Study for the development of an endurance testing method for washing machines

Feasibility study for potentially standardised methods

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List of abbreviations and definitions

ADT  Accelerated Degradation Test
AF   Acceleration Factor
ALT  Accelerated Life Test
AT   Accelerated test
dg   directorate-general
EEI  Energy Efficiency Index
FEM  Finite Element Method
IEC  International Electrotechnical Commission
ISO  International Organisation for Standardisation
MTTF Mean Time To Failure
NSF  National Sanitation Foundation (1)
ONR  Österreichisches Normungsinstitut Regel (2)
PAS  Publicly Available Specification
R & D research and development
RMC  remaining moisture content
URL  Uniform Resource Locator
WM  washing machine

(1) Now NSF International.
(2) Now Rules of the Austrian Standards Institute.
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A shorter version of this work was presented during two international conferences:

- eceee 2017 Summer Study (29 May — 3 June June 2017), Belambra Presqu’ile de Giens, (France)
- EEDAL2017 International Conference on Energy Efficiency in Domestic Appliances and Lighting (13 — 15 September 2017), Irvine, California (USA)

Authors

Paolo Tecchio, Fulvio Ardente and Fabrice Mathieux work for the DG Joint Research Centre Directorate D – Sustainable Resources, Unit D3 – Land Resources. The three authors already performed an analytical environmental assessment (3) of the washing machine product group by means of the Durability indexes of the method ‘Resource Efficiency Assessment of Products’ (REAPro).

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Executive summary

The present report focuses on the analysis of durability of washing machines. In particular, the main objective was to develop an endurance procedure to test performance of washing machines, to highlight strengths, limitations and potentials for future improvements.

Background

Durability plays a key role to enhance resource conservation and to contribute to waste minimisation. Prior JRC research analysed the environmental benefit obtainable thanks to the lifetime extension of washing machines, considering a lifecycle approach (\(^\ast\)). The former study was focused on enhanced durability and reusability of products, with scenarios developed to screen the potential effect on environmental impact categories. Previous research, in particular, provided insights and statistics about frequent failures observed by a repair operator, considering thousands of repair services. We identified that vibration and mechanical stress during use represent main sources of stress for the whole washing machine. Especially, low-quality shock absorbers and ball bearings can fail, and this represents a relevant issue, since the high cost of repair may induce the user to discard the appliance. The study also highlighted the need of standardised procedure to test durability of washing machines.

Proposed endurance test

A possible endurance test is here proposed considering the whole product tested under stressed conditions. The test has been conceived to have results in a relatively short amount of efforts and time, in order to be easily implemented and verified. It has been also analysed through initial experiments. The endurance test is based on a series of actions:

- **Pre-conditioning**: the appliance is installed according to the instructions of the manufacturer, provided in the user manual;
- **Initial examination**: the washing machine undergoes an initial visual inspection, to verify whether the machine is intact and undamaged, and fit for the test. Furthermore, the maximum unbalance tolerated by the machine (at rated highest speed) is identified;
- **Testing**: the test consists of a series of 500 spinning cycles, spaced out by one washing cycle every 100 spinning cycles. The spinning cycles are run with the maximum unbalance tolerated by the machine. The washing cycles are run without the artificial load, which is substituted by a base load;
- **Recovery**: after the last spinning cycle, the washing machine observes a rest period;
- **Final examination**: the washing machine performs a final washing cycle, monitoring the performance parameters (e.g. energy and water consumption, cycle duration, etc.) and then undergoes a visual inspection.

Results of trials

Two washing machines from different manufacturers were selected for the trial, called WM A and WM B. A third WM (called WM C) was initially considered for this trial, but it did not perform as expected during the initial examination. WM C did not reach the declared maximum spin speed during the spinning cycles, nor during the normal washing cycles with standard cotton programmes and with cotton load, and therefore was excluded. Both tested machines are currently on the market, declaring an Energy Efficiency class A+++ (EU Regulation), highest spin speed at 1600 rpm and spinning

performance class A (RMC < 45 %). Both are declared having a maximum washing
capacity of 8 kg of cotton load.

The proposed endurance test was applied to the two machines. Even though no hard
failures occurred during the experiments, results clearly showed that not all of the
washing machines are able to sustain such a test without abrasion, or performance
deterioration. An issue concerning the applicability of such endurance test may be
represented by the different control procedure software implemented in the washing
machine. The control procedure detects unbalanced loads and reacts in different ways
according to the software settings. For instance, three main options have been observed:

- The washing machine recognises the unbalanced load thanks to the control
  procedure, and it performs the spin cycle normally if the unbalance is below a
certain threshold defined by the manufacturer of the device;
- The washing machine recognises the unbalanced load, tries to correct the
  unbalance into the drum, limiting the overstress as much as possible, and then
  performs the spin cycle. The attempts to re-balance the load could be repeated
  several times;
- The washing machine recognises the unbalanced load and does not perform the
  spin cycle or it alters the way of spinning (shorter time and/or reduced spin
  speed).

During the experimental trials, it was observed that the third option influenced
particularly the behaviour of one of the two washing machines. As a result, spinning
cycles were run with a reduced spin speed, for longer time, making a comparison with
the performance of the other washing machine not possible. This reaction of the machine
might eventually result on one hand in a reduced stress for its mechanical parts (and
potentially a longer lifetime) but, on the other hand, users do not obtain the expected
performance of the machine (e.g. lower spinning speed and lower spin-drying efficiency
compared to the value declared by the machine programme).

Concerning the influence of such control procedure on the proposed endurance test, it is
remarked that it was not possible to keep equal testing conditions for the two case
studies. Such an issue could be overcome by defining a standardised program for
washing machines that would imply a common behaviour of the machines during the
endurance testing. The requested maximum tolerated unbalance should not be too high,
not to overstress the machines’ capability. Otherwise such a stressful testing procedure
would diverge from real-life behaviour and endurance of the washing machine.

It is important to remark that the trials performed did not show a correlation between the
stress induced by the spinning and potential failures that the machine could suffer during
its lifetime, or a correlation with the number of years a device will mechanically last.
Even if failures had occurred (e.g. when running a trial with a higher number of spinning
cycles), it would have been difficult to correlate these with the lifetime of the device. As
such, a testing protocol based on pure spinning cycles could even be counter-productive
if used to ‘measure’ and compare durability performance of washing machines, as it
induce stresses that are not usual in the washing machine common use.

**Conclusions and perspectives**

Our research highlights that endurance testing can refer to different aspects of the
durability, as the assessment of the lifetime of the machine (e.g. in terms of number of
cycles that the machine can achieve) or to the evolution of the performance (in terms of
the variation over time of e.g. the energy consumption, spin speed, washing cycle
duration). Furthermore, our research proved that the effective performance (e.g.
remaining moisture content, washing time, maximum spin speed, spin-drying efficiency
class) can be deteriorated (or altered by the machine) already after some initial cycles of
the testing. These considerations lead to the main conclusion that a durability test could
simultaneously introduce a certain level of stress, for a certain amount of time, and
introduce a limit on the performance decline of the washing machine. Durability test
would not be devoted to the ‘measurement’ of the average lifetime, but could aim at
ensuring that a device is able to fulfil what is declared on the product fiche even after a significant number of working cycles.

The promotion of the durability of the machines could be based on these points, for example, by performing one or more tests following standards already existing (e.g. the EN 60456), in which relevant performance parameters are measured at the beginning and after a certain number of cycles. It is expected that machine should maintain (or, alternatively, producer should declare) the product performance after a pre-set sequence of standard washing/spinning cycles. These standard cycles could simulate an average operation of the machine for a certain time frame (e.g. two years).

Further work is needed to define a manageable and relevant testing method, but the testing of durability needs to consider the whole product and the way it is specifically used. Future developments may complement or replace spinning cycles (with fixed unbalance loads) with a series of various washing and/or spinning cycles, with loads and programmes closer to the average user behaviour. In this case, the machine would also be more systematically subject to the possible combination of the impact of thermal and mechanical stress with the chemical impact due to the use of detergents. Nonetheless, such changes in the testing procedure may lead to more long-lasting and, potentially, more expensive tests.

As a concluding remark, the presented research not only represents a starting point to develop procedures to test durability of washing machines, but also a potential trigger to systematically address durability aspects of household appliances and electric and electronic equipment. Testing durability performance of products can be successful only if these are based on affordable and reproducible test procedures. This research had the objective to contribute in this sense and to highlight the need of development of such testing conditions.

This report has been developed within the project ‘Technical support for environmental footprinting, material efficiency in product policy and the European Platform on LCA’ (2013-2017) funded by the Directorate-General for the Environment.
1 Introduction

This study is part of a technical support contract signed between DG Environment and DG Joint Research Centre, regarding Environmental Footprinting, material efficiency in product policy and the European Platform on LCA (2013-2017). In particular, Task and Deliverable 8 are entitled ‘Develop/test potentially standardised method on material efficiency, to be applied to relevant product groups’ and aim at developing feasibility studies on potentially standardised methods for assessing durability of products.

The main objective of this report consists of outlining and testing a procedure for assessing durability of electric washing machines for household use. In particular the report will:

- investigate existing endurance tests,
- define whether such endurance tests can be suitable for a possible standardised testing procedure,
- develop and test a durability procedure on exemplary washing machines, and
- assess the durability procedure and provide guidelines for future development.

Durability proved to be a relevant criterion in the context of circular economy, and product lifespan extension is among the main product design strategies to address material efficiency (Allwood and Cullen, 2012; Ghisellini et al., 2015). However, durability tests for complex products (such as electrical household appliances and similar devices) are expensive and long lasting procedures (Tecchio et al., 2017). The growing need to compare properties of electrical devices in a reliable, repeatable and faster way poses further issues.

As stated before, the target of this work is to introduce a draft procedure for testing durability of washing machines, with the following features:

- Reliability: the test should be applicable to the broad selection of washing machines currently on the market, or under development;
- Repeatability: the test should not be affected by test–retest variability, in other words the variation in measurements taken by a different person or instrument on the same item, under the same conditions, and in a short period of time;
- Duration: the duration of the test should not exceed a reasonable timing (e.g. few months maximum) from the first operation to the last measurement; accelerated life testing can serve this purpose;
- Cost: as a consequence of the previous bullet point, the cost of this test should be reduced as much as possible, especially if compared to conventional long lasting tests.

An example of procedure for testing durability is the Commission Regulation (EU) No 666/2013 of 6 July 2013, implementing the Directive 2009/125/EC, with regard to Ecodesign requirements for vacuum cleaners. The Regulation introduced thresholds for the durability of specific vacuum cleaner parts. The hose, if any, shall be durable so that it is still usable after 40,000 oscillations under stain. The operational motor lifetime shall be greater than or equal to 500 hours (European Union, 2013).
Chapters 2 and 3 of the present report concern:

- a literature review, with a focus on the state of the art of washing machine durability, the average usage in Europe, frequent failure modes and different existing theories behind durability tests;
- the study of existing international standards, currently dealing with safety of electronic devices and household appliances, endurance requirements for washing machine parts and guidelines to assess the performance during the washing cycle;
- comments and feedback from experts that were contacted during the study in order to gather information about tests, non-disclosed procedures, failure mode statistics and possible answers to the question of methods able to measure or to verify durability.

Chapter 4 provides the scientific background about the dynamics of a horizontal axis washing machine, which can be seen physically as a vibrating system where the tub (including the drum) is fixed with springs on the top of the housing.

Finally, a novel procedure for durability testing is proposed in chapter 5. The proposed method is a first attempt to find a framework in which several washing machine types can fit in and, eventually, a point of discussion for further improvements and diversification. The results of the proposed method are presented in chapter 6 and discussed in chapter 7.
2 Background information

Nowadays, most of the modern industrial operations are based on a linear approach, where raw materials are extracted and processed, products are manufactured, and eventually disposed at the end of their service life. This linear ‘take, make, dispose’ model is inherently unsustainable and leads to increase material scarcity around the globe (Ellen MacArthur Foundation, 2016). This issue is also highlighted in the Communication of the European Commission titled ‘Closing the loop — An EU action plan for the circular economy’ (European Commission, 2015a). The strategy of the European Commission, instead, is to support and commit to a sustainable, low carbon, resource efficient and competitive circular economy, a strategy that includes the shifting of the concept from ‘waste’ to ‘resources’, boosting the market for secondary raw materials and taking a series of actions to encourage recovery of critical raw materials (European Commission, 2015a).

Material efficiency aspects such as durability, reparability, upgradability, recyclability, or the identification of certain materials or substances are recognised to be key elements for material efficiency and will be systematically examined, especially in the context of ecodesign (European Commission, 2015a). For this purpose, a mandate to European standardisation organisations (5) was issued in 2015, in order to develop standards on material efficiency (European Commission, 2015b).

The importance of durability, in particular, is therefore becoming increasingly recognised, as Europe strives to move towards a circular economy where products are designed and manufactured in a way that helps conserve resources and minimise waste. Nevertheless, it also corresponds to a main feature for consumers (Wieser and Tröger, 2016). A survey conducted by WRAP (2013a) highlighted how product durability and warranties are two aspects which a significant percentage of final customers are prepared to pay more for (6). However, as reported by Ricardo-AEA (2015), durability as a stand-alone concept has not yet been specifically addressed within European product policies. European standards for the assessment of material efficiency aspects for products, including the durability assessment, are currently under development (7).

The analysis herein presented responds to the commitment of giving emphasis on assessment of durability of products and development of endurance testing methods.

2.1 Durability and service life

The International Electrotechnical Commission (IEC) provides a definition for durability, describing this property as ‘the ability of a product to perform as required, under given conditions of use and maintenance, until the end of useful life’ (IEC, 2015). Besides this technical statement, used by standardisation, various authors researched on the existing definitions of durability. The main findings are briefly summarised hereinafter, in order to contextualise the scope of this study.

Ardente & Mathieux (2012) investigated several possible definitions of durability available in literature and found out that there is no common understanding of the concept, but most of the authors associate products durability to their resistance (e.g. the degree to which a product tolerates stress or trauma without failing). Ricardo-AEA (2014) listed a series of other possible meanings, including a proposed definition of durability applicable to the Ecodesign Directive:

(5) The European Committee for Standardisation (CEN), the European Committee for Electrotechnical Standardisation (Cenelec) and the European Telecommunications Standards Institute (ETSI).

