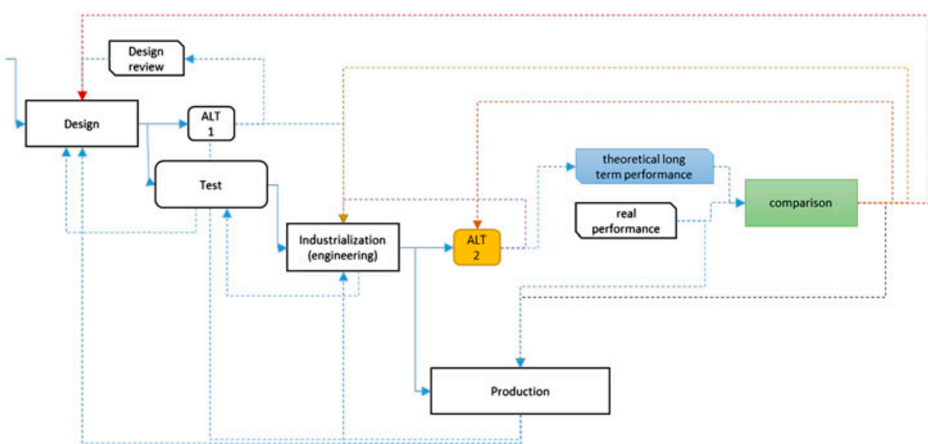

Figure 2. Possible interactions between industrialization ALTs and the other phases of product development. The second application of ALTs (ALT2) can have many interactions (dashed lines) with the other stages of development, making it possible to improve the process as a whole.

3.1. Case study

To verify the goodness of fit of ALTs as a greater support to the design, engineering and production steps, we applied them to a real case, to sustain the process of developing a new model of washing machine. The manufacturer decided to launch onto the market a new model developed on the basis of an existing top product with important innovations regarding the enhancement of the maximum drum capacity without altering the case size. This new specification had some relevant consequences since it involved the redesign of one of the most important components of the product: the oscillating system.

Reliability performance of the unchanged components was previously studied by the manufacturer, and a lot of information coming from warranty data analysis was available. So the real challenge was to assess the reliability performance of the new oscillating system during the industrialization phase, but the classical tests were unable to highlight any sources of criticality.

The manufacturer was interested in this issue for several reasons. First of all there was the need to validate the design and industrialization steps through an experimental approach in order to discover the real limit of the new solution and, if necessary, redesign the new component.

Another important goal was to adopt a methodology in order to keep the quality of the manufacturing process under control. Line set-up, suppliers changes, process capability demonstrated in the past to be important issues that could influence the company's product reliability. Therefore, some deviations or drifts should be evaluated as quickly as possible in order to avoid consequences on customer satisfaction due to any increase in faults. Moreover, an early and fast reliability performance assessment can be always very useful in the viewpoint of warranty analysis and service demand forecasting and planning.

The application of ALT to this case study is not trivial because, according to international scientific publications, no study was published regarding the specific application of ALTs to the oscillating system of a washing machine. Only a paper was presented by Park, Park, Kim, and Cho (2006) regarding the implementation of ALTs on the drain pump of a washing machine. Nevertheless, the research expertise of the authors in the context of accelerated degradation and testing as in De Carlo, Borgia, and Tucci (2014) and the comparison between in-house and field reliability have allowed us to design and fulfil the tests, see Borgia, De Carlo, Tucci, and Fanciullacci (2013). Also the ability to extend the applications of known methods and to apply new approaches to existing methods falls within the competence of the authors, as shown in De Carlo, Borgia, and Tucci (2011).

3.2. Experimental procedure

As said, the most important role for the identification of the product reliability performance using ALT is played by the testing phase. Before performing tests, it is fundamental to plan and determine the characteristic of the sample and the stressscheme. Planning activities were performed according to the specifications, the budget and the time constraints imposed by the manufacturer. These led to: (1) the choice of the component to be tested; (2) the failure mode to be stressed and the different levels of overstress; and (3) the test length and the number of samples tested at each level.

