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The Hybrid-Agile Design of Experiments Methodology

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The Hybrid-Agile Design of Experiments Methodology

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Abstract. A DOE (Design of Experiments) is the laying out of a detailed experimental plan in advance of doing the experiment. Optimal DOEs maximize the amount of information that can be obtained for a given amount of experimental effort. The traditional DOE methodology is waterfall-type methodology implying a sequential and linear life-cycle process. The success of the experiment and usefulness of the results are highly dependent on the initial experimental setup and assumptions, and does not allow to go back and change something that was not well-documented or thought upon in the design stage. The fast-changing software development industry have made it understandable that the traditional waterfall methodology for developing systems, which follows similar patters to the traditional DOE, lacks the agility required for developing robust systems. These limitations have triggered the development of *agile*: a type of incremental model of software development based on principles that focuses more on flexible responses to change, instead of in-depth planning at the design stage. This paper proposes the hybrid-agile DOE methodology – a methodology that incorporates agile principles in traditional waterfall DOE methodologies – to design effective experimental layouts that allow for improvement during the experimental trial process. The methodology is applied to the natural ageing of adhesives tapes for building applications. This methodology can overcome traditional DOE, by adding agility in the whole process, especially in cases where the investigated products lack prior information and are characterised by large variability.

1. Context

1.1. Introduction

This work was conducted as a part of an R&D project aiming to develop robust test, evaluation and prediction methodology for ensuring durable adhesive airtight solutions for energy efficient buildings. Airtight building envelopes are essential for energy efficient buildings, and to meet increasing airtightness requirements, the use of adhesive tapes for sealing joints in air barrier systems have become commonplace. Consequentially, the long-term energy efficiency and moisture safety of the buildings are dependent on the continuous performance of the adhesive joints. However, there is a substantial lack of knowledge regarding the testing and prediction of durability of adhesive tape airtight solutions for building applications. A thorough review of the state of the art, as well as an account of the challenges associated with durability testing of adhesive airtight solutions can be found in reference [1] and [2].

Accelerated ageing tests are often used to estimate the ageing behaviour and long-term-durability of materials by exposing them to aggravated levels and/or frequency of typical stress factors encountered in in-use condition. Confidence in accelerated ageing tests must be established by correlation with natural ageing in typical in-use conditions. Ideally, accelerated ageing tests should preserve the failure modes, degradation mechanisms and ranking of materials/products observed in in-use condition. The natural ageing experiment on wind barrier tapes presented as a case in this paper is the first step towards designing an accelerated test method for adhesive airtightness solutions which satisfy the correlation requirements to natural ageing. The joint testing will be in the form of small-scale tests (peel and shear strength). Though a correlation has not been found between airtightness and peel/shear strength [3], they are nevertheless suitable test methods for evaluating the impact of ageing on joint performance and for subsequent correlation to accelerated ageing programs.

There are several aspects of adhesive tape durability testing which makes it an interesting and challenging case for efficient design of experiments (DOE): a) The inherent complexity of the airtightness solution: Each air tightening joint consists of a substrate (typically membranes and/or structural building components), and a tape which consists of a (often multicomponent) carrier/backing and a pressure sensitive adhesive. Together they make a complex composite, where each constituent layer, and the interaction between the layers have a different response and sensitivity to climate exposure stress factors.; b) The high level of co-dependence of the factors in the experiment – e.g. the peel strength of a tape cannot be measured independently of a substrate.; c) The unsuitability of known DOE methodologies such as fractional factorial design due to the categorical or stochastic nature of the input factors.; d) The lack of detailed knowledge on the composition of the different adhesive tape products on the market due to trade secrets.; e) The possibility of unpredicted tape/substrate interactions leading to unusual degradation [4].; and f) The diverse and stochastic climate conditions expected to influence the adhesive tape durability in actual applications.