(6) From a consumer perspective, 53 % of customers said they would be prepared to pay more for a washing machine that had a longer lifetime. 87 % of customers said they would be prepared to pay more for a washing machine that had a longer guarantee (WRAP, 2013a).

‘Durability is the ability of a product to perform its function at the anticipated performance level over a given period (number of cycles — uses — hours in use), under the expected conditions of use and under foreseeable actions. Performing the recommended regular servicing, maintenance, and replacement activities as specified by the manufacturer will help to ensure that a product achieves its intended lifetime’.

Moreover, Ricardo-AEA (2014) discussed the possibility of creating an extended definition of durability, in order to include repair, design for repair and remanufacturing.

‘A product to maintain its functions over time and the degree to which it is repairable before it becomes obsolete … In other words, a product should not cease to function after relatively little usage and its reparability should not be hindered by its design’.

According to the technical report ‘Guidance on material efficiency considerations in environmentally conscious design of electrical and electronic products’ (IEC, 2016), the durability of a product will depend on many factors, including the materials chosen and the way they are incorporated into the product. Therefore, care should be taken when selecting materials to ensure that they are compatible with the expected lifetime of the product when used in application. Equalisation of the projected lifetime of each part/component in the product could prevent the product from being disposed prematurely due to minor faults. If not possible, the ease of repairing the product or reusing the part could be considered.

In this report we refer to service life as the useful life of an electric or electronic equipment, able to perform its function at the anticipated performance level over a given period (number of cycles — uses — hours in use), under the expected conditions of use and under foreseeable actions.

The typical service life of a washing machine is a key parameter for stakeholders and has been monitored by manufacturers, for internal R & D purposes, and, more in general has been investigated in several published studies. JRC (2016) summarised most of the data on washing machine lifetime in the preparatory study on washing machines, to be used for the analysis of the product group and the identification of relevant Ecodesign implementing measures for washing machines and washer dryers.

Generally, manufacturers can achieve increased durability in washing machines through materials selection and high-quality components. More robust appliances can be also obtained using higher amounts of metals, for example, thus meaning a heavier and more expensive product for final consumer and a probably higher environmental impact related to the manufacturing phase of the product life cycle (JRC, 2016).

However, the average service life of electric and electronic products is in decline (Prakash et al., 2016), with detrimental environmental consequences (Bakker et al., 2014). Prakash et al. (2016) conducted an analysis of the first useful service life of electrical and electronic appliances, and for most of the analysed product groups it has decreased over the last years. Prakash et al. (2016) also observed that an increasing number of functional electrical and electronic appliances are replaced, because of the desire to possess an even better appliance, but also proved that an increasing share of appliances are replaced or disposed of before they reach an average first useful service life or age of 5 years.

Several figures about washing machine service life can be found in literature. ISIS-ENEA (2007) used 15 years as a presumed service life in the Ecodesign preparatory study Lot 14. Ardente and Mathieux (2012) assumed an average lifetime of 11.4 years, in order to assess the environmental impact of possible lifetime extensions. This value was then changed to 12.5 years by Tecchio et al. (2016), who performed an updated durability analysis of WMs, based on figures available in JRC (2016). In another recent study, Prakash et al. (2016) stated that the first useful service life for washing machines is in average 11.9 years in Germany, but varies between 9 and 20 years when several geographical areas (including extra-European countries) are considered. Moreover Prakash et al. (2016) reported an increase in the need for replacing devices being less
than 5 years old due to a defect, with a replacement rate of 15% in 2012 and just 6% in 2004. According to the survey conducted by Hennies and Stamminger (2016), washing machines were discarded by interviewees after 12 years of service life, while about 20% of washing machines do not reach a lifespan of 5 years. On average, interviewees would expect an average lifespan of 13.2 years.

2.2 Durability and environmental effects

In general, consumers want durable goods, such as household appliances, to last considerably longer than they are used (Wieser and Tröger, 2016). From ecological perspective, long-life products perform better than short-life products, considering environmental impact categories (Prakash et al., 2016). A longer lifetime delays the end-of-life processes (e.g. recycling), enhancing the material efficiency during the service life of products. However, there is a number of factors to take into consideration, such as cost implications, consumption patterns, energy efficiency improvement, impact on refurbishment potential and limits from existing manufacturing methods (Ricardo-AEA, 2015). In particular, extended durability should be adequate to the technological progress and must not result in increased energy consumption in the use phase, if newer products have significantly better energy performance (Ardente et al., 2012; Bundgaard et al., 2017; Tecchio et al., 2016). Ardente and Mathieux (2012) and Tecchio et al. (2016), proved through a life-cycle based approach that environmental benefits may be gained by extending the service life of washing machines, even when this lifetime extension delays the purchasing of a more energy efficient product. Evaluations were done considering average products, lifetime extensions of 1-6 years and energy efficiency improvements of newer products up to 20%, compared to the old ones. If compared with a standard scenario (baseline washing machine lifetime, substituted by a new product after the average service life), extended lifetime scenarios (in which the WM is substituted by a new one after an extended service life) can potentially reduce environmental impacts.

2.3 Washing machine washing cycles

According to the feedback received by stakeholders, the number of cycles might be a better indicator than the number of years, for assessing the durability of a washing machine (private communications). Anyways, indicative correlations between expected number of cycles and equivalent years of use can be estimated; highly reliable and robust products might last for 5,000 washing cycles (up to 20 years), against 1,800-3,000 cycles of typical appliances (JRC, 2016). Nonetheless, the more the frequency of usage increases, the more the service life of washing machines decreases — because a machine operates the number of wash cycles for which it is engineered, no matter in which time span these cycles take place (Hennies and Stamminger, 2016).

Also in this case several figures representing the weekly (or yearly) number of washing cycles per final user can be found in literature, as summarised in Table 1.
Table 1. Number of washing cycles per year (and per week) according to different sources. Where not specified, data refer to the average European usage.

<table>
<thead>
<tr>
<th>Cycles/year (cycles/week)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>166 (3.2)</td>
<td>(A.I.S.E., 2013) year 2011</td>
</tr>
<tr>
<td>172 (3.3)</td>
<td>(A.I.S.E., 2013) year 2008</td>
</tr>
<tr>
<td>182 (3.5)</td>
<td>(JRC, 2016) referring to A.I.S.E.</td>
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<td>182 (3.5)</td>
<td>(JRC, 2016) referring to Stiftung Warentest</td>
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<tr>
<td>198 (3.8)</td>
<td>(Kruschwitz et al., 2014)</td>
</tr>
<tr>
<td>200 (3.8)</td>
<td>(VHK, 2014)</td>
</tr>
<tr>
<td>220 (4.2)</td>
<td>(European Union, 2010a)</td>
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<tr>
<td>234 (4.5)</td>
<td>(Kemna and Stamminger, 2005)</td>
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<td>244 (4.7)</td>
<td>(Energy Saving Trust, 2013) U.S.A.</td>
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<tr>
<td>250 (4.8)</td>
<td>(Tucci et al., 2014)</td>
</tr>
<tr>
<td>295 (5.7)</td>
<td>(Regulations, 2012)</td>
</tr>
</tbody>
</table>

As defined by the Commission Regulation 1061/2010 (European Union, 2010a), the number of standard washing cycles for cotton programmes, used for calculating the annual consumption values, is 220. This number has been further researched by the University of Bonn that found how the average number of washing cycle per year in Europe has changed from 4.0 to 3.8 cycles per week (Kruschwitz et al., 2014). This means that using an assumption of 220 cycles per year is conservative and overestimates the annual energy consumption, making 200 cycles/year an alternative estimation (VHK, 2014).

2.4 Warranty

‘Many people assess product lifetime through the length of the manufacturer’s guarantee. Therefore selling longer-life products can still make commercial sense, where backed by a longer guarantee’ (WRAP, 2013). In a survey conducted by WRAP, about 87% of costumers said they would be prepared to pay more for a washing machine that had a longer warranty. Extended warranty, therefore, can contribute as a resource efficiency measure, as highlighted also by other relevant studies.

Bundgaard et al. (2017) examined how resource efficiency requirements can be further implemented into implementing measures and voluntary agreements under the Ecodesign Directive. Extended warranty, upgradability and ease of repair, spare parts availability and modularity are considered by the authors as relevant material efficiency aspects and, more in general, criteria that contribute to the product lifetime extensions. Bundgaard et al. (2017), furthermore, concluded their study by saying that durability should be included in the Ecodesign Directive as a possible resource efficiency requirement. However, it is important to ensure that prolonging the lifetime of the product is the environmentally best solution in a life cycle perspective (JRC, 2016).

According to the preparatory study developed by JRC (2016), extended warranty options vary across European countries. The stakeholders who participated in their survey informed that the warranty provided by manufacturers is typically 2 years, even though it can also be between 2 and 5 years, depending on the model. Extended warranty can apply also to specific washing machine components (e.g. motors with 10-year warranty).
The authors of this report developed a non-exhaustive online investigation about the extended warranty offered by ten washing machine manufacturers. Information about warranties was collected directly on manufacturers’ websites, in June 2015. Results of this investigation show that while all of the manufacturers shall provide a minimum of 2-year warranty for the whole product (two years from the time of delivery as specified in the European Directive 1999/44/EC (European Union, 1999)), they have different strategies for extended warranties.

Two manufacturers offer a 3-year free warranty, for the whole washing machine, after the registration of the product on the manufacturer website. Six manufacturers offer an optional warranty of 5 years for the whole product, and costs depend on the initial price and the type of product; two of them also offer longer optional warranties of respectively 8 and 10 years (again for the whole product), while for another manufacturer, not included in the first group of six, the extended warranty has a duration of 8 years. Finally, four manufacturers provide a free-of-charge warranty of 10 years for the washing machine inverter drive. In this cases, only the specific component is covered by the free-of-charge warranty, while the cost of transport and the manual labour is not included.

From this analysis it is possible to conclude that all of the manufacturers included in this investigation were ready to provide assistance for the maintenance of their washing machines, going beyond the legal thresholds of 2 years. The most offered optional assistance consists of a 5-year time frame.

2.5 Frequent failures

‘In the scientific community, it is supposed that the product lifetime is generally a planned parameter and serves as an orientation for the product designers and developers. The planning of a product lifetime is, however, dependent upon many factors, such as stress, abrasion stock, maintenance, technological change, fashion, shift in values and other external environmental influences’ (Prakash et al., 2016).

On top of what reported by Prakash et al., the authors highlight how washing machine parts (or functions) can be subject to failures, compromising the functioning of the overall machine in the worst-case scenario.

An extensive statistical analysis of frequent failures was carried out by the authors, assessing a database of thousands of repair services provided by the repair centre Reparatur- und Service-Zentrum (R.U.S.Z), located in Vienna (Tecchio et al., 2016). Most recurring failure modes involved the electronics (including control electronics, control panels, program selectors, relays, line filters, etc.), shock absorbers and bearings, doors (including seals, handles, hinges and locks) and carbon brushes (Figure 1).
Figure 1. 6,672 repair services with detected failures resulted in 9,492 total failure modes — the chart also differentiates between repaired and unrepaired washing machines. Source: Tecchio et al. (2016).

The failure category focused on bearings and shock absorbers is ranked at the top of the frequent failure modes, excluding electronics. With this failure mode it is very likely to have a case of multiple failure modes (69% of cases). Tecchio et al. (2016) provided an overview of the two main failures, highlighting how the majority of bearing-related failures are not repaired because of the high cost, while shock absorbers are repaired in almost 58% of cases (Figure 2 and Figure 3).
Even though electronics, shock absorbers and bearings were the two most recurring failure modes, they did not represent the most-repaired parts. The highest record of positive repairs related to doors, and carbon brushes. Overall, 69 % of the identified failure modes were successfully repaired (Tecchio et al., 2016).

Beside of the previous analysis performed by the authors, few statistics on frequent failures exist in literature and most of them resulted from a survey among consumers. Ardente and Mathieux (2012) have already identified potential critical parts for the lifetime of washing machines; key parts are represented by the motor, the pump, the drum and the control boards (especially if printed circuit boards are exposed to fluctuations in mains voltage supply (JRC, 2016)), but also other components may experience frequent failures, such as ball bearings, sealants, heaters, etc. Consumer organisations confirm these findings with surveys at the European level, with doors, drain pumps and spinning function representing the most occurring failures, according to final
users (Altroconsumo, 2013; OCU, 2015). Finally, the American Insurance Institute for Business Home and Safety published a multi-company and multi-region study of homeowners’ insurance claims from water damage caused by washing machines. This study revealed the criticality, in case of water damages, of the supply hose and its average age at failure, 8.7 years. Results are summarised in Table 2.

Table 2. Frequent failures for washing machine parts/functions, according to different sources. Results are expressed as a percentage (in case of surveys) or by a mark, where no detail is available.

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronics (control/engine/programs)</td>
<td>14 %</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shock absorbers &amp; bearings</td>
<td>14 %</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Door (handle/hinge/lock/seal)</td>
<td>11 %</td>
<td>X</td>
<td>X</td>
<td>12 %</td>
<td>7 %</td>
<td></td>
</tr>
<tr>
<td>Carbon brushes</td>
<td>10 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circulation/drain pumps</td>
<td>8 %</td>
<td>X</td>
<td>X</td>
<td>8 %</td>
<td>10 %</td>
<td></td>
</tr>
<tr>
<td>Foreign objects</td>
<td>6 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine, condenser &amp; tachogenerator</td>
<td>5 %</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hose (inlet/outlet)</td>
<td>5 %</td>
<td>X</td>
<td></td>
<td></td>
<td>55 %</td>
<td></td>
</tr>
<tr>
<td>Aquastop/valves</td>
<td>4 %</td>
<td></td>
<td></td>
<td></td>
<td>18 %</td>
<td></td>
</tr>
<tr>
<td>Switches</td>
<td>4 %</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drive belt/pulley</td>
<td>3 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>3 %</td>
<td></td>
<td></td>
<td></td>
<td>13 %</td>
<td></td>
</tr>
<tr>
<td>Line/pump filters</td>
<td>3 %</td>
<td>X</td>
<td></td>
<td></td>
<td>11 %</td>
<td></td>
</tr>
<tr>
<td>Heater &amp; thermostats</td>
<td>3 %</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drum &amp; tub</td>
<td>3 %</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Pressure chamber/control</td>
<td>2 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detergent drawer/hose</td>
<td>2 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cables/plugs</td>
<td>2 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spinning function</td>
<td></td>
<td></td>
<td></td>
<td>10 %</td>
<td>7 %</td>
<td></td>
</tr>
<tr>
<td>Water leakage</td>
<td></td>
<td></td>
<td>9 %</td>
<td></td>
<td>4 %</td>
<td></td>
</tr>
<tr>
<td>Corrosion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6 %</td>
</tr>
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</table>

From an engineering point of view, washing machines are subject to several types of stress, including thermal, hydraulic, extreme vibration, and mechanical stress and chemical stress to materials during use. Detergents can cause changes to thermal properties and eventually lead to component failures, if combined with thermal and mechanical stress. Thus, appropriate design for strength and durability are considered key aspects to provide reliability to the product. It is essential that machines are designed to withstand these stresses for a defined number of years of use (WRAP, 2011).
In particular, RREUSE (2012) reported a series of failures derived from low quality of materials and components. Low quality shock absorbers and ball bearings can fail if exposed to high spin speeds and therefore reduce the lifespan of washing machines; in many cases, the replacement of ball bearings requires the purchase of a complete washing unit (including the drum), whose cost is comparable to a new device. Other reported problems related to quality of materials and reason of early failures concerns the rubber of sealants and the membrane of pressure switches. Finally, heaters can stop working prematurely, especially in regions with hard water.