ALTs focused on the new mechanical oscillating group (formed by the tub and the drum) being the main innovation introduced in the new model, with an unknown behaviour. The new mechanical group was bigger than the previous one, in order to contain a larger quantity of clothes. The improvements were: a new material, a decreased thickness of the drum and of the tub and several new reinforcement ribs. The design changes implied also a lower gap between the tub and the drum both in static and dynamic conditions. It is important to analyse the latter parameter because it influences the probability that the two components collide, causing a failure: the wider the distance between the two components, the lower the probability that the drum comes into attrition with the tub. According to the root cause analysis of the field repairs, the contact between these two components is one of the most common failure modes. Hence, we decided to perform tests with only one overstressing parameter. The mechanical overstress chosen was a load imbalance placed inside the drum, since it intensifies the drum deformation and its attitude to get in contact with the tub. It also overloads the bearing group, producing heat and possibly deforming its polymeric housing.

The drum imbalance is normally regulated by the electronic control unit that stops the washing cycle if it exceeds a threshold value decided by the manufacturer. The maximum user-allowable imbalance was the baseline. Three equally spaced levels of overstress for testing the washing machines were elected: 165, 200 and 237% of the baseline. These values came from the results of a previous FEM analysis and were confirmed by the designer of the assembly.

The three overstress levels were applied during a programmed washing cycle that, after a marketing survey, was identified to be the most common washing cycle performed by the standard user. It consists of two phases: 90 min of low speed cycles and 20 min of spin cycle. The experimental measures acquisition was carried out only during the spin phase, when the group reaches its most severe dynamic conditions (maximum rotating speed).

It should be added that, according to the results of some preliminary tests, it was found that the usage rate does not affect the failure mode considered in this study. Hence, cycles carried out at low speed can be neglected without altering the results.

For each level of overstress, eight washing machines were used. The sample sizes were chosen accordingly to the planning sets proposed by Yang (1994, 2007), and Yang and Jin (1994) with the 'compromise test plans' and to the requirement of the company in terms of resources and time dedicated, while overstress levels were imposed by designer knowledge. With the 'compromise test plan' methodology, test variables were chosen to minimize the asymptotic variance of the estimate of a life percentile at the user stress level. Given as an input the higher stress level, the censoring time (500 cycles), the total number of machine to be tested (24) and the shape (β) and scale (α) parameter at the user and at the highest stress level (derived from historical data), we could calculate the asymptotic variance of the MLE of the mean life of the Weibull distribution at the user stress:

$$\mathrm{Var} = \frac{\sigma^2}{n} V \tag{7}$$

where $\sigma = 1/\beta$, n is the total number of units tested and V is the standardized variance defined by Yang and Jin (1994). Hence, because σ and n are predetermined, we can calculate the lower and the intermediate stress levels and the number of units to be allocated at each stress level by minimizing V. Yang (2007), using a numerical method, presents a table where, for various sets of input parameters, the optimum value of V is calculated.

The sample sizes obtained mathematically were also dynamically compared with the experimental evidences obtained with previous tests.

Tests were designed as right censored by imposing 500 cycles as censor 'time', which corresponds to an average of 2 years of use. For each test, every 50 cycles, a cycle called 'characterization' was performed. During this cycle, the load was set at the user level; afterwards, the machine was loaded again with the imbalance already established. The aim of the characterization cycle will be explained in the next paragraph.

3.3. Experimental set-up

A laboratory with three positions for the simultaneous testing of washing machines was set up in order to implement ALTs. In each test station, the washing machines were put into metal cages for safety reasons. In fact, in case of contact between the drum and the tub, especially with high imbalances, the drum coupling could break and could be thrown outside the washing machine by its inertia, with severe risks for the safety of workers.

During the tests, three different types of sensors were set on each washing machine in order to monitor those parameters useful for a following degradation analysis. This would be performed using also the data acquired during the 'characterization' cycle.

The measurement system consisted of three types of sensors, each one with its hardware and software acquisition equipment. To measure the drum–tub gap, four sensors were used: three longitudinally placed on the top of the tub, and the fourth at the back side.

Vibrations were measured with three sensors which monitored the acceleration along the axes of a Cartesian tern with origin on the top of the tank, z-axis vertically upwards, x-axis parallel to the axis of the drum and directed anteriorly. The vibration acquisition system consisted of a data logger with signal-processing capabilities connected to the three accelerometers.