The DOE methodology presented in this paper was developed to meet the challenges of natural ageing of adhesive tapes for building purposes. It is presented in a generalised fashion, to highlight the underlying principles and facilitate adaption for other scientific experiments. The methodology could be especially useful for building physics experiments, which often involve long-time observations and include categorical factors with a high level of co-dependence.

1.2. Design of Experiments

The (statistical) design of experiments is an efficient procedure for planning experiments so that the data obtained can be analyzed to yield valid and objective conclusions. A design of experiments or experimental design is the laying out of a detailed experimental plan that aims to describe and explain the variation of information under conditions that are hypothesized to reflect the variation in advance of doing the experiment. The traditional DOE methodology is waterfall-type methodology implying a sequential and linear life-cycle process. In this type of experimental set-up, the success of the experiment and effectiveness of the results are highly dependent on the initial experimental setup and assumptions and does not allow to go back and change something that was not well-documented or thought upon in the design stage. This characteristic, and especially in long-term testing, can be inconvenient because it requires a well-chosen DOE before the experimental phase starts. However, finding a well-chosen DOE, or the optimal one, can be challenging and may not be that straightforward, especially if very little information a priori is found or there exists numerous variations of the investigated material/products, which makes it difficult to optimize the cost while testing a representative pool.

It can be argued that there exist different experimental designs seeking the same objective given the combination of different discrete and continuous variables that can be involved. Optimal experimental designs maximize the amount of "information" that can be obtained for a given amount of experimental effort [1]. The latter can be seen as a multi-objective optimization problem given a set of boundary conditions (i.e. the minimum accuracy in order to deliver results with confidence or minimum scope, in order to deliver a representative pool). Figure 1 depicts the possible domain where acceptable DOE(s) may exist by optimizing for the following opposite objectives:

- **Scope of the experiment**: the extent the experiment provides a significant representation of the investigated materials. In our case study, the following parameters govern this characteristic: a) number of tapes; b) number of substrates; c) number of exposure conditions; and d) number of test methods.

- **Accuracy of the experiments**: the extent the experiment provides confidence in the results. In our case study, the following parameters govern this characteristic: a) number of parallels; b) number of test intervals; and c) duration of exposure for each tape-substrate combination.
- **Cost of the experiment**: the cost associated to number of materials and test used in the experiment. In our case study, it concerns the cost associated to: a) number of combinations tape-substrate; b) number of tests; c) time and space for carrying out the experiments; and d) human resource costs.

The additional challenge with traditional waterfall approach is that the chosen DOE is selected during the design phase and cannot be changed afterwards. In cases where prior information is available for materials to be tested, an expert judgment can elaborate on finding an optimal DOE; however, such static characteristic poses a challenge when experimenting with new materials or in cases where prior information about the products is lacking. As a result, the waterfall-type DOE lacks the agility to improve itself during experimental trial process when more information may become available once preliminary results are available. Across non-construction industries such static characteristic has been overcome by introducing *agile*. Agility is a principle that has been widely implemented in emerging and fast-changing industries – i.e. the software development industry – during the past decades to accommodate for fast changes that can prevent accumulative errors or unnecessary work during the development phase. While agile approaches are mainly being used in software developments, their principles can also be accommodated in other applications such as the experimental design.