As a final remark, we identify that vibration and mechanical stress during use represent main sources of stress for the whole washing machine. Especially low quality shock absorbers and ball bearings can fail, and this represent a relevant issue, since the high cost of repair may induce the user to discard the appliance.

2.6 Durability tests

‘Testing durability is a very long and costly process — by the time we’d get results for a model, it probably wouldn’t be on the market anymore’ (CHOICE, 2015).

From a previous literature review, no international standards have been identified for the assessment of the durability and lifetime of the whole washing machine (Ardente et al., 2012; Tecchio et al., 2017). Consumer organisations may have laboratories equipped to carry out endurance tests on household appliances, but what they typically measure is a series of washing performance parameters (such as dirt removal, spinning performance, rinse performance, water consumption, energy consumption, ease of use and noise), because of the already mentioned constrains.

Several manufacturers of household appliances claim to perform durability tests on sample devices before putting them in the market. Tests are generally based on intensive use, in order to simulate the total number of washing cycles during lifetime. These procedures may be used to develop procedures potentially standardisable, even though the process can be still classified as expensive and time consuming.

The consumer association Altroconsumo (1) published results of a research on durability and failure modes of washing machines in 2015. A particular endurance test was performed: for each washing machine 2,500 cycles of rinse and spinning were executed, setting the spinning at the maximum speed. The used load was composed by cotton clothes (85 %) and a spongy material (15 %) and corresponded to 60 % of the rated capacity. A total of 24 washing machines (2) from Belgian, Italian, Portuguese and Spanish retailers have been tested in order to understand their resistance to overstressed conditions. The rinse and spin function was chosen as it is recognised as the main source of stress for the whole washing machine (the spinning function in particular, due to the mechanical stress) and 2,500 cycles were chosen as representative of a 10-year lifetime. The spinning function was performed at the maximum speed. A final inspection, performed through the partial disassembly of machines, highlighted that main components stressed in these conditions were the motor, the pump and the door. A total of 4 devices failed during testing and consequently they needed repairs before finishing the 2,500 cycles; repairs were not covered by warranty and were performed by professional repair operators in two occasions. After the test, the main parts subject to wear were the belt, the shock absorbers, the counterweight and the drain hose. Twelve devices experienced breaks in the door gasket and an unspecified number of machines started having problems due to the noise (Altroconsumo, 2015).

The duration of each rinse and spin cycle was not specified by Altroconsumo and it is not clear if the programme time and the programme schedule were the same for all of the washing machines. In the case the washing machines were able to recognise the load

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(1) www.altroconsumo.it
(2) 12 brands, each manufacturer represented by a top-class model and a low-cost model.
and vary the cycle duration, this may result in different stresses during the test, and the consequent low reliability in comparing the results.

According to JRC (2016) report, another consumer organisation, the German Stiftung Warentest, developed and carried out durability tests for washing machines on an annual basis since 20 years. For each model on test three washing machines of the same model are run for a total of 1,840 cycles in different programs with practice-oriented load and usual heavy duty detergents, corresponding to a lifetime of around 10 years with 3.5 wash cycles per week.

Tests at the component level are probably easier and faster. A ball bearing manufacturer, for instance, used endurance tests for a new one-way clutch with built-in ball bearing which was developed and adopted for fully automatic washing machine. Results and detail of the research were published in 2000 in the company engineering journal. The rotating endurance test was run for over 3,000 hours at 1,000 rpm (equivalent to 36,000 loadings of approximately 5 minutes of spin-drying). Cycle tests in actual washing machines have been performed too and consisted of 2,600 hours of continuous cycle operation (equivalent to 5,200 washing cycles) (Ishiyama and Iga, 2000). These tests lasted respectively 125 and 108 days, in the condition of continuity. Even if not directly applied on the washing machine as a whole, these experiments highlighted again the need for an accelerated procedure able to reduce the time required to obtain reliable results. However, cross-sectorial procedures, intended for such purposes, are not available, as often developed for a particular part or function of the device.

2.7 Accelerated life testing

Because of the existing competition in the household appliances market, washing manufacturers try to develop devices 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. R & D achieved a very high level of reliability; as a consequence testing procedures of products have become very lengthy, since devices are not prone to fail. Traditional reliability performance tests seem to be no longer efficient enough and solutions are needed to accelerate them while not losing significance and correspondence with user experience (Tucci et al., 2014).

Engineers in the manufacturing industries have used accelerated test (AT) experiments for many years; the purpose of these experiments is to acquire reliability information quickly. However, estimating the failure-time distribution or long-term performance of components of high-reliability products remains particularly difficult (Escobar and Meeker, 2007).

There are different methods of accelerating a reliability test, in particular by increasing the use rate of the product, and/or by increasing the level of stress under which test units operate. Accelerated Life Tests (ALTs) with increased use rate do attempt to simulate actual use and they can be an effective method of acceleration for some products; use-rate acceleration may be appropriate for products such as electrical motors, relays and switches, and certain home appliances. Also, it is common practice to increase the cycling rate (or frequency) in fatigue testing; the manner in which the use rate is increased may depend on the product. Anyway, the relationship between accelerating variables and the actual failure mechanism is usually extremely complicated. Thus other environmental factors should be controlled to mimic actual use environments (Escobar and Meeker, 2007).

Accelerated life tests were used by Tucci et al. (2014) as an integrated method for washing machine design. In detail, they used ALTs to test the behaviour of a new mechanical oscillating system for washing machines. The independent variable chosen for the reliability model was the number of standard washing cycles, with a censoring time

(19) https://www.test.de/
fixed at 500 cycles, corresponding to an average of 2 years of use (250 cycles per year). The test was run with a total number of 24 washing machines, each equipped with a load imbalance placed inside the drum, representing the only over-stressing parameter (since it intensifies the drum deformation). Each test cycle consisted of two phases, with 90 minutes of low speed cycles and 20 minutes of spin cycle. For each test, every 50 cycles, an actual washing cycle was performed, in order to control how the washing performance evolves during the test (Tucci et al., 2014).

In another study developed by the same Institute, De Carlo et al. (2013) used the same strategy to estimate the reliability of washing machine parts through Accelerated Degradation Tests (ADTs). ADTs focus on so-called soft failures, damages caused by the degradation process that will eventually lead to failure and malfunction, while during ALT execution researchers look for traditional failures that permanently affect the functionality of the product. The test procedure was the same used by Tucci et al. (2014), a uniform over-stress during the entire duration of the experiment, in order to make some inferences about the performance in normal conditions of use. Again, 24 machines were tested with 500 spinning cycles of 30 min each (reducing therefore the duration of each washing cycle from 1.5 hours to 30 min). In this case the spinning cycle is relevant since the target of the study is again to observe the drum deformation. The maximum imbalance permitted in the drum was a rubber plate with a load of 400 g, then other three levels of stress were applied (650, 800 and 950 g) (De Carlo et al., 2013).

Regarding ATs and washing machine parts, Park et al. (2006) conducted a research aimed to develop an accelerated test as to demonstrate a reliability goal of the pump assembly, within an affordable amount of time and in an economic way. In this case study, the authors used a step-stress test in order to verify the operating limit of the pump assembly in certain environmental stresses. Moreover, an accelerated test was conducted also to measure the annual failure rate and the mean time to failures (MTTF) of the component. High temperature and voltage were used as stress factors to accelerate the failure of the assembly. The value of the acceleration factor \((AF)\) was estimated to be 16 at the high stress condition compared to the use condition. It also showed that all of the tested units survived for 500 hours at the overstressed condition \((40 \, ^{\circ}C \, and \, 264 \, V, \, instead \, of \, 220 \, V, \, as \, it \, is \, well \, known \, that \, the \, failure \, of \, a \, pump \, motor \, assembly \, is \, stimulated \, by \, temperature, \, voltage \, and \, solid \, particles \, suspended \, in \, water)\) (Park et al., 2006). The authors used 255 hours as representative of the annual operating time of the assembly.

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 investigated all of the possible failure modes (Tucci et al., 2014). Park et al. (2006) concluded their work by asking how reliability of a product can be improved. First of all, it is necessary to identify the failure modes through various time-consuming tests (this conclusion is in line with Tucci et al. (2014)). Next, failures should be analysed and failure mechanism determined. Moreover, De Carlo et al. (2013) stated that a Finite Element Method (FEM) analysis was useful (almost necessary) to prepare suitable overstressed conditions.

These conclusions are relevant in the case of new products (or new components) development, before and after they are launched to the market. However, they must be taken into consideration also in the case of new endurance test/durability procedures development for washing machine.

A load imbalance may represent the easiest way to introduce a mechanical over-stress during the test. However, the drum imbalance is normally regulated by the electronic control unit during the actual use, which stops the washing cycles if it exceeds a threshold value decided by the manufacturer. To overcome this issue, Tucci et al. (2014) first measured what was the maximum allowable imbalance (i.e. the mass of the load imbalance, placed inside the drum of the washing machine) tolerated by the machine (11) Lifetime distribution at a use condition over lifetime distribution at an accelerated test condition.
(i.e. the control unit allows the spinning function). Then they bypassed the control unit of the device with external controls and used the maximum allowable imbalance has a baseline, adding then three levels of overstress (165 %, 200 % and 237 % of the maximum allowable imbalance).

2.8 International standards

A popular opinion about endurance tests for washing machines arose from the questionnaire filled by stakeholders, during the research conducted by JRC (2016): existing safety standards cannot be directly converted into durability standards, since the formers are used by companies to test the appliance safety under extreme conditions to ensure consumers’ safety during functioning of the appliance, also in case of incident.

For these reasons, safety standards demand requirements which are extremely stringent, as it was also reported from our interviews with stakeholders. Conditions and thresholds used for safety do not reflect the actual usage and the actual product lifetime. Anyways, these standards might represent a good starting point for starting a standardisation process focused on durability of household appliances. Furthermore, overstressed conditions are typical of accelerated life tests too and this may represent another step towards the durability cause. In this context, safety standards and testing conditions should be checked in order to make sure they are applicable for an alternative purpose. Furthermore, the pass/fail criteria may need to be redefined (JRC, 2016).

As already stated, there exist only few standards originally designed for durability purposes and besides tests for durability of components, no widely established test standards for the durability of whole products with regard to their functional quality exist. In this section, the following possibly standards are introduced and endurance tests are detailed:

- IEC 60068-1:2013 — Environmental testing. Part 1: General and guidance;
- IEC 60456:2010 — Clothes washing machines for household use — Methods for measuring the performance;
- IEC 60335-1:2010 — Household and similar electrical appliances — Safety. Part 1: General requirements;

Other relevant documents (standards, green labelling requirement, NGO procedures) have been explored as well to better understand if other product parts/functions can be tested. These documents are considered pertinent to this research as they mention procedures, tests or simply requirements which can be possibly adapted to the washing machine case study:

- IEC 61747-10-1:2013 — Liquid crystal display devices — Part 10-1: Environmental, endurance and mechanical test methods — Mechanical;
- IEC 61747-10-2:2014 Liquid crystal display devices — Part 10-2: Environmental, endurance and mechanical test methods — Environmental and endurance;
ISO 6804:2009 — Rubber and plastics inlet hoses and hose assemblies for washing-machines and dishwashers — Specification;

2.8.1 IEC 60068-1:2013

The standard is primarily intended for electrotechnical products and includes a series of methods for environmental testing along with their appropriate severities. Tests are designed to assess the ability of specimens to perform under expected conditions of transportation, storage and operational use; various atmospheric conditions for measurements are prescribed as well (IEC 60068-1, 2013). The test procedures described in this IEC standard are used as reference in the draft EU Ecolabel criteria for ‘Personal, notebook and tablet computers’ with regard to durability testing of portable computers (JRC, 2016). IEC 60068-1 deals with generalities, while IEC 60068-2 is divided into different specific classes, each of them characterised by specific tests:

- A: cold
- B: dry heat
- C: damp heat (steady state)
- D: damp heat (cyclic)
- E: impact (shock)
- F: vibration
- G: acceleration (steady state)
- J: mould growth
- K: corrosive atmosphere
- L: dust and sand
- M: air pressure
- N: change of temperature
- Q: sealing
- R: water (rain, dripping water)
- S: radiation
- T: soldering
- U: robustness of terminations

2.8.2 IEC 60456:2010

IEC 60456:2010 is devoted to the performance measurements and assessment of washing machines for household use. It specifies methods for measuring the performance of clothes washing machines, with or without heating devices utilising cold and/or hot water supply. It also deals with washing machines which specify the use of no detergent for normal use, appliances for water extraction by centrifugal force (spin extractors) and is applicable to appliances for both washing and drying textiles (washer-dryers), with respect to their washing related functions (IEC 60456, 2010). Even though durability as a performance is not mentioned, the standard informs about test conditions, testing preparation procedures, performance measurements and performance assessments (Table 3).
Table 3. Test conditions, preparation procedures, performance measurements and assessment according to IEC 60456:2010

| Test conditions | Ambient conditions (electricity supply voltage and frequency, water hardness, temperature and pressure, ambient temperature and humidity); Test materials (cotton base load, synthetics/blends base load, polyester base load for wool programme, wool specimens, detergents); Equipment (reference machine, spectrophotometer, equipment for conditioning the base load, standard extractor, iron, titration equipment); Instrumentation and accuracy (instruments, minimum resolution, minimum accuracy). |
| Testing preparation procedures | Preparation after installation, test series, test run; Detergent dose and placement; Determination of test load mass. Pre-treatment and normalisation. |
| Performance measurements | Washing performance (assessment of test strips); Water extraction performance (washing machines and spin extractors); Rinsing performance (spin extraction and sampling, alkalinity measurements, titration); Energy and water consumption (procedure). |
| Performance assessment | Evaluation of washing performance; Evaluation of water extraction performance; Evaluation of rinsing performance; Evaluation of energy consumption; Evaluation of water consumption; Shrinkage during the wool washing programme. |

This standard specifies that each machine is subject to a series of 5 test-cycles to ensure accurate and repeatable results. Two sources of uncertainty of measured results have to be taken into consideration (statistical uncertainty and the uncertainty of the measuring method itself, with 95 % confidence interval). Finally, Annex S presents the data to be reported for the reference machine and the test washing machine. Durability, endurance, lifetime, service life, repairs are not mentioned.