The bearing temperature was measured by two thermocouples in contact with the bearing. The two values were then averaged to obtain a more reliable value.

Test activities were preceded by a calibration phase in which the measuring instruments and their software were set to ensure a proper operation. Finally, the data obtained from experimental tests were appropriately post-processed in order to make them suited for an eventual degradation analysis.

3.4. Experimental outcomes

ALTs were performed on 24 machines equally distributed over the three overstress levels according to the standard methodology. The first important outcome was the identification of a new (hidden) failure mode (in addition to those already known by the not accelerated tests and experience) that never occurred before. It involved the new oscillating system and it occurred seven times out of a total of eight failures. Although this fact is not a proof of the equivalence of ALT and HASS, it is an empirical evidence of some similarities, at least for industrial product with significant mechanical components, where the vibration and heat produced by the functioning of the product itself can be used as stress factors for other components, even revealing hidden failure modes.

The results obtained from the three overstress levels are shown in Table 1; next to the number of cycles performed by the machine, in brackets, it is indicated if the test finished without any failure (C – censored) or if a failure occurred (F – failed).

Table 1. Outcomes of the 24 tests (censored C, failure F). The test is right censored at 500 cycles (corresponding to 2 years of use).

	Load imbalance		
Machine	65%	80%	95%
1	500 (C)	500 (C)	50 (F)
2	500 (C)	500 (C)	350 (F)
3	500 (C)	500 (C)	250 (F)
4	500 (C)	500 (C)	300 (F)
5	500 (C)	350 (F)	300 (F)
6	500 (C)	500 (C)	350 (F)
7	500 (C)	500 (C)	500 (C)
8	500 (C)	500 (C)	400 (F)

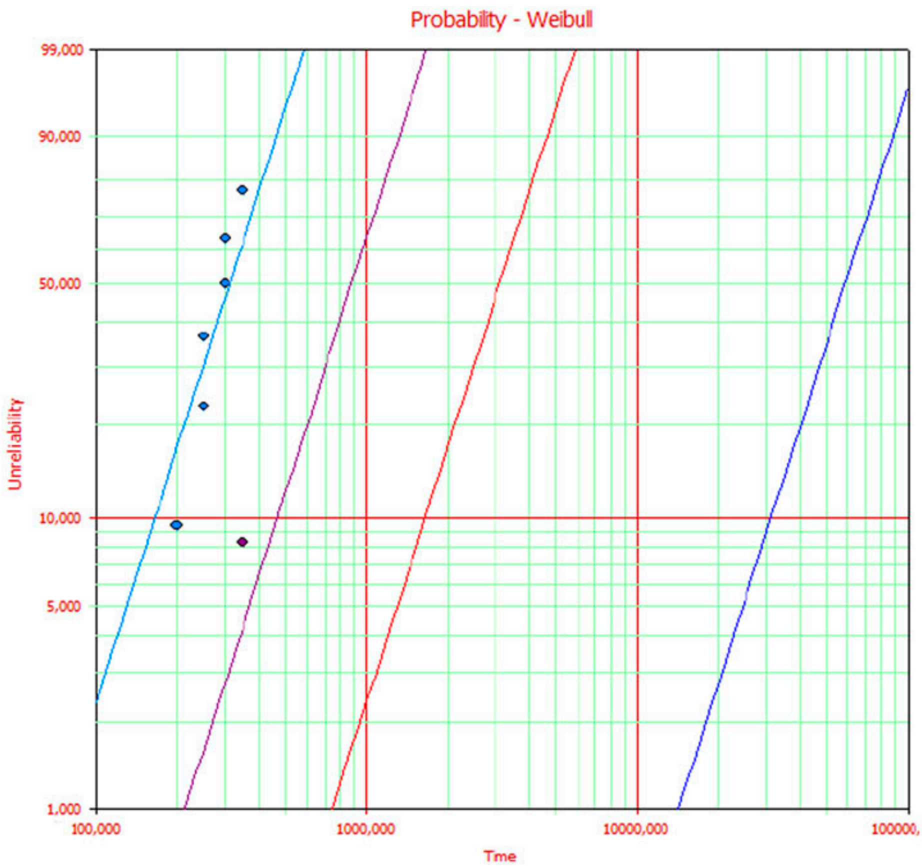

Figure 3. Weibull chart of the four life data distribution. From the left to the right you can see 237, 200, 165 and 100% distributions. Parallel lines indicate that the distributions have the same shape factor.