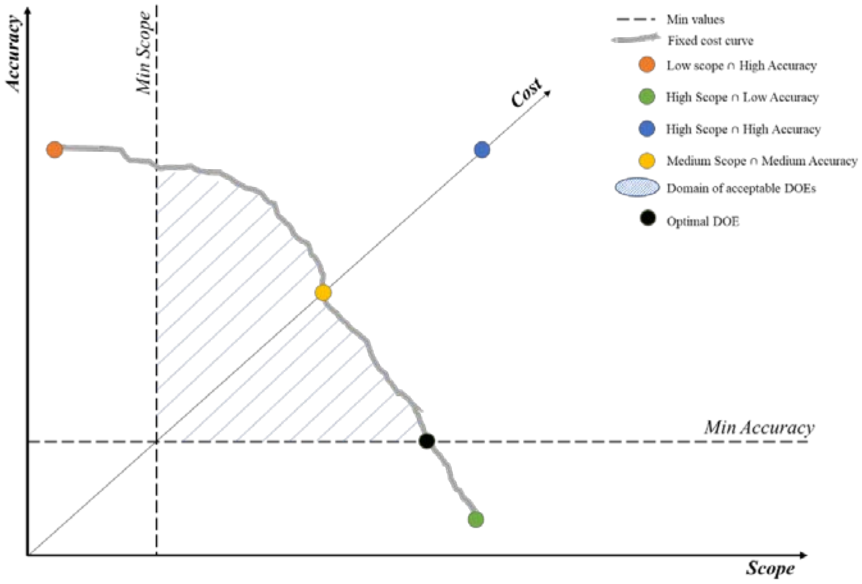

Figure 1. The domain of acceptable DOEs as a function of scope, accuracy and cost.

1.3. Aim and objectives of the study

The study aims to propose a hybrid-agile design of experiment methodology by incorporating agile principles into the traditional waterfall design of experiments methodology. The aim is achieved by addressing the following objectives:

- review the traditional DOE methodology and provide an overview of its advantages and disadvantages;
- review the agile approaches in the software industry and highlight transferable principles that can add value when designing experiments;

- propose a hybrid-agile DOE framework that grates agile principle into the traditional DOE and agile principles; and
- showcase the proposed framework with an example of a long-term natural ageing of adhesive tapes for building applications.

2. Waterfall methodology: Traditional DOE

The statistical software JMP [5], a unit of SAS, provides a six-step framework for designing an experiment, running the experimental trials, and analysing the results. The steps (See Figure 1) adapted from the JMP Design of Experiments Guide are the following: *a) describe*: determine the aim and objectives of the experiment; *b) specify*: determine or specify an assumed model that it is believed that adequately describes the physical situation, which represent an initial model that ideally contains all the effects expected to be estimated; *c) design*: generate a design that is consistent with the assumed model and evaluate this design to understand its strengths and limitations, and to ensure that it provides the information needed, given the assumed model and also the aim and objectives; *d) collect*: conduct each of the trials and record the response values; *e) fit*: fit the assumed model to the experimental data; and *f) predict*: use the refined model to address the experimental aim, determine which effects are active, find factor levels to optimize responses, or build a predictive model.

Figure 2. The waterfall approach to experimental design

The traditional DOE methodology is waterfall-type methodology implying a sequential and linear life-cycle process. The advantages of a traditional waterfall DOE are the following: a) easy to design and manage; b) allows for the long-term effects of testing (an essential quality for natural ageing experiments); and c) the managing and processing costs are lower. The disadvantages of a traditional waterfall DOE are the following: a) the results are only available at the end and do not allow for improvement during the process. Hence, the effectiveness of DOE can only be evaluated at the end without having the possibility to move back and make changes in the previous steps.; b) the outcome of the experiment relies heavily on the validity of the assumed model(s) in the "specify" stage; and c) accurate specifications that bridge the aim with the design of experiments can be challenging when there is insufficient previous experience to build upon.

3. Agile methodology: Lesson learned from the software industry

The recent boom in software developments have made it understandable that the traditional waterfall methodology for developing systems, which follows similar patters to the traditional DOE presented above, lacks the agility required for developing robust systems. As a result, the agile methodology has been developed. Agile is the ability to create and respond to change. It is a way of dealing with, and ultimately succeeding in, an uncertain and turbulent environment [6]. Agile software development is based on an incremental, iterative approach that happens during a fixed amount of time, also called sprints, instead of in-depth planning at the beginning of the project. Agile methodologies are open to changing requirements over time and encourages constant feedback from the end users. The goal of each iteration is to produce a working product, whose outcome is used for the next iteration. Agile principles can be incorporated into traditional DOE by providing the means to update and improve the experimental design during the experimental trial phase. Figure 2 presents in a schematic manner the agile approach applied to experimental design.