The standard can be used in the draft procedure (Chapter 5) to define environment and boundary conditions (air pressure, temperature, test materials, etc.) and to measure and assess principal washing machine parameters and to observe how they evolve over time. Parameters like water extraction (for Spin-drying efficiency class calculation) and rinsing performance can be of particular relevance.
2.8.3 IEC 60335-1:2010

Several standards related to product safety exist. These standards indirectly address quality and/or durability of products and components, such as IEC 60335 series. IEC 60335-1, in particular, deals with the safety of electrical appliances for household and similar purposes, with rated voltage being not more than 250 V for single-phase appliances and 480 V for other appliances, defining general safety requirements (IEC 60335-1, 2010).

A general safety requirement (which indirectly addresses durability) is specified in the Annex H, while other specific requirements are detailed in parts 2. Annex H regards switches and specifies conditions to test the appliance. Before being tested, switches are operated 20 times without load. Then, the endurance test consists of 10,000 cycles of actuation, unless otherwise specified (100 cycles if without interlock).

2.8.4 IEC 60335-2-7:2008

IEC 60335-2-7 is devoted to washing machines and deals with the safety of electric devices for household and similar use, that are intended for washing clothes and textiles, with rated voltage being not more than 250 V for single-phase appliances and 480 V for other appliances. This standard is also applicable to electric washing machines for household and similar use employing an electrolyte instead of detergent (IEC 60335-2-7, 2012). In particular, Section 18 is devoted to Endurance and two functions of the washing machines have to undergo endurance tests because of particular safety requirements.

The lid or door is subjected to 10000 cycles of opening and closing (45° for lids, 90° for doors, speed of opening about 1.5 m/s; force 50-200 N for opening, closing force is 2 times this requirement for lids and 5 times for doors). For the first 6,000 cycles, the appliance is supplied at rated voltage and operated so that the interlock mechanism is energised and de-energised each cycle. For the last 4,000 cycles, the appliance is not connected to the electric power supply. For appliances having a drying function, the total number of cycles is increased to 13,000 (9,000+4,000 cycles).

Furthermore, the braking mechanism of appliances having a lid that can be opened during the water extraction is subject to tests. The procedure requires the appliance to be supplied at 1.06 times rated voltage and operated under normal operation until the motor reaches the highest speed. The lid is then fully opened. The test is repeated after the drum has been at rest for a period long enough to ensure that the appliance does not attain an excessive temperature. The test is repeated 1,000 times, with the textile materials re-saturated with water at least every 250 cycles.

Nevertheless, appliances shall demonstrate stability to mechanical hazards and shall not be adversely affected by an unbalanced load. The test proposed by this standard consists of fixing an unbalanced load with a mass of 0.2 kg or 10 % of the rated capacity of the washing machine (whichever is greater) inside the drum, and then operating a water extraction cycle for a total of four cycles. The appliance shall not overturn and the drum shall not hit other parts except the enclosure. After the test, the appliance shall be fit for further reuse.

2.8.5 Other relevant documents

IEC 61747-10-1:2013

IEC 61747-10-1 lists test methods applicable to liquid crystal display (LCD) devices. This may be relevant as several large white goods (including washing machines) are using liquid crystal displays for the control panel, such as LCD touchscreens, for instance. The standard takes into account the mechanical robustness test methods as outlined in IEC
Specific tests regard not only robustness, but also vibration resistance, shock tests, acceleration tests and bond strength test.

**IEC 61747-10-2:2014**

More detail is added in IEC 61747-10 part 2. Several test methods applicable to liquid crystal display devices exist. According to the standard, the choice of the appropriate tests depends on the type of devices. In this document, the following test methods for liquid crystal display devices are introduced:

- Rapid change of temperature: two-chamber method;
- Specified change rate of temperature: one-chamber method;
- Storage (at high temperature);
- Storage (at low temperature);
- Low air pressure;
- Damp heat, steady state;
- Damp heat, cyclic;
- Composite temperature/humidity cyclic test;
- Light exposure;
- Electrostatic discharge (ESD) testing.

The standard recalls that regarding the change of temperature, tests ‘Na’ and ‘Nb’, specified in IEC 60068-2-14, are applicable. Temperature vary from −50-0 °C (low test temperature) to 30-100 °C (high test temperature). Exposure times and number of cycles are specified in the document. Concerning Damp heat tests, test ‘Cab’, specified in IEC 60068-2-78, is applicable for the steady state case (temperature 40-85 °C, humidity 85-93 %) and test ‘Db’, specified in IEC 60068-2-30, for the cyclic case (40 °C and 10 cycles or 60 °C and 5 cycles).

Light exposure test is divided into two main procedures: simulated solar radiation at ground level (test ‘Sa’, IEC 60068-2-5) and simulated indoor daylight through window glass (ISO 18909:2006). Finally, ‘ESD’ test shall be in accordance with IEC 60747-1.

**ONR 192102:2014-10-01**

The Austrian document ONR 192102 is a list of rules for voluntary excellence labelling of durable, repair-friendly designed electrical and electronic appliances, including washing machines. Manufacturers of electrical and electronic equipment, who intend to mark their products with a label for repair-friendly designed appliances, have to test their products according to ONR 192102 requirements verifying compliance with a test report. The standard consists of a system with three levels of achievement (good, very good, excellent) based mostly upon reparability criteria, to ensure products are not discarded sooner than is necessary as the result of a fault or inability to repair a fault (JRC, 2016; ONR 192102, 2014).

Even though no specific testing procedures and techniques are detailed, there are two mandatory requirements related to the achievable service life of a washing machine:

- Minimum achievable service life: 10 years;
- Minimum availability of spare parts: 10 years after the last production batch.

Increased product service life (over 10 years) and increased availability of spare parts provide additional points.

**PAS 141:2011**

PAS 141 regards waste electrical and electronic equipment (WEEE). It is provided by the British Standards Institution to set out requirements to manage the process of preparing used electrical and electronic equipment, but also WEEE for reuse (PAS 141, 2011). The standard provides practical advice and also covers the preparation process for the reuse of electronic equipment and components. It applies to all organisations that deal with the preparation of equipment for reuse, so it can be indirectly connected to the durability
aspect, since it is a material efficiency measure that aims to extend the lifetime of the device.

A guideline protocol has been developed by WRAP (12). The protocol describes a series of minimum tests that should be performed on washing machines, washer/dryers and tumble dryers in order that the product can be considered functional and fit for re-use. However, the procedures are mainly based on visual checks (JRC, 2016).

ISO 6804:2009

ISO 6804 title provides specification for rubber and plastics inlet hoses and hose assemblies for washing-machines and dishwashers. In particular, there are requirements for three types of rubber or plastics inlet hoses and hose assemblies for washing-machines and dishwashers connected to the domestic water supply at a pressure not exceeding 1 MPa. It is applicable to the following types of hose:

- Type 1: rubber hoses for unheated water supply (maximum temperature 70 °C)
- Type 2: rubber hoses for heated water supply (maximum temperature 90 °C)
- Type 3: plastics hoses for unheated water supply (maximum temperature 60 °C)

Performance requirements for finished hoses are assessed through a series of tests, for instance bending tests, flexing tests, resistance to kinking, resistance to hydrostatic pressure after ageing, resistance to ozone or weathering, resistance to hydraulic-pressure impulse test, etc. (JRC, 2016).

(12) http://www.wrap.org.uk/
3 Experts consultation

Experts from universities, certification institutes, consumer organisations and industry have been contacted and interviewed, in order to gather information about durability tests for washing machines. The main reason for this expert consultation phase was the need to understand whether accelerated tests can be suitable for testing durability of washing machines, considering the broad variety of options (materials and technology) currently available on the market. Several opinions were collected and summarised in the next sections.

3.1 Experts from the Academia

Scientists from European research institutes were contacted in order to gather information about their experience in terms of endurance testing and accelerated life testing.

Expert Prof. Rainer Stamminger was contacted before his involvement in the testing phase. Specific questions about the feasibility of accelerated test were posed, to which he replied with a preliminary feedback. According to the interview, ALTs can be obtained through mechanical stresses introduced by a higher imbalance of the load in the drum and/or by a higher spin speed, but this was judged not representative of the actual life, therefore inferences between the artificially stressed condition and the actual stress condition may not be reliable. An issue may be represented by the different procedures included in the control procedure software by washing machine manufacturers; for example, the artificial load placed inside the drum can be recognised by the device, which reacts in different ways according to the software settings. For instance, if the unbalance exceeds a certain threshold defined by the manufacturer for each device, there are three main options:

- The washing machine recognises the artificial load, but performs the spin cycle anyway;
- The washing machine recognises the artificial load, tries to correct the unbalance into the drum, limiting the overstress as much as possible, then performs the spin cycle;
- The washing machine recognises the artificial load and does not perform the spin cycle or it alters the way of spinning (shorter time and/or reduced spin speed).

Regarding the third option (the washing machine recognises the artificial load and does not perform the spin cycle), even if the machine is forced to spin with the unbalance, this would create a situation which the machine was not designed for and that would not occur during the real operations. This aspect could represent a barrier to accelerated tests, as these would be not replicate a real life situation.

On the other hand, conventional lifetime tests do not require overstressed conditions, but they can be very long lasting procedures. Typically, at least three devices of the same model are tested under real-life working conditions, 24 hours per days, 7 days per week. The test duration often exceeds 8-9 months and the cost for a test can be very high.

Other scientists were contacted and consulted on the topic, in particular experts in the field of mechanical engineering and industrial engineering. Their expertise comprehends finite element method (FEM) analysis and accelerated life testing, which they applied to a washing machine case study.

In detail, they conducted a research on the reliability of a new component for washing machines, in support of a domestic appliance manufacturer. The research was initially focused on early failures of washing machines (within the first weeks/months after delivery), in order to understand key parts and main issues for future designs, to better organise the life cycle assistance and to evaluate the volume of spare components for
replacement. Subsequently, they performed ALTs and ADTs to a new drum design, aiming at the reliability evaluation of the new component.

Based on their experience, they underlined the fact that different washing machines technologies exist, as well as different materials used for components. Thus, establishing a common test procedure may arguable to stakeholders. In one hand, focusing on the mechanical stress is correct because it represents the main reason of failure for the whole washing machine, but other failure modes are not included or can be independent from mechanical shocks, such as corrosion for instance.

In conclusion, the second group of research discussed the applicability of a common ALT procedure. The significance of a generic test is not excluded, especially if the test aims at verify the durability of a specific part/function (e.g. the spinning function), but ALTs and ADTs are more conveniently used as tools for specific product (e.g. one washing machine type), having full detail about the design (e.g. FEM analysis).

3.2 Experts from consumer organisations

Consumer organisations investigate, test and compare goods and services, in order to provide unbiased advice to consumers and to identify possible consumer issues.

A European consumer organisation was contacted in order to understand their experience in terms of washing machine durability tests. The organisation has been testing washing machines for 30 years, proving relevant experience on the field. Technicians were asked to express their opinion regarding endurance tests and, to their knowledge, it seems there is no cheap, fast and reliable solution. Having poor experience in terms of accelerated tests, they did not add detail to the feedback given by the Academia. They highlighted the fact that different manufacturers claim their washing machine lifetime expectancy be equal to 10-20 years, without specifying the test procedures. Because of this, they presume the use of accelerated tests by manufacturers, even though ALTs are not disclosed and probably parameters and test conditions are developed specifically for each washing machine.

Also in this case, lifetime tests performed by the consumer organisation require 24 hours per days, 7 days per week. The test duration often exceeds 8-9 months, using more than 1,800 washing cycles with standard clothes. Washing cycles do not include an unbalance or an artificial load, since overstress conditions are not considered in performance standards.

Example of endurance tests performed by consumer organisations were detailed in section 2.7.

3.3 Experts from testing and certification institutes

Certification institutes are often coupled with test laboratories. Test objectives are to check and verify product features in accordance with applicable national and international testing procedures and standards.

During the investigation on extended assistance offered by manufacturers (summarised in section 2.4), it was possible to know that some manufacturers offer extended warranty for specific washing machine parts. Two manufacturers, in particular, tested the inverter motor drive and got a certificate claiming that the component underwent a lifetime test and is manufactured to reach a minimum lifetime of 20 years.

The testing and certification institute was contacted in order to understand which endurance test has been adopted to verify the device, with particular interest for the use of ALTs. However, only conventional procedures were used to test inverters. The reference washing machine annual usage was set to 220 cycles/year (European Union,
2010a) and, accordingly, 2,200 full cycles were used for a 10-years operational lifetime and 4,400 full cycles for 20 years, for an overall duration of respectively 7-8 and 15-16 months. The institute is often asked to perform safety tests and energy efficiency tests on this kind of household appliance, therefore EN 60335-1 and EN 60335-2-7 are the two main international standards used as references. Safety requirements, according to their technicians’ opinion, can be taken into account also for lifetime procedures, as durability is also a measure of how a device is able to work without possible accidents that may represent a risk for the consumer.

Highlights about endurance tests:

- Endurance tests were used to test a specific washing machine part, not the overall device;
- Three products were tested in parallel (the so-called double 3 method);
- A washing machine is typically subject to other sources of stress (thermal, hydraulic, vibrations, etc.), other than mechanical stress; therefore the artificial load placed inside the drum may not be representative of the other sources.