Data represented in Table 1 are used to estimate the reliability distribution at the user stress level. As already mentioned, a two-parameters Weibull distribution was used to fit the life data obtained during testing activities at the three overstress levels.

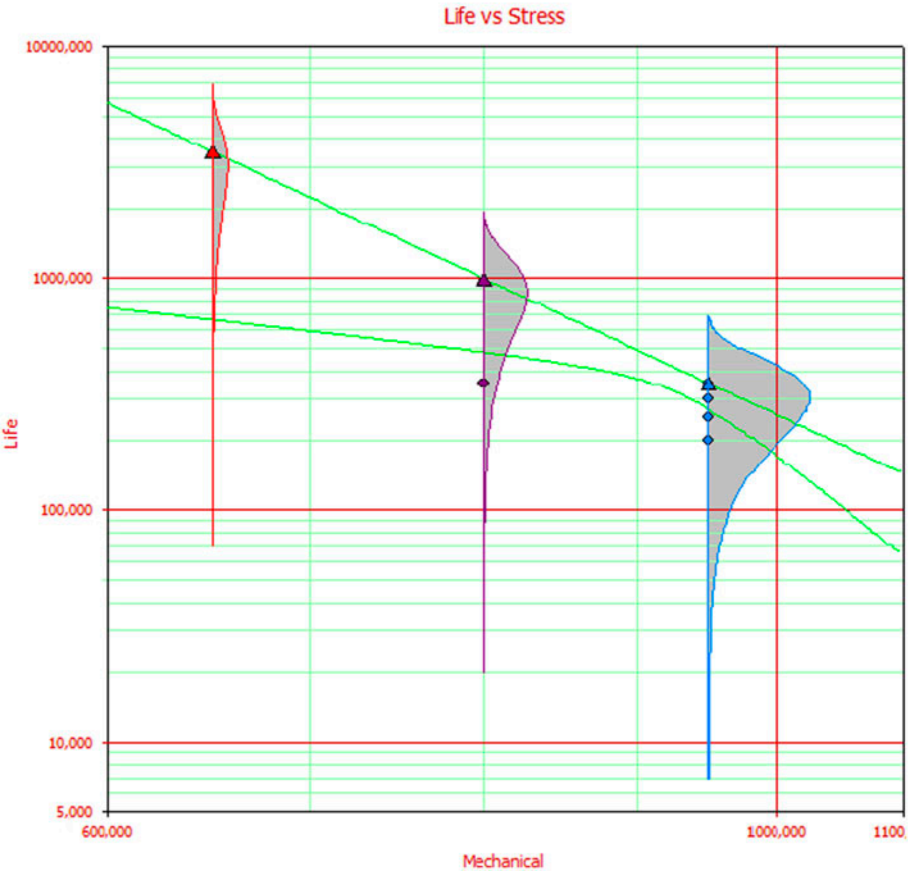

Figure 4. Correlation between the three different levels of overstress (abscissa) and the component life (ordinate) with the 97% lower confidence interval of the frequency distributions.

Based on the maximum likelihood method, the shape parameter β was calculated. Its value is 2.97 and it is equal in every distribution at all levels of overstress (165, 200 and 237%). The assumption of constant shape parameter is evident from the graphical representation of the four straight parallel lines on the Weibull chart (Figure 3).

Hence, the reliability at the user stress level follows a Weibull distribution with $\beta = 2.97$ and $\alpha = 53{,}166$ cycles. This distribution is derived from the correlation between life and mechanical stress obtained by the inverse power law (Figure 4).