The agile approach may offer certain advantages when integrating them to the traditional waterfall one; however, considering the primary objective of natural ageing there are also some disadvantages to consider. The advantages of an agile-based DOE are the following: a) the iterative process allows for intermediate understanding, which is very advantageous for products whose performance is unknown or only marginal; and b) the iterative process allows for continuous improvement of the design of experiments that will be carried out in the future. The disadvantages of an agile-based DOE are the following: a) the short-term process associated to each iteration does not allow for a long-term performance of the materials; and b) the cost associated to the additional iterations may turn out to be higher compared to the traditional one.

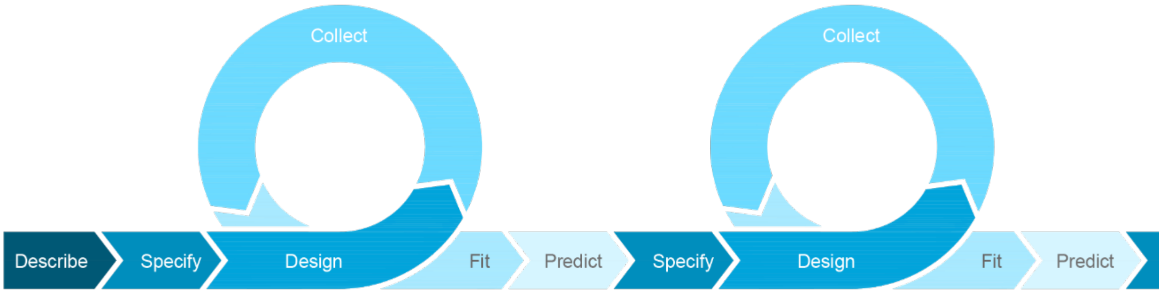

Figure 3. The agile approach to experimental design

4. The proposed hybrid-agile design of experiments methodology

As argued before, both methodologies – traditional waterfall and agile – are characterised by their advantages and disadvantages corresponding to different objectives and settings of the experimental trials. Therefore, a hybrid approach – an integration of both methodologies – may enable a more holistic knowledge creation by optimising the application of each methodology in specific batches to be tested, and hence, maximising the benefits in the specific time duration of the experiments. This would allow for an experimental setup that is originally designed by expert judgements and then constantly updated, and hence optimized, based on incremental results during the experimental trial phase. This methodology can be regarded as a way to running sensitivity analysis about experimental design during the experimental trials, to understand better the effectiveness of experimental design during the process, and subsequently, allow for its update and improvement based on the incremental outcomes.

Figure 4 shows the process for optimizing the DOE during the experimental trial phase. In this fictious example, a DOE (red coloured) has been selected by initially choosing high scope - testing several different materials – and lower accuracy – few parallels for each material. After the first sprint, the results show that few of the materials require more parallels to achieve the necessary confidence about the uncertainty of the results – higher accuracy – and other materials may require fewer, giving the opportunity to test new materials, and hence, increasing the scope. The DOE is updated (green line) after the first sprint takes place, and the level of scope is reduced slightly while the level of accuracy is increased while the cost is kept fixed. This process is iterative until an optimal point has been reached or the experiment trials are over.

The proposed hybrid-agile methodology consists of three batches, each governed by agile or waterfall principles to accommodate specific objectives. Its application to the natural ageing of adhesive tapes is shown in Figure 5. The first batch is designed based on waterfall principles, and it presents a waterfall experimental setup based on an initial model supported by expert judgement. The scope and accuracy are fixed from the design stage. The second batch is design based on both agile and waterfall principles and presents an experimental setup which will generate results at different time intervals, to allow for a better understanding of time-dependent characteristics of selected products and their accuracy. The setup of the first sprint is decided during the design stage, while the total number of sprints and their duration will be based on the testing results of their previous part(s). The third batch is based only on agile principles and presents an experimental setup that tests different products, different duration and settings in different and varying sprints. The short sprints will allow for a horizontal view of the performance of a wide range of products exposed to different settings. The decision regarding the accuracy and scope of each sprint will be based on the outcome acquired from all batches. Table 1 presents the main differences between the three batches based on three main DOE conflicting objectives: scope, accuracy, and cost.