3.4 Experts from industry

Experts from industry participated in the investigation on existing endurance tests for washing machines, providing comments and procedures used to verify minimum endurance of products.

According to the experts, accelerated durability tests have been specifically developed for R & D purposes and are currently used to test washing machine endurance. As mechanical stress represents the main reason of washing machine damages, the test is characterised by a stressed condition during the spinning function.

Conventional tests with stressed condition consists of placing an artificial load (e.g. a rubber plate) inside the drum. Test cycles are performed with 10-20 minutes of spinning and 2 minutes of spinning at the maximum speed. Test cycles are repeated 500 times. A total of 10 washing programs (without artificial load, but with standard clothes) are run at certain intervals, in order to check the overall washing machine performance and to verify possible degradation.

Tests are semi-automatic and this can significantly reduce the duration of the test. Experts stated that other washing machines may react differently on unbalances during spinning and this may limit the comparability of such test, when other brands are tested.

Other main comments are listed hereafter:

- Rinse+spinning cycles may be used in lieu of spin cycles. In this case there is not only the mechanical stress, but also hydraulic stress and the involvement of other degradable parts such as the drain system and the pump;
- Sponge materials can be used as an artificial load, especially in the case of Rinse+spinning cycle;
- Manufacturers may implement a control system able to avoid the spin cycle in case of excessive stress; however, the maximum spin velocity represents the shortest cycle and testing time to verify the mechanical robustness of a device;
- Laboratory durability tests (both conventional and accelerated) do not represent the actual life anyway, but aim at verifying particular endurance characteristics, predefined by the manufacturer.

It is finally recommended to develop endurance testing in order to assess and improve the design of new products and, consequentially, avoid or reduce product’s failures.
3.5 Experts from repair service centres

With the intention of gathering information about frequent and early washing machine failures, a repair centre was involved in the research. The discussion with the stakeholder focused on two key subjects:

- Reparability, as a general concept;
- Washing machine failure modes (an extensive analysis was proposed in Tecchio et al. (2016)).

Being reparability the core business of a repair centre, reparability of products is considered a fundamental aspect for circular economy. Reparability can be also seen as a key driver for economy, as the possibility to create new jobs in Europe is significant. Main issues faced by independent repair services are the limited access to devices documentation and the impossibility to access the software.

A final comment about the product’s lifetime was given. Refurbished and repaired washing machines have the possibility to extend the service life of the device subject to a failure; it has been estimated that washing machine lifetime, with regular maintenance and repairs can range 10-20 years, with some outliers reaching 25-30 years. Therefore, 10 years may represent the minimum lifetime expectancy for brand-new washing machines.

3.6 Section summary

At the moment it seems there is no solution for a short, cheap and reliable lifetime test, suitable for the whole category of washing machines. Especially accelerated tests seem to be more suitable for a washing machine part rather than the overall product.

Major research demands for the development of new endurance tests for washing machines are listed as follows:

- Tests should be shorter and less expensive than conventional tests (that require 8-15 months,
- Tests should be repeatable;
- Tests should provide relevant, significant and reliable results.
4 Dynamics of a horizontal axis washing machine

Horizontal axis washing machines can be seen physically as a vibrating system where the tub (including the drum) is fixed with two (sometimes up to four) springs on the top of the housing (Figure 4). As such, it may be described in a simplified way by the formulas of a free oscillation. This oscillator is energised by the movement of the drum, which is rotating with an angular velocity $\omega$. Considering $r$ being the radius of the drum and $g$ the gravitation acceleration, any kind of laundry will stick to the inner wall of the drum when the following condition is verified:

$$\omega > \sqrt{\frac{g}{r}}$$

This will be the case for angular velocities $\omega$ of about 60-70 rpm for the usual dimensions of household washing machines. As the laundry may not distribute evenly on the wall of the drum, some unbalancing may occur. For simplification purposes, it is assumed that the unbalance can be mimicked by just one mass. The force of the movement of the oscillator now depends on the mass $m_u$ of the unbalance which is rotating and will cause the total drum to displace. Such kind of forced oscillation is well-known due to its resonance behaviour. At the resonance frequency, defined with the following formula:

$$\omega_r = \sqrt{\frac{K}{m}}$$

Where $K$ is the spring constant and $m$ is the total mass of tub and drum, this would lead to an infinite amplitude. This frequency is typically between 200-400 rpm for horizontal axis washing machine designs, thus, between the frequency for washing (about 50 rpm) and spinning (1,000 rpm and more). Additional dampers are installed (shock absorbers in Figure 4) to introduce a damping of the movement of the tub to limit the amplitude to that which can be afforded by the space between the tub and housing of the machine.

Figure 4. Two-dimensional sketch of a washing drum as an oscillating system without (left) and with (right) unbalanced mass (Boyraz and Gündüz, 2013).
This kind of system is well-known as forced oscillation with damping and described in the one dimensional case by a simple differential equation:

\[ m \frac{d^2x}{dt^2} = F_0 \sin \omega t - c \frac{dx}{dt} - Kx \]

Here, \( m \) is the accelerated mass, \( F_0 \) the oscillating force, \( c \) the damping factor and \( K \) the spring constant.

At frequencies much below the resonance, the solutions of this equation show (Figure 5) that the amplitude \( A \) (equal to the ratio of the accelerating force \( F_0 \) divided by the spring constant \( K \) of the movement) is at 1.0. The phase \( \phi \) between the orientation of the unbalance mass \( m_u \) and the movement of the tub/drum is close to 0, which means the displacement and the force are in phase. When the frequency of the force applied is much greater than the resonance frequency, the amplitude decreases inversely as the square of the frequency of the applied force increases. It is also proportional to the magnitude of the force. At very high frequencies, the displacement and force are out of phase by 180°, meaning the oscillation of the tub has the opposite direction to the force originating from the unbalanced mass. In between, when the frequency of the applied force is close to the natural resonance frequency of the oscillator, the amplitude of the movement depends very much on the quality function \( Q \), which comprises especially the damping characteristics. At this frequency, there is also the point where the phase changes from being in phase with the agitating force to being in the opposite direction.

![Figure 5. Frequency dependence of amplitude (a) and phase (b) for various values of Q](Srinivasan, 2009)

Such an oscillator driven by an external force also absorbs energy. The energy absorbed by the oscillator is equal to the energy dissipated due to damping. The absorbed energy equals viscous force multiplied by velocity.

### 4.1 Damping of the vibrating system

The vibratory force generated often leads to a loosening of fasteners, excessive wear of bearings, formation of cracks and structural as well as mechanical failures. Electronic
malfunctioning through fracture of solder joints and abrasion of insulation around conducting wires can also occur. There are also many practical situations in which a delicate machinery has to be isolated from vibratory impacts to which it is subjected. Vibration isolation techniques are applied to reduce the undesirable effects of vibration. The design of a vibration isolation system is based on the theory of forced vibration. The vibration isolation system is said to be active or passive depending on whether the external power is required for the isolator to perform its function or not. A passive isolator consists of a resilient member (stiffener or spring) and an energy dissipater (dampener). Examples of passive isolators include metal springs, cork, felt, pneumatic springs and elastomer (rubber) springs. An active isolator is composed of a servomechanism with a sensor, signal processor and an actuator. A lot of scientific work is studying the system kinematics (Bae et al., 2002; Chen et al., 2015; Conrad and Soedel, 1995; Nygårds and Berbyuk, 2012; Türkay et al., 1995) and probably even more work is done in industry to find the ideal compromise between the unbalance occurring during spinning of the load, spring dimensioning, damper characteristics and the gravimetric weight of the whole oscillating system. The lower the maximum unbalanced mass to be expected, the less the gravity mass of the whole 'swinging' system needs to be or the lower the space between tub and housing must be.

But, also the lifetime of relevant parts of a washing machine are affected heavily by the unbalanced mass, as this is induced as vibration to all parts, especially to those on the oscillation group. This explains why it is so important to know and to restrict the unbalanced mass strictly in relation to the design of the structure and components used to avoid lifetime failures.

Figure 6. Frequency dependence of mean power absorbed by an oscillator for various values of Q (Srinivasan, 2009)
4.2 Unbalance measurement and strategies to influence the unbalance

A load imbalance may represent the easiest way to introduce a mechanical stressed condition during the test. However, the drum imbalance is normally regulated by the electronic control unit (or control procedure) during the actual use, which stops the washing cycles if it exceeds a threshold value decided by the manufacturer. Typically, a control procedure for unbalanced conditions influences the distribution of the textile load before the beginning of the spinning function. When an equal distribution is achieved, the unbalanced load stress is lower and therefore higher spin speeds may be achieved. If the load cannot be equally distributed, as it was with the fixed unbalanced load adopted in these tests, the control procedure may either limit the mechanical stress to the structure by reducing the spinning profile (especially by reducing the highest spin speed and its duration) or may decide to try to redistribute the textile load.

Measuring the actual unbalanced mass occurring during a spinning cycle is a prerequisite for being able to control or reduce it. The most straightforward way of measuring the unbalanced mass is to measure the displacement of the tub during low spinning (but above the critical speed needed to fix all textile articles to the drum surface). However, this requires an accurate sensor and, thus, additional costs. Therefore, the way most used is to utilise information which is already available: the speed of the motor driving the drum. This speed is measured, anyhow, as it is used to control the speed of the drum. Depending on the total size of the unbalance, the spin speed measured will vary: when the unbalanced mass is lifted, the speed of the motor will be lower; when the unbalanced mass is reducing, it will additionally accelerate the movement and, thus, the motor speed. Thus, the variation of the motor speed compared to the intentional speed provides a good measure for the size of the unbalanced mass. This is, however, not an absolute measure of the mass, but a relative measure which needs to be calibrated to the motor control characteristics. Additionally, it depends on the total mass of the drum including the textile load, as this gives the inertia which is influenced by the unbalance. Nevertheless, it is a simple and cost-effective way to assess the unbalanced mass. It is used in combination with special speed profiles which intend to distribute the textile load on the inner drum surface as equally as possible. These profiles ramp up the speed of rotation slowly between about 50 rpm, where the textiles are still falling down, up to about 130 rpm where all textiles are fixed to the inner drum surface by the centrifugal forces (Figure 7). At this point, the measurement of the unbalance may already indicate that it is too high to continue the spinning to spin speeds above the resonance frequency without the amplitudes being too high for the tub. As a consequence, the spinning would be stopped and the spin speed reduced to below 50 rpm to allow the textile to tumble again. Then, a next ramp-up would try to achieve a better distribution of the textiles on the inner drum surface and measure the unbalance achieved again. This process may go on for several times. If an unbalance is achieved which does not exceed the acceptance limit, a second phase of spinning may occur at a somewhat lower spin speed, for example, at 90 rpm, and another measurement of the unbalance may be carried out. This second measurement will give a more precise value of the unbalance, as some of the water bound in the textiles will have already been extracted. Again, a decision will be taken at the end of this phase whether or not the spinning to high spin speed is continued. Many variations of this ramp-up profile are implemented in almost all washing machines from different manufacturers, but the principles are generally very similar.
Figure 7. Spin speed profile for measuring the unbalance twice and taking decisions after each measurement (own figure)

When the decision is taken to go to a high spin speed, an attempt is made to pass the region of the resonance frequency as quickly as possible (the problem is that when the acceleration is too fast, too much water will be extracted in too short a time to pump it away) (Figure 8).

Figure 8. Typical spinning profile with a first water extraction phase followed by a third unbalance measurement and decision about the actual spinning profile (own figure)
Water is extracted in a first water extraction phase at about 800 rpm and, thus, the inertial mass of the drum will be reduced. This will allow a third unbalance measurement at a low spin speed to be made with higher accuracy. Following this measurement, a decision will be taken on the final spin speed profile used to get the best possible water extraction of the textiles, also considering the mechanical stress, especially to the bearings of the drum.

It is important to remark that the physical model of the horizontal axis washing machines describes a real and complex phenomenon, where several oscillation modes occur. As such, several resonance frequencies may exist and the washing machine may suffer from different mechanical stresses when spinning, also due to non-constant mass of (wet) load and point of gravity. During the spinning at low spin speed (e.g. below 600 rpm), the load is partially rearranged, while at higher spin speed (e.g. above 600 rpm), the mass is decreasing because the water is extracted, while the load is pressed on the inner part of the drum due to the increasing centrifugal forces. This effect results in variable unbalances that cause relevant stresses to machine components.

### 4.3 Influence on lifetime of bearing

The nominal lifetime $L$ of ball bearings is given by following formula:

\[
L = \frac{16666}{n} \cdot \left(\frac{C}{P}\right)^p
\]

Where:
- $C$ is the basic dynamic load rating [N];
- $P$ is the dynamic equivalent bearing load [N];
- $n$ is the rotation speed in [rpm];
- $p$ is the lifetime exponent (for ball bearing $p = 3$).

As $P$ is proportional to the centrifugal force $m \cdot \omega^2 \cdot r$ and $\omega$ proportional to $n$, the expected lifetime $L$ is inversely proportional to the spinning speed to the power of five and inversely proportional to the unbalanced mass to the power of three. This explains why it is so important to know and to restrict the unbalanced mass well in relation to the design of the ball bearings to avoid lifetime failures. Another way to cope with the implication of the unbalance of the textile load during spinning are ways to balance the unbalance by another weight directly opposite to the unbalanced mass. This is relatively easy, as any flexible mass above the resonance frequency will automatically take a position opposite to the unbalanced mass due to the phase difference of close to 180° between the mass and the deflection of the tub. These dynamic balancers can be separated into two distinct groups: liquid-filled systems and mechanical systems (Chen et al., 2015; Conrad and Soedel, 1995; Son et al., 2012). A hydraulic balancer belongs to the liquid-filled systems. Obstacles are often made inside the hydraulic balancer to control the liquid’s movement. Alternative designs fill in liquid (water) actively according to the amount of unbalance needed (patent DE 19616985) in ‘hollow spaces’ inside the drum. A ring, pendulum or ball balancer belong to the mechanical systems. The mechanical systems have an advantage over the liquid-filled systems in that they are capable of precise balancing. Both types of system require additional active or passive reacting elements which are costly and, therefore, not found in many washing machines on the market.
5 Durability test: procedure proposal

5.1 Introduction

According to the information collected, a durability test based on a series of spinning cycles is considered by the authors as relevant, as the mechanical stress which a washing machine is subjected to during spinning represents a main reason of damages. Spinning operations cause vibrations and oscillations, especially due to unbalanced load, resulting in stressing all main machine components.