Fundamental for service planning were the reliability performances at 500 and 1250 cycles; in fact, 500 cycles correspond to two years of standard usage – the normal warranty period – while 1250 cycles represent an extended warranty (5 years of usage). As regards these values, the estimated reliability performance was very close to one. It is important to underline that the values found were the average ones; as a precautionary measure, we have adopted the lower limit of the confidence interval, because it indicates the pessimistic reliability values for each number of cycle. Hence with the unilateral confidence level chosen (97%) there was a lower reliability of 99.2% for 500 cycles and 89.78% for 1250 cycles (Figure 5). Furthermore the user level was set to maximum

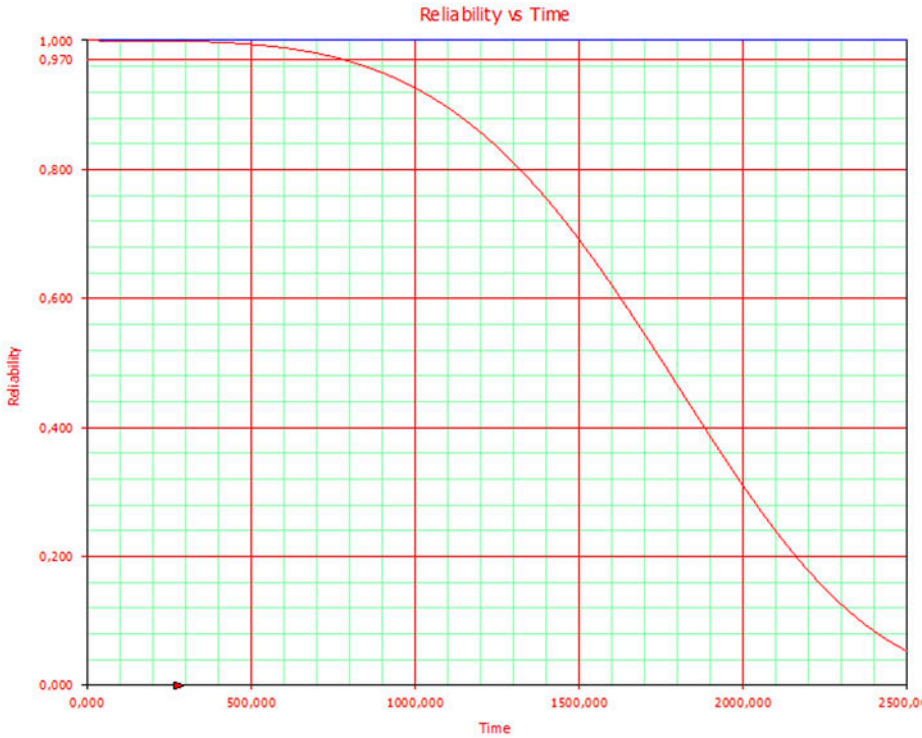

Figure 5. Lower 97% confidence interval limit of the estimated reliability function at the user stress level.

unbalance allowed by the control unit, which is not the average unbalance that loads the product during its life.

The value of 97% was chosen because it is the best reliability performance level to obtain a good trade-off between production costs and service costs. In accordance with the manufacturer, reliability performance specification was then used to calculate the number of cycles that ensures a reliability performance of 97%: 800 cycles that correspond to 3 years and 2 months. The mean life was equal to 1248 cycles (about 5 years).

As a further elaboration of the test results, it was possible to obtain the reliability surface as a function of the stress level and of the number of the performed cycles (Figure 6).

4. Discussion

The aim of the study was to develop a test methodology able to simultaneously identify the reliability performances of a domestic washing machine and to use it to sustain the industrialization phase. This procedure was carried out fulfilling deadlines and tight budget constraints.

By applying ALTs in an innovative manner (after the engineering phase and in parallel to the production), the experimental results identified some critical events related to the production phase of the new mechanical assembly. Satisfying the test duration requirements, ALTs gave results in less than 30% of the traditional test time. During the