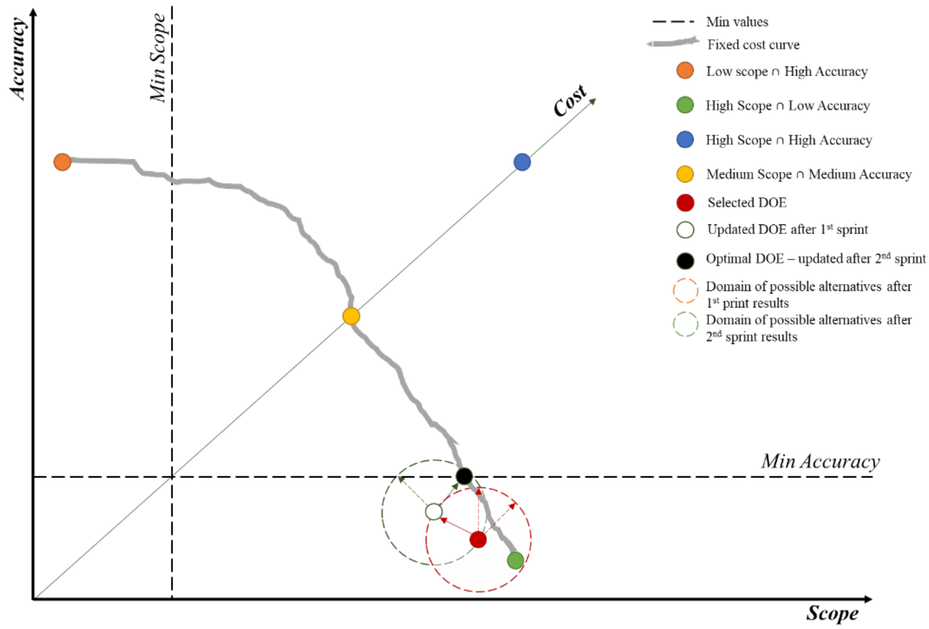

Figure 4. The agile process enabling the finding of the optimal DOE while the experiments take place.

Table 1. Characteristics of different batches present in the hybrid-agile DOE methodology

	Type	*Scope*	Accuracy	*Cost*
Batch 1	Waterfall	Fixed	Fixed	Fixed
Batch 2	Agile & Waterfall	Flexible	Flexible	Fixed
Batch 3	Agile	Flexible	Flexible	Flexible

Batch 1 – Waterfall methodology
Objective: Acquire knowledge on the longest possible natural ageing of the main and most common products representing the market.
Application to natural ageing of tapes: A selection of tape-substrate combinations will be aged as long as the study allows for. The specimens will only be tested in fresh condition and at the end of the experimental period. The tapes and substrates will be selected in order to get a broad representation of the wind barrier tapes on the market and a wide range of substrate properties. The selection will be based on initial models and the available knowledge at the start of the experiment. The specimens in Batch 1 will be aged both behind cladding and directly exposed to the weather conditions. Both peel and shear strength of these tapes will be tested to get information on a broad range of failure modes and change in adhesion strength for different loads.
Duration: Fixed, maximum duration as the experiments can allow.
Products: Products assumed to be representative of the market based on initial assumptions.
Outcome: Knowledge about the long-term performance of products representative of the market.
Batch 2 – Waterfall ∩ Agile methodology
Objective: Understand the gradual ageing (weathering/ degradation rate) of key products in the market.
Application to natural ageing of tapes: Batch 2 consists of a smaller selection of tape-substrate combinations to allow for more frequent testing without exceeding the allocated budget. Nevertheless, the experimental matrix is large enough to enable basic sensitivity analysis of the different input variables. In Batch 2 tape-substrate combinations which are expected to show varying degradation