On the other hand, as a washing machine is subject to other different sources of stress, the spinning test may not affect all of the device components with the same impact. Moreover, some components may be damaged with higher probability by hydraulic stress, rather than mechanical stress. For these reasons, a second endurance-test version, with rinse and spinning cycles instead of just spinning cycles, is available in Annex 1.

5.2 Procedure proposal

The following sections aim at defining the procedure proposal for a durability test based on a series of spinning cycles.

5.2.1 Scope

This procedure introduces a proposal of method to test the durability of electric washing machines for household use.

5.2.2 Terms and definitions

**Washing machine**: appliance for cleaning and rinsing of textiles using water which may also have a means of extracting excess water from the textiles (EN 60456, 2011).

**Programme**: series of operations which are pre-defined within the washing machine and which are declared by the manufacturer as suitable for washing certain textile types (EN 60456, 2011).

**Operations**: each performance of a function that occurs during the washing machine programme, such as pre-wash, washing, rinsing, draining or spinning (EN 60456, 2011).

**Washing cycle**: complete washing process, as defined by the programme selected, consisting of a series of operations (wash, rinse, spin, etc.) and including any operations that occur after the completion of the programme (EN 60456, 2011) (13).

**Standard 60 °C cotton programme**: a complete washing cycle suitable to clean normally soiled cotton laundry, which is also the most efficient programme in terms of combined energy and water consumptions for washing that type of cotton laundry at that temperature, as specified in the Commission Delegated Regulation (EU) No 1015/2010 (European Union, 2010b).

**Spin speed**: rotational frequency of a drum during spin extraction (EN 60456, 2011).

**Maximum spin speed**: the rated highest spin speed (measured in revolutions per minute ‘rpm’) as declared by the manufacturer in the product fiche.

**Spinning cycle**: a spinning cycle consists of a washing machine spin operation with a defined minimum duration, in which the spin speed can be variable.

**Spinning test**: a series of spinning cycles.

(13) The terms used for this definition in EN 60456:2011 is simply ‘cycle’. ‘Washing cycle’ is here used to avoid misunderstands.
**Washing test**: a series of washing cycles.

**Spin extraction**: water-extracting function by which water is removed from textiles by centrifugal action. This is included as a function (built-in operation) of an automatic washing machine (EN 60456, 2011).

**Base load**: textile load used for testing, without stain test strips or wool shrinkage specimens (EN 60456, 2011).

**Artificial load**: rubber plate fixed inside the washing machine drum.

**Rated capacity**: maximum mass in kg of dry textiles of a particular type which the manufacturer declares can be treated in the washing machine on the selected programme (European Union, 2010a).

**Rated voltage**: voltage assigned to the appliance by the manufacturer (EN 60456, 2011).

**Water extraction performance**: measured as the remaining moisture content (EN 60456, 2011).

**Energy consumption**: the energy consumed over a programme (EN 60456).

**Water consumption**: measured as water volumes (EN 60456).

### 5.2.3 General procedure and conditions

The procedure is applicable to electric washing machines for household use, that are intended for washing clothes and textiles, their rated voltage being not more than 250 V for single-phase appliances (BS EN 60335-2-7 (14); BS EN 60335-1 (15)).

**Test sequence and conditions**: the durability test should be compliant with the following actions, according to IEC 60068-1 Part 1 (16):

- Pre-conditioning;
- Initial examination;
- Testing (exposure of a washing machine to test conditions and measurements);
- Recovery (stabilisation);
- Final examination.

According to EN 60456 (17) the following conditions shall be verified during the test:

- The supply voltage to each test washing machine should be maintained throughout the test at 230 V ± 1 % or at 400 V ± 1 %, as defined by the manufacturer’s installation guide. If more than one option for installation is available and no clear indication for testing is given, the supply voltage should be 230 V ± 1 %. The supply voltage measured during the tests should be recorded (EN 60456:2011). The supply frequency to each test washing machine shall be maintained at the rated voltage ± 1 % through the test (EN 60456);
- Hard water shall be used, with a total water hardness of (2.5 ± 0.2) mmol/l (EN 60456);
- The temperature of water supply shall be 15 ± 2 °C (EN 60456);
- The static pressure of the laboratory supply water at the inlet of each washing machine shall be maintained at (240 ± 50) kPa throughout the test, including during filling operations (EN 60456);
- The ambient temperature of the test room shall be maintained at (23 ± 2) °C (EN 60456);
- Test materials (base loads) have to be compliant with EN 60456.

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(14) Household and similar electrical appliances — Safety — Part 2-7: Particular requirements for washing machines

(15) Household and similar electrical appliances — Safety — Part 1: General requirements

(16) Environmental testing — Part 1: General and guidance

(17) Clothes washing machines for household use — Methods for measuring the performance
5.2.4 Pre-conditioning

The appliance shall be installed according to the instruction of the manufacturer in the ‘user manual’. In particular, the appliance shall be placed on a horizontal support and shall be parallel to the horizontal support in all directions.

The appliance shall be supplied at the rated voltage as defined in Section 5.2.3 and shall be equipped with an artificial load as described in section 5.2.6.1.

5.2.5 Initial examination

The washing machine shall undergo an initial visual inspection, in order to verify whether the machine is intact and undamaged, and the appliance is fit for the test use. This shall be done by taking off the top and any side part of the housing of the washing machine (the functioning of the machine shall not be compromised). The status of the machine should be documented by pictures, especially of the motor, dampers, springs, tub, belt, bearings and bottom of the housing. A spin speed measuring sensor should be installed. This may necessitate the drilling of holes into the back side of the housing. The tub and the measurement equipment shall not impede each other.

The inspection shall also check if the machine is provided by the ‘spinning’ programme, whose characteristics shall be in line with requirements at the point 5.2.6.1. In particular, the max unbalance tolerated by the machine (at rated highest speed) has to be identified. This should be done by operating the machine in the defined spinning programme without any load and with the unbalanced load known beforehand. If no unbalanced load is known beforehand, the unbalanced load should be started at 100 g and increased by 100 g. The spinning profiles shall be recorded and compared to the spinning profile without any load. Additionally, the spinning profile is compared to a programme execution with rated capacity in the Standard 60 °C cotton programme. Deviations shall be reported. The maximum amount of unbalance tolerated is the unbalance at which no significant deviations (i.e. ± 50 rpm) in the maximum spin speed from the spinning profile without load is observed.

5.2.6 Testing

The test is applied to the washing machine taking into account its mechanical robustness and the capability to perform washing operations after a series of stressed cycles.

The test is composed by two phases:

1. Spinning test: test under mechanical stress, for a total of 500 spinning cycles;

5.2.6.1 Spinning test

The spinning test consists of a series of 500 spinning cycles, spaced out by one washing cycle every 100 spinning cycles. The washing machine shall successfully perform the spinning test and failures shall not occur. Each spinning cycle consists in running the spinning programme of the washing machine (WM) with the following specifications:

- Minimum spinning duration: the average recorded maximum spin speed during the time of 1 minutes should be at no time more than 50 rpm lower than the average spin speed recorded during the spinning with no load during the 1 minutes of spinning when the maximum spin speed is reached. If the average spin speed is lower and/or if the time of 1 minutes of maintaining the highest spin speed is not reached, shall be noted in the report. The test may be carried out before the execution of the series of 500 spinning cycles and only verified by visual inspection of the spin speed if the requirement is maintained during the test series;
• Artificial load: a rubber plate load with a mass of 0.5 kg (18) for performing the spinning cycle, fixed inside the drum with a spring rod, and placed half-way along the drum length.

After each spinning cycle, a rest period with a minimum duration of 10 minutes shall be observed before starting a new cycle (IEC 60335-2-7). Between two consecutive spinning cycles doors shall not be opened.

Before the first spinning cycle and then every 100 cycles, the artificial load is removed in order to execute the washing test, as detailed in 5.2.6.2.

5.2.6.2 Washing test

The washing test consists of a series of washing cycles to be run without the artificial load: the first washing cycle is run before the first spinning cycle and then one washing cycle is scheduled every further 100 spinning cycles (meaning after the 100th, 200th, 300th, 400th, for a total of 5 washing cycles). To perform the washing test, the artificial load is removed and substituted by the base load, according to EN 60456.

The programme for the washing machine performance test shall be ‘standard 60 °C cotton’ programme at full load. According to Annex C of EN 60456 the cotton base load shall consist of sheets, pillowcases and towels. However, the requirement for an average age of the load (Annex I of IEC 60456) is not requested. Folding and loading shall be compliant with Annex H of IEC 60456. No detergent is used for this test. After the six washing cycles, the load should be washed according to IEC 60456 in hard water using the normal detergent dosage.

The following performance parameters shall be measured for each washing cycle according to EN 60456, and compared to the measurements obtained during the first washing cycle:
- Total energy consumption [kWh];
- Total water consumption [l];
- Cycle duration [min];
- Water extraction performance.

Another parameter that shall be monitored is the actual maximum spin speed reached by the washing machine [rpm] and an rpm-diagram [min; rpm] of the cycle shall be developed.

The washing machine shall successfully perform all of the washing cycle operations. A visual inspection should follow the washing to detect leakages in the hoses.

5.2.7 Recovery (stabilisation)

After the 500th spinning cycle, the washing machine shall observe a rest period for stabilisation. The objective is to restore the initial conditions before starting the final examination phase. The recovery period should be at least 2 hours.

5.2.8 Final examination

After the recovery, the washing machine shall perform a final washing cycle (the 6th) and then undergo a final examination based on:
- the testing of the performance parameters as expressed in section 5.2.6.2 (energy consumption, water consumption, cycle duration, water extraction performance, actual maximum spin speed reached by the washing machine and a rpm-diagram of the cycle).
- the visual inspection.

(18) If the washing machine does not run the ‘spinning’ programme because of the excessive unbalance detected, the mass of the artificial load shall be decreased to the maximum unbalance load tolerable by the machine for performing the ‘spinning’ programme, as specified in section 5.2.5.
After the testing of the performance parameters, the test washing machine shall be disconnected from the grid power. The visual inspection consists in the examination of the washing machine, in order to check whether the following components are undamaged after the test:

- Supply hoses, drain hoses
- Motor (motor brush, drive belt or inverter electronics)
- Drum
- Drain pump (drain function)
- Drum bearings
- Shock absorbers
- Electronics
- Wiring

In particular, the following problems shall not occur:

- Water leakage from hoses
- Loosen drum (drum not properly fixed inside its housing)
- Unexpected noise from drum bearings
- Broken wires or damages of insulation
- Loss of connectivity of wires and clamps
- Cracks on printed circuit boards

### 5.2.9 Summary and estimated duration

The estimated duration of each test phase is:

- pre-conditioning and initial examination: 2 hour
- 10 minutes per spinning cycle, and
- 10 minutes per rest period, and
- 3 hours per washing cycle (including visual inspection);
- Recovery: 2 hours;
- Final examination: 8 hours.

Therefore, in case of semi-automatic (19) durability testing, the total time to run the test is estimated in approximately 200 hours, divided as follows:

- pre-conditioning and initial examination (manual): 120 min
- 500 spinning cycles (automated, including resting): 10,000 min
- 6 washing cycles (manual, including inspection): 1,080 min
- recovery: 120 min
- final examination (manual): 480 min

The launch of the spinning cycles can be performed manually or, when possible, automatically. This implies that the duration of the test can last from 10 to 25 working days, depending on the level of automation of the spinning test. A graphical representation of the overall test is represented by means of a Gantt chart, in Figure 9.

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(19) The sequence of spinning cycles can be automatised, while the washing cycles need manual operations.
Figure 9. Representation of the durability test procedure using a Gantt chart
5.3 Test requirements

The single 8 or double 3 test methods are both suggested in IEC 60410 as:

- Single 8 test: eight products shall be tested to the declared number of operating cycles (for general endurance test and specific endurance tests); if the number of failed devices does not exceed two, the test is considered passed.
- Double 3 test: three products shall be tested to the declared number of operating cycles (for general endurance test and specific endurance tests); the test is considered passed if there is no failure, and failed if there is more than one failure. Should there be only one failure, then three additional products are tested to the declared number of operating cycles and providing there is no additional failure, the test is considered passed.

These two tests can be relevant to test a limited number of products on the same statistical characteristics.

As some washing machine components may be damaged with higher probability by hydraulic stress, rather than mechanical stress, an alternative procedure based on the 'Rinse & spin' programme is also presented in Annex 1, as an alternative.
6 Results

6.1 Exemplary washing machines

Two washing machines from different manufacturers were selected for the test, called WM A and WM B. A third WM (called WM C) was initially considered for this test, but it did not perform as expected during the initial examination and therefore was excluded. In fact, WM C did not reach the declared maximum spin speed ($20^{\circ}$) during the spinning cycles (even with a relatively low unbalanced weight of 100 g), nor during the normal washing cycles with cotton programmes and a standard cotton load. It was not possible to identify reasons for this behaviour, nor to understand if it results because of a manufacturing defect. Thus, the authors decided not to replace the device and proceed with WM A and WM B only. Further detail about the spinning profiles are given in Annex 2.

Both machines A and B are currently on the market, declared in Energy Efficiency class A+++ (EU Regulation), declared highest spin speed at 1600 rpm and spinning performance class A ($\text{RMC < 45 \%}$). Both are declared having a maximum washing capacity of 8 kg of cotton load.

During the spinning cycles, rubber plates have been used to mimic a constant imbalance. These plates were placed to the inner drum surface with a spring rod fixed to the opposite side of the drum. At first, both machines were operated with different fixed unbalanced weights to see how the control procedure for unbalance works. The unbalanced load consisted of rubber plates fixed to the inner part of the tub with a spring rod, as in Figure 10.

![Rubber plates and spring rods](image)

Figure 10. Rubber plates and spring rods

($20^{\circ}$) In both cases, the maximum spin speed reached was under 1,000 rpm, while the declared maximum spin speed is 1,600 rpm.
WM A delivered the same spinning profile for all unbalanced weights up to 500 g (Figure 11).