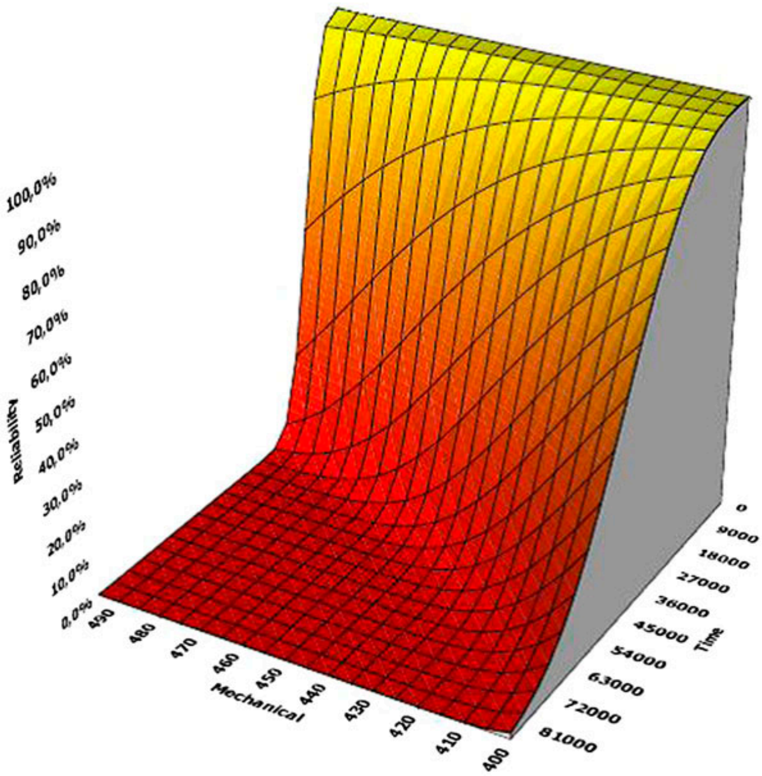

Figure 6. Reliability surface. In a three-dimensional space, the reliability values depend on the number of cycles performed and on the level of stress applied. By this graphical representation, it was simple to assess the reliability performance of the washing machine defining the stress level and the number of cycles.

FMEA analysis, particular attention was dedicated to determinate a realistic overstress that could lead to a truthful failure mode (Lu, Loh, Brombacher, & Ouden, 2000). In fact, although imbalance values that cause failures were higher than the maximum value that was normally allowed, their systematic occurrence should led the manufacturer to well investigate the causes of such phenomena. The failure mode found was catastrophic because it could stop the functioning of the washing machine and cause severe damages. Although reliability performance was not alarming, they were useful to give indications to production managers and designers about the root cause of such a problem which was identified in a supplier change.

ALTs have, therefore, demonstrated their potential in identifying production problems, but might they also be integrated with field data? As a matter of fact, it may happen that the reliability values obtained through the life test performed in the laboratories inside the company (in-house) are different from those that come from field (estimated using the service data). This difference can be due to the fact that ALTs were designed incorrectly because they do not exactly represent the actual product use conditions. Comparing the in-field and the in-house reliability data could give a quick validation about the goodness of the test design that took place in the early product stages, giving the opportunity to the company for continual improvement of these tools along the lifecycle of the product.

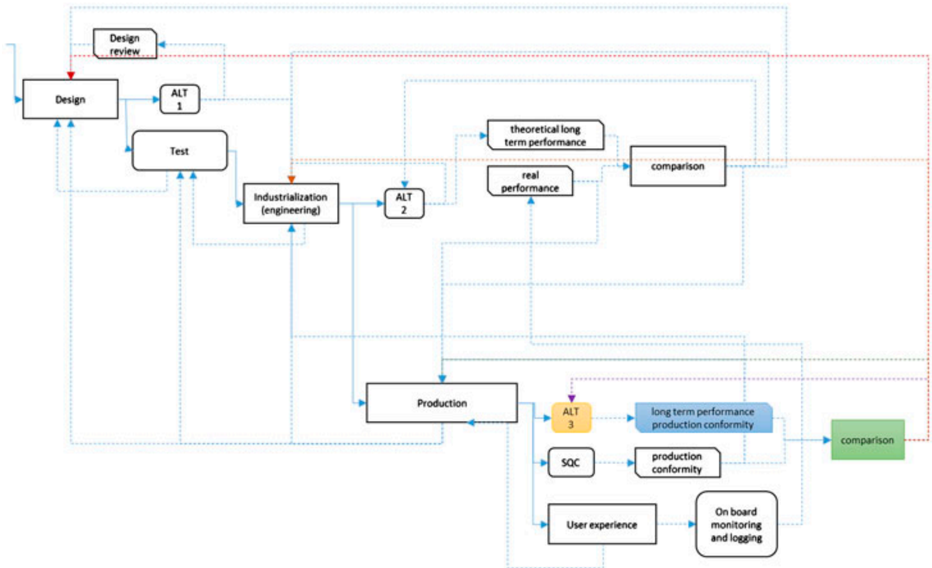

Figure 7. A possible third application of ALTs (ALT3). In the figure is shown how the experimental results of accelerated tests can be integrated in to the SQC to predict the long-term performance of the goods produced.

The favourable results and the demonstrated ability of these tests to reveal hidden failure modes as well, prompted us to think that ALTs could be a tool to be used even after the industrialization phase. Their results could be fundamental for the ultimate estimation of the optimal warranty period and for the full sizing of the supply system involved with the service. If the warranty period is known, the manufacturer could plan and manage all the activities necessary for the service, reducing costs while ensuring a high quality of the service offered. Consider, for example, the ability to plan the production and distribution of all the spare parts and their stocks or the possibility to extend the warranty period.

To sum up, in the previous paragraphs we introduced the typical use of ALTs, which reflects the ideas on which they were originally developed (Figure 1) and the use of ALTs as they have been implemented in the present work by the authors (Figure 2). The results of the study are very encouraging and have also suggested to the authors to propose an additional application area of ALTs to support industrial production. This third mode includes the steps of production and of use by end-users, as shown in Figure 7.

The idea behind this application is that the accelerated testing provides an insight into the long-term performance of the goods under investigation. This investigation, usually made on prototypes or first series' items, can be also extended to the production stage, in which it could stand beside the widespread techniques of SQC. This deployment is feasible because of the small sample size, compatible with the nature of a destructive test performed on production batches; it is also effective because they are able to reveal hidden failure modes, differently from traditional SQC in final testing. Finally, differently from the field data returned analysis, the production ALTs (ALT3 in Figure 7) make it possible to intervene in the production more promptly. In this way the manufacturer is able to proactively develop and maintain the production under control, contrasting negative production trends. As a further implementation, if the product is equipped with a system of on-board data logging and monitoring, the information downloaded from the assets during technical assistance may provide a benchmark for comparing the ALTs results. Ultimately, the possibilities of integration of ALTs during the phases of design, engineering and production are many and allow you to fully support each of these phases.

The use of ALTs as a tool to be applied in parallel with SQC is still in progress in the case study, as the production of the new model of washing machine has just started yet. The experience done in the design phase and the hidden defects discovered and corrected, albeit not related to the failure mode studied, gives an excellent outlook on its effectiveness for the planned downstream utilization.

ALTs showed their potential but also highlighted some critical issues and limitations. For example it is essential to have a dedicated laboratory for the experimental measurements and to have scrupulously investigated the aspects of all the possible failure modes (e.g. by means of an FMEA). After finding all possible failure modes, before running ALTs, you need to identify the most frequent or catastrophic ones through a deep Pareto analysis. It should analyse and classify all the data coming from the service reports. It is therefore clear which enormous effort must be taken, even before the execution of the tests. A great work across all the departments involved in the product development (design, materials, structural, etc.) is needed. Consequently, a considerable amount of resources and time is necessary to develop the preparation phase of the tests, in addition to their execution. Companies that have invested in this direction will be able to easily overcome the problems related to implementation and evaluation of reliability performance such as determination of threshold values and the choice of parameters. The results obtained have wide confidence intervals; it would be interesting to increase sample sizes for the three overstress levels in order to obtain more confident outcomes. In particular, it would be interesting to increase the number of machines tested at the lowest level of stress (165%). Another alternative could be the implementation of unequally spaced overstress levels, increasing only the lower stress level; in this way we could obtain more failure data without incrementing the number of washing machines tested.

A future development of the case study will be to characterize the standard functioning of the washing machine using the data acquired with the sensors and logged in the control unit; these can be also used to compare, at any time, the standard performance with those of machines just produced. Any difference found will be the issue of investigations aimed at finding non-compliances of production process.

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