Figure 11. Spin speed profiles of WM A, recorded during the extra spinning programme for various fixed unbalanced weights

WM B only showed an expected profile (up to 1600 rpm) for the lowest unbalanced weight of 200 g (Figure 12). For higher unbalanced weights, the machine repeatedly tried to distribute the load more equally on the drum surface and, when this failed, decided to spin at lower spin speeds.
Figure 12. Spin speed profiles of WM B, recorded during the extra spinning programme for various fixed unbalanced weights

Seeing both results, it was decided to start the spinning tests with an unbalanced load of 300 g for both machines.

6.2 WM A: spinning cycles

Figure 13 shows the maximum spin speed and spinning duration for WM A from spinning cycle 1 to 500. Regular gaps between the data indicate the execution of the washing cycle after all 100 spinning cycles. It is also indicated the unbalanced weight used. The initial unbalance load of 300 g was chosen as for this mass, both machines showed in the initial test a straightforward spinning without redistribution phase (see Figure 11 and Figure 12). WM A performed at these conditions without any problems. Therefore, after 159 spinning cycles it was decided to increase the weight of the unbalance mass to 500 g, the maximum unbalanced load considered for this test, for the remaining spinning cycles. WM A showed a constant spinning rate at a spin speed of 1,605 — 1,610 rpm for about 145 sec most times. The increase of the unbalanced load at the 160th cycle caused a reduction of the spinning time to about 107 sec for about 50 % of the cycles, then returning at the usual average duration of 145 sec. It was observed that WM A moved about 10 cm away from its original standing position in 20 cycles, although it was positioned well at the beginning of the test series. This movement always occurs in the first spinning tests of the day after the unbalanced weight was increased to 500 g (probably because dampers were cold). The machine was always placed back to the original position for the next cycle.
6.3 WM B: spinning cycles

WM B (Figure 14) showed a more variable behaviour. At the beginning, the maximum spin speed reached was only 1,400 rpm, with an unbalanced load of 300 g. However, this speed increased cycle by cycle and, after about 20 cycles, it reached 1,540 rpm. The spinning time was about 150 to 175 sec. At the same time in the testing when on WM A the unbalance was increased to 500 g the unbalance of WM B was increased to 350 g (at the 108th cycle) to also induce a maximum stress on the structure of this machine. Then, the maximum spin speed dropped to below 1,500 rpm and the duration varied between 120 and 180 sec. From the 222th cycle onwards, the maximum spin speed dropped further to 1,468 rpm, which was kept constant for most of the cycles up to the end of the test. Spinning time varied between 140 and 230 sec. The total time of the spinning programmes extended by more than 10 minutes, due to continuous attempts of the control procedure to redistribute the load. This redistribution was however not possible due to the fixed unbalanced mass.

Figure 13. Spinning profile parameters: maximum spin speed and spinning duration for WM A from cycle 1 to 500.
Figure 14. Spinning profile parameters: maximum spin speed and spinning duration for WM B from cycle 1 to 500.

6.4 Washing cycles

Complete washing programmes (Standard cotton 60 °C) were executed following the standard EN 60456, modified according to section 5.2.6.2. Diagrams of all six washing cycles for water intake, energy consumption and spin speed over time are shown for WM A (Figure 15) and WM B (Figure 16). Water consumption for WM B was not correctly recorded the first two cycles, therefore it is only reported for cycles 3-6, in Figure 16. The profiles of WM A, especially the spinning profile, look very similar without any problems due to unbalance. Relevant differences are visible in the spinning profile, especially regarding the final spinning for WM B. It seemed that a full spinning occurred only in the first run, while the spinning in all other runs are somehow truncated by the control procedure.

The instability of the spinning process does also show up in the RMC of the spun load (Table 4). While WM A shows almost constant RMC values for all washing programmes, RMC results for WM B were affected by higher variation. For WM B only the RMC value of the first washing cycle is aligned with the declared class A of spinning performance.

Table 4. Remaining moisture content (RMC) of the six washing cycles

<table>
<thead>
<tr>
<th>Remaining moisture content (RMC)</th>
<th>WM A</th>
<th>WM B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washing cycle 1 (before spinning cycles)</td>
<td>44 %</td>
<td>42 %</td>
</tr>
<tr>
<td>Washing cycle 2 (after 100 spinning cycles)</td>
<td>43 %</td>
<td>56 %</td>
</tr>
<tr>
<td>Washing cycle 3 (after 200 spinning cycles)</td>
<td>44 %</td>
<td>52 %</td>
</tr>
<tr>
<td>Washing cycle 4 (after 300 spinning cycles)</td>
<td>46 %</td>
<td>50 %</td>
</tr>
<tr>
<td>Washing cycle 5 (after 400 spinning cycles)</td>
<td>44 %</td>
<td>50 %</td>
</tr>
<tr>
<td>Washing cycle 6 (after 500 spinning cycles)</td>
<td>44 %</td>
<td>51 %</td>
</tr>
</tbody>
</table>
Figure 15. Profiles of water intake, energy used and spin speed for the six washing cycles for WM A (high-resolution images are available in Annex 3).
Figure 16. Profiles of water intake, energy used and spin speed for the six washing cycles for WM B (high-resolution images are available in Annex 4).

6.5 Visual inspection

A visual inspection was performed before and after the testing. To do so, the backside cover sheet and the top plate were removed. Pictures were taken for parts that may be subject to deterioration or damages during the testing. None of those parts exhibited any sign of abrasion, stress or leakage. Rubber debris was found in WM B during the spinning cycles and at the final inspection, due to the contact of the door gasket to the rotating drum. Indeed, the stainless steel front side of the drum in WM B came in contact with the rubber door gasket under the stresses test conditions, causing abrasion of the rubber.

Some spots of debris were also found on WM A, but much smaller in size and of a dark colour. However, it was not possible to identify the origin of the debris.
7 Discussion

Results of the spinning cycles clearly show the behaviour of the control procedure when detecting an unbalanced situation, with the objective of mitigating the stress induced by this unbalance load to the structure and components of the washing machine. On one hand, this ensures a reduced stress on the WM structure as the control procedure tries to avoid the excessive wearing of key components and preventing early failures. On the other hand, the consumer may have to wait longer for the execution of the washing programme, as the repeated attempts to distribute the load equally takes time and, if the maximum spin speed and duration is limited, it also reduces the spinning efficiency, meaning that the load is wetter than it could or should be. In conclusions, these situations may directly affect the declared performance of the washing machine (e.g. maximum spin speed during spinning) and users may not obtain the expected performance of the machine (e.g. lower spinning speed and lower spin-drying efficiency compared to the value declared by the machine programme), as declared on the product fiche.

Looking specifically at the performance of the two washing machines, the overall durability test showed that the execution of washing and spinning programmes is not carried out uniformly throughout the five hundred spinning and the six washing cycles. The spinning tests showed variations in maximum spin speeds and respective durations. WM A showed uniform trends (Figure 13), with a spinning duration at the maximum spin speed ranging from 100 to 145 s, when the unbalance load was 500 g. On the other hand, WM B results were very variable (Figure 14) and stable trends can be observed in cycles 401-500, when the unbalance load was 350 g. In this range, the maximum spin speed was about 1460 rpm, kept for 170 s, in average. It was additionally noticed that the running time of the spinning programme in WM B did prolong by about 10 min from the first to the 500th spinning cycles. We remark that a third WM named as ‘C’, initially considered for this test, was excluded because did not reach the declared maximum spin speed during the spinning cycles with unbalances, nor during the standard washing cycles with full load.

Regarding washing cycles, results for WM A show comparable behaviour regarding spinning in all of the six washing cycles (Figure 15). For WM B, instead, the declared highest spin speed is reached in just one of the six washing trials (run #1 in Figure 16). In the other trials, the highest spin speed is not reached or is only reached for a very short time. If these results were to be confirmed in a test carried out fully according to EN 60456:2010, the declared spin speed (1,600 rpm) and spinning performance (class A) of this machine may be challenged.

Looking specifically at the problems due to deterioration of the machine, it was mentioned the presence of rubber debris at the end of the spinning cycles, in WM B. Under no stress conditions, there is normally a gap of about 1 to 3 mm between the (rotating) drum and the door gasket. Under stress conditions, however, the drum is deformed during spinning and the gap may be reduced to 0 mm and, consequently, abrasion starts. In the long run, leakages in the rubber door gasket may result.

Regarding WM A, it was recorded an unexpected movement of the machine in the first spinning tests of the day, in the first spinning cycles right after the increase of the unbalanced load to 500 g. A higher friction of cold dampers might explain this. During conventional/real washing cycles, dampers are typically already warm when the spinning function is starting. In this case, instead, dampers were cold due to the resting.

The method adopted in this endurance testing was similar with the testing applied by other authors as Altroconsumo (2015) and De Carlo et al. (2013). Altroconsumo observed hard failures (21) in four of the twenty-four washing machines analysed, but through a test of 2500 rinse & spin cycles, with partial load (60 % of the rated capacity, of which 85 % cotton textile and 15 % sponge material), which can be very lengthy. De

(21) Traditional failures permanently affecting the functionality of the product (De Carlo et al., 2013).
Carlo et al., instead, used 500 spinning cycles with different unbalance loads, but in their experiments, the control procedure of the WM was by-passed through external controls, making the testing not simply applicable to washing machines in the market, and the stress testing conditions not representative of the stress caused during the normal use by the customers.

Our approach, on the other hand, aimed to be relatively fast (500 spinning cycles and 6 washing cycles) and applicable to different washing machines, without deactivating the control procedure for unbalance detection. The research aim of having a standard procedure to measure and assess the durability of WMs is relevant, but the definition of loads (and therefore mechanical stress) representative of the effective user operation remains a challenging issue.
8 Conclusions

The objective of this research was to develop an endurance test for WMs based on a series of pure spinning cycles with fixed unbalanced loads. The test has been applied to some exemplary washing machines currently on the market in order to check if these are able to sustain a series of stress conditions, without any hard failure permanently affecting the functionality of the product.

Beside of the presence of rubber debris found in one of the two WMs tested, probably due to the contact of the door gasket with the rotating drum, the application of the durability test did not show any significant failures of any part of the two exemplary washing machines used in this testing experiment.

However, the two WMs reacted differently to the stress induced by the testing procedure and this implied different testing conditions for the two machines. In general terms, WMs have different control procedures regarding unbalanced loads: differences regarding the procedures and precision in detecting the unbalanced load, differences regarding the procedures to uniformly distribute the textile load at the start of spinning cycle, and different reactions in adapting the spinning profile to a certain level of stress. In our research, the control procedure for unbalanced conditions of one of the two WMs (WM B) systematically tried to modify the distribution of the textile load before and after the beginning of the spinning cycle. Since the unbalance was fixed and in order to prevent damages, the control procedure of WM B reduced the maximum spin speed and the spinning length. This reaction of the machine could eventually result in a reduced stress and potentially in a reduced risk of failures. However, on the other hand, customers not aware of such behaviour cannot obtain the expected performance of the machine (e.g. lower maximum spinning speed and lower spin-drying efficiency compared to those declared). Nonetheless, it is important to remark that washing machine components are subject to relevant stresses due to the rearrangement of the load and non-constant point of gravity (at lower spin speed, the washing machine tries to balance the load evenly, while at higher spin speed the mass is decreasing because water is extracted, and increasing centrifugal forces press the load on the inner drum wall). One particular incident, due to these types of stress, could be the starting point of component or machine failure.

A third case-study WM (WM C) was initially considered for testing, but was only subjected to the ‘initial examination’ phase. Indeed, the machine did not reach the maximum declared spinning speed during the spinning cycles with unbalances, nor during the standard washing cycles with full load (22). Due to these evidences, WM C was excluded from the test.

The presence of such control procedures, dealing with unbalances, did not allow the keeping of equal testing conditions in our tests. Such an issue could be thought to overcome by defining a standardised program for WMs (23) that would imply a common behaviour of the machines during the endurance testing. However, the requested maximum tolerated unbalance should not be too high, not to overstress the machines’ capability. Otherwise, such a stressful testing procedure would diverge from real-life behaviour and endurance of the WM.

Nevertheless, our research highlights that endurance testing can refer to different aspects of the durability, as the assessment of the lifetime of the machine (e.g. in terms of number of cycles that the machine can achieve) or to the evolution of the performance (in terms of the variation over time of e.g. the energy consumption, spin speed, washing cycle duration).

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(22) The machine did reach the declared maximum spinning speed only if totally empty. However, already small unbalances, even those naturally occurring when fully loading the machine at the declared maximum capacity, were preventing the machine to spin at the maximum spinning speed, even during standard cotton programmes.

(23) It is not necessary that such program would be available to the customers. The program could be used for the testing purpose only.
Concerning the assessment of the lifetime, it is important to remark that the tests we performed, based on 500 spinning cycles, did not show a correlation between the stress induced by the spinning and potential failures that the machine could suffer during its lifetime, or a correlation with the number of years a device will mechanically last. Even if failures occurred (e.g. when running a test with a higher number of spinning cycles), it would be difficult to correlate these with the lifetime of the device. A testing protocol based on pure spinning cycles could even be counter-productive if used to ‘measure’ and compare durability performance of WMs, as it induce stresses that are not usual in the WMs common use.

On the other hand, our research proved that the effective performance (e.g. remaining moisture content, washing time, maximum spin speed, spin-drying efficiency class) can be deteriorated (or altered by the machine) already after some initial cycles of the testing. In our specific experiment, both washing machines successfully passed the test (as no hard failure occurred) but the control procedure of one of the two machines played a relevant role in this results by modifying its spinning profile and maximum speed, in order to reduce the mechanical stress induced by the spinning cycles.

Based on results in section 6, we also conclude on the relevance of linking durability tests to real life stress conditions and to the relevance of keeping the performance of the product. Parameters such as the reaction of machines to unbalance, the actual spinning profile, the maximum spin speed and the remaining moisture content after spinning are considered relevant to assess durability. While dedicated stress tests on certain functions may be useful for some aspects (like safety test or test at the design stage), the testing of durability needs to consider the whole product and the way it is specifically used.

Further work is needed to define a manageable and relevant testing method. Future developments on the procedure listed in section 5 may complement or replace spinning cycles (with fixed unbalance loads) with a series of various washing cycles, with loads and programmes closer to the average user behaviour. In this case, the machine would also be more systematically subject to the possible combination of the impact of thermal and mechanical stress with the impact of detergents. It is important to remark that such tests could be more expensive and more long-lasting. In case of future developments in this direction, the selection of washing programmes could include various temperature levels and could consist mainly of short programmes. In this way, the overall duration of such a test could be reduced to become closer to the length of the stress test applied in this work. The number of washing cycles, for instance, could be set to simulate two or more years of washing practice in an average European household.

These considerations lead to the main conclusion that a durability test should simultaneously:

- Introduce a certain level of stress, for a certain amount of time;
- Introduce a limit on the performance decline of the washing machine.

In other words, such a durability test would not be devoted to the ‘measurement’ of the average lifetime, but would aim at ensuring that a device is able to fulfil what is the declared on the product fiche even after a significant number of working cycles.

It is also remarked that policy measures could be developed to promote the durability of the machines based on these points. This could be based, for example, by performing one or more tests following standards already existing (e.g. the EN 60456), in which relevant parameters \(^{(24)}\) are measured at the beginning and after a certain number of cycles. Policy measures could prescribe to maintain (or, simply, to declare) product performance after a pre-set sequence of standard washing/spinning cycles. These standard cycles could simulate an average operation of the machine for two years, for example. Any approach on testing the durability of washing machines should be

\(^{(24)}\) It could include also parameters that are already the target of EU Energy label or Ecodesign implementing measures.
meaningful, both in terms of representativeness of the real life functioning, and in terms of resource efficiency and therefore environmental sustainability.

This research also aimed at further stimulating the discussions between industry and policy-makers about industrial practices that will enable a circular economy, focusing in particular on durability and product lifetime extension. Promotion of durability at the whole product level proved to be needed and could be encouraged by standardisation. Nonetheless, implementing a mechanical stress test would encourage WM manufacturers to design products with better mechanical properties, establishing therefore a minimum mechanical robustness, independent of programs applied by real customers.

Endurance and performance measurements could be successful only if these are verifiable based on affordable and reproducible test procedures. This research had the objective to contribute in this sense and to highlight the need of development of such testing conditions. The example of WMs has the potential to trigger activities to develop standards on durability for other household appliances and similar electrical appliances.
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Annexes

Annex 1. Alternative procedure based on the 'Rinse & spin' programme

The procedure proposal of Chapter 5 was based on the condition that the running of spinning cycles with unbalanced load causes stresses to all machine’s components. On the other hand, during the service life of the washing machine, some components are more affected by other stresses rather than mechanical (e.g. hydraulic and thermal stresses). For this reason, an alternative procedure proposal is here presented, based on the use of the 'rinse & spinning' programme of the machine.

The alternative durability test has the same structure as in section 5.2, but it substitutes the spinning test (5.2.6.1) with a series of ‘rinse & spin’ cycles.

For this test, some additional definitions are provided:

- **Rinse & spin**: a combined washing machine operation in which the two functions rinse (detergent removal) and spin (water extraction) are performed together.
- **Rinse & spin cycle**: a ‘rinse & spin’ cycle consists of a washing machine rinse & spin operation with a defined minimum duration, in which the spin speed can be variable.

The ‘rinse & spin’ cycles should have the following specifications:

- Minimum duration of the spinning: the ‘rinse & spin’ cycle shall include the spinning running for a minimum of 10 min/cycle (of which the maximum spin speed shall be reached and maintained for at least 2 min/cycle);
- Artificial load: a rubber plate load with a mass of 0.5 kg (25) for performing the spinning cycle, fixed inside the drum with a spring rod, and placed half-way along the drum length.

The washing machine shall successfully perform 500 ‘rinse & spin’ cycles and failures shall not occur. After each ‘rinse & spin’ cycle, a rest period with a minimum duration of 10 minutes shall be observed before running a new cycle (IEC 60335-2-7). Between two consecutive ‘rinse and spin’ cycles doors shall not be opened. Before the first spinning cycle and then every 100 ‘rinse & spin’ cycles (meaning after the 100th, 200th, 300th, 400th and 500th) for a total of 6 cycles, the artificial load is removed in order to execute a washing test, as in section 5.2.6.2. Successively the machine undergoes the recovery phase and the final examination as in sections 5.2.7 and 5.2.8.

(25) If the washing machine does not run the ‘spinning’ programme because of the excessive unbalance detected, the mass of the artificial load shall be decreased to the maximum unbalance load tolerable by the machine for performing the ‘spinning’ programme, as specified in section 5.2.5.
Annex 2. Washing machine C (excluded)

WM C was excluded from further testing after the initial examination and pre-tests. In detail WM C did not reach the declared maximum spin speed during the spinning cycles when some unbalance was present (even when the unbalance was set at 100 g), nor during the normal washing cycles with standard cotton programmes with the nominal machine load. In both cases, the maximum spin speed reached was under 1,000 rpm, much below than what declared on the product fiche, namely 1,600 rpm.

A summary of the pre-test is detailed hereinafter:

- Spinning cycles without load: max spin speed reached 1,600 rpm;
- Spinning cycles with 100 g fixed load: max spin speed reached ~ 1,000 rpm;
- Spinning cycles with more than 100 g fixed load: max spin speed reached ~ 1,000 rpm;
- Washing cycle with standard cotton load: max spin speed reached 1,000 rpm.

It is not possible to draw conclusions from these evidences, as only one machine was tested and this behaviour may result from a manufacturing defect. However, the authors decided not to proceed with further tests, nor to replace the device. This partial testing proves, anyway, that machines can be very sensible to unbalances, even small unbalances generated by the standard loads in standardised cotton programmes.

The following pictures are representing the measured energy consumption and spin speed in different conditions:

1. Washing cycle (60 °C Eco programme) with 6,7 kg of cotton load
2. Spinning cycle with an unbalanced load of 500 g
3. Spinning cycle with an unbalanced load of 103 g
4. Spinning cycle without load

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WM C – 7kg 60°C Eco
Washing Cycle

WM C with 6,7 kg load
WM C - Spinning

WM C with unbalanced load 103 g

WM C - Spinning

WM C with unbalanced load 500 g
WM C - Spinning

WM C
no load
Annex 3. WM A washing cycles — HQ images

Figure 17. Profiles of water intake, energy used and spin speed for the 1st washing cycle for WM A

Figure 18. Profiles of water intake, energy used and spin speed for the 2nd washing cycle for WM A
Figure 19. Profiles of water intake, energy used and spin speed for the 3\textsuperscript{rd} washing cycle for WM A

Figure 20. Profiles of water intake, energy used and spin speed for the 4\textsuperscript{th} washing cycle for WM A
Figure 21. Profiles of water intake, energy used and spin speed for the 5th washing cycle for WM A

Figure 22. Profiles of water intake, energy used and spin speed for the 6th washing cycle for WM A
Annex 4. WM B washing cycles — HQ images

Figure 23. Profiles of water intake, energy used and spin speed for the 1st washing cycle for WM B

Figure 24. Profiles of water intake, energy used and spin speed for the 2nd washing cycle for WM B
Figure 25. Profiles of water intake, energy used and spin speed for the 3rd washing cycle for WM B

Figure 26. Profiles of water intake, energy used and spin speed for the 4th washing cycle for WM B
Figure 27. Profiles of water intake, energy used and spin speed for the 5th washing cycle for WM B

Figure 28. Profiles of water intake, energy used and spin speed for the 6th washing cycle for WM B
Annex 5. Washing machine EU Energy label

Energy labels were developed by the European Union to indicate energy efficiency and performance of products. The labelling requirements and the new energy label layout for individual product groups are created under the EU’s Energy Labelling Directive (European Union, 2010c).

Figure 29. Uniform Energy label for washing machines

Figure 29 shows an example of EU Energy label, uniform in all of the member States. The product label has 7 classes (from A+++ to D), but does not include a washing performance class, as an A class washing performance is mandatory for all washing machines with a washing efficiency class greater than 3 kg. The following figures are then specified:

- Annual energy consumption in kWh/annum (based on 220 standard cycles);
- Annual water consumption in litres/annum;
- Capacity in kilograms (rated capacity in kg of cotton for the standard 60 °C cotton programme at full load or the 40 °C cotton programme at full load, whichever is the lower);
- Spin-drying efficiency class;
- Noise emissions in decibels in dB.

The annual energy & water consumptions and the spin-drying efficiency class indicated on the label are calculated on the basis of:

- 60 °C cotton programme at full and partial load;
- 40 °C cotton programme at partial load;
- Left-on mode and in off-mode.
Values for the annual water consumption and the spin-drying efficiency class are based on the same set of washing cycles as the energy consumption data (CECED, 2015).

**Commission Delegated Regulation (EU) No 1061/2010**

The Commission Regulation 1061/2010 of 28 September 2010 specifies a uniform design and content for the label for household washing machines, and the requirements as to the technical documentation and the fiche for household washing machines.

Moreover, this regulation defines how to calculate the information included in the label:

- weighted annual energy consumption (AEc) in kWh per year, rounded up to the nearest integer in accordance with Annex VII;
- weighted annual water consumption (AWc), in litres per year, rounded up to the nearest integer in accordance with Annex VII;
- the spin-drying efficiency class as set out in point 2 of Annex VI;
- airborne acoustical noise emissions, during the washing and spinning phases, for the standard 60 °C cotton programme at full load.

The energy efficiency class of a household washing machine is determined on the basis of its Energy Efficiency Index (EEI), determined in accordance with Equation (1) and Table 5.

\[ EEI = \frac{AEc}{SAEc} \cdot 100 \]  

(1)

SAEc indicates the standard annual energy consumption of the household washing machine, calculated in kWh/year as follows:

\[ SAEc = 47 \cdot c + 51.7 \]  

(2)

Where c is the rated capacity of the household washing machine for the standard 60 °C cotton programme at full load or the standard 40 °C cotton programme at full load, whichever is the lower. AEc is weighted considering the energy consumption of the standard 60 °C cotton programme at full load (42.8 %), the energy consumption of the standard 60 °C cotton programme at partial load (28.6 %), the energy consumption of the standard 40 °C cotton programme at partial load (28.6 %), the weighted power in ‘off-mode’ and in the ‘left-on mode’.

Table 5. Energy efficiency classes (European Union, 2010a).

<table>
<thead>
<tr>
<th>Energy efficiency class</th>
<th>Energy Efficiency Index (EEI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A+++ (most efficient)</td>
<td>EEI &lt; 46</td>
</tr>
<tr>
<td>A++</td>
<td>46 ≤ EEI &lt; 52</td>
</tr>
<tr>
<td>A+</td>
<td>52 ≤ EEI &lt; 59</td>
</tr>
<tr>
<td>A</td>
<td>59 ≤ EEI &lt; 68</td>
</tr>
<tr>
<td>B</td>
<td>68 ≤ EEI &lt; 77</td>
</tr>
<tr>
<td>C</td>
<td>77 ≤ EEI &lt; 87</td>
</tr>
<tr>
<td>D (least efficient)</td>
<td>EEI ≥ 87</td>
</tr>
</tbody>
</table>

The spin-drying efficiency class of a household washing machine is determined on the basis of the remaining moisture content (D), determined in accordance with Equation (3) and Table 6.
The weighted remaining moisture content (D) of a household washing machine is calculated in percentage as follows and rounded to the nearest whole percent:

\[
D = \left( 3 \cdot D_{60} + 2 \cdot D_{60\frac{1}{2}} + 2 \cdot D_{40\frac{1}{2}} \right)/7
\]  

(3)

where:

- \(D_{60}\) is the residual moisture content for the standard 60 °C cotton programme at full load, in percentage and rounded to the nearest whole per cent;
- \(D_{60\frac{1}{2}}\) is the residual moisture content for the standard 60 °C cotton programme at partial load, in percentage and rounded to the nearest whole per cent;
- \(D_{40\frac{1}{2}}\) is the residual moisture content for the standard 40 °C cotton programme at partial load, in percentage and rounded to the nearest whole per cent.

Table 6. Spin-drying efficiency classes (European Union, 2010a).

<table>
<thead>
<tr>
<th>Spin-drying efficiency class</th>
<th>Remaining moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (most efficient)</td>
<td>D &lt; 45</td>
</tr>
<tr>
<td>B</td>
<td>45 ≤ D &lt; 54</td>
</tr>
<tr>
<td>C</td>
<td>54 ≤ D &lt; 63</td>
</tr>
<tr>
<td>D</td>
<td>63 ≤ D &lt; 72</td>
</tr>
<tr>
<td>E</td>
<td>72 ≤ D &lt; 81</td>
</tr>
<tr>
<td>F</td>
<td>81 ≤ D &lt; 90</td>
</tr>
<tr>
<td>G (least efficient)</td>
<td>D ≥ 91</td>
</tr>
</tbody>
</table>

New EU Energy label

A proposal to repeal the Directive 2010/30/EU was prepared in 2015. This proposal follows up on the Energy Union Framework Strategy and intends to replace Directive 2010/30/EU on the indication by labelling and standard product information of the consumption of energy and other resources by ERPs (European Commission, 2015c).

According to the proposal, the European Commission carried out an ex-post evaluation of the Energy Labelling Directive, discovering that energy labelling is a principal driver for innovation and the majority of consumers recognise and understand the energy label. Furthermore, Ecodesign and Energy labelling measures in place are effective and bring tangible and substantial energy and cost savings. Implementation of the two Directives is estimated to save 175 Mtoe of primary energy per year by 2020 (around 15 % of these savings are estimated to be ascribable to energy labelling measures).

It is recognised that potential for further reduction of environmental impacts exists (aspects of reusability, recyclability, and recoverability, recycled content, use of priority materials, hazardous substances and durability). The objectives and main principles of the current Energy Labelling Directive are retained but the proposal clarifies, strengthens and extends the scope of the current Directive’s provisions by:

- Updating the label and allowing for rescaling;
- Improving enforcement;
- Creating a database of products covered by energy labelling obligations;
• Making clearer the obligations of the various parties;
• Improving the link between energy labelling and measurement standards.

The Commission should provide a working plan for the revision of labels of particular products, implementing a technical, environmental and economic analysis of the product groups concerned. This analysis should also look at supplementary information including the possibility and cost to provide consumers with information on the performance of an energy-related product, such as its absolute energy consumption, durability or environmental performance, in coherence with the objective to promote a circular economy.

Delegated acts relating to specific product groups shall specify, where appropriate, the use of other resources and supplementary information concerning ERPs. With supplementary information it is intended information on the functional and environmental performance of an ERP, such as its absolute energy consumption or durability, which is based on data that are measurable by market surveillance authorities, is unambiguous and has no significant negative impact on the clear intelligibility and effectiveness of the label as a whole towards customers.
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