curves and rates will be included. The specimens in Batch 2 will be aged both behind cladding and directly exposed to the weather conditions. Only peel strength will be tested because previous results [7, 8] show that the peel strength is more sensitive to ageing. For each tape-substrate combination and exposure condition, a specific number of the specimens (parallels) will be taken out and analysed after different durations of ageing. The specimens taken out after a specific ageing duration is defined as a *part*. The total number of parts is not pre-defined at the start of the experiment, which allows for agility in the experimental setup with regards to ageing durations and parallels, and even gives the possibility to move some specimens from one exposure condition to another. Part 1 has a pre-defined ageing time of 6 months, and a set number of parallels [5].
Duration: Varying/distributed throughout the total duration of the experiments
Products: A smaller range of products which are expected to show varying degradation curves and rates, and which are assumed to represent the market.
Outcome: The development of adhesion strength and failure modes as a function of time, from which it will be possible to use regression analysis to estimate degradation curves and rates. The rates can be plotted against corresponding rates from accelerated ageing and analysed for correlation.

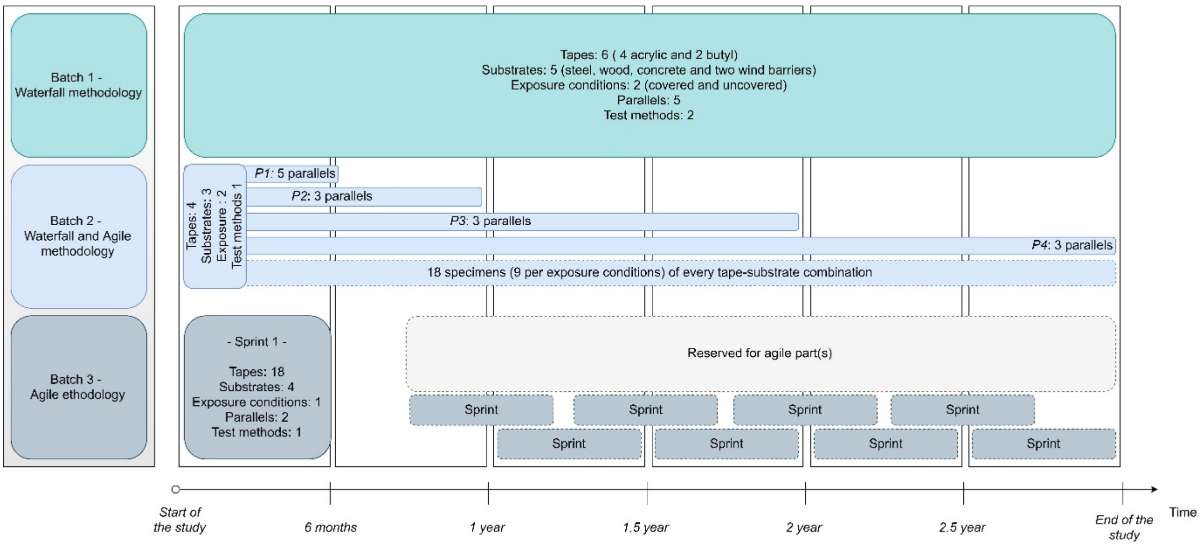

Figure 5. The hybrid-agile DOE applied to natural ageing of adhesive tapes for building purposes.

Batch 3 – Agile methodology
Objective: Expand the knowledge about natural-ageing knowledge on additional products, boundary conditions and/or initial settings.
Application to natural ageing of tapes: Only the first sprint is fully defined at the start of the experiment. The second sprint is also outlined. Sprint 1 is designed to give indications that can be important for further experimental design. A large amount of tape-substrate combinations will be tested, at the sacrifice of amount of parallels. This means that while this sprint could result in valuable indications for the design of further sprints, it is less suitable for statistical analysis. It will give indications at an early stage if the selected tapes in Batch 1 and 2 are not representative. Sprint 2: A carefully selected specimen series should be repeatedly measured after short periods of the same duration (6 months) but starting at different times (shifted 3 or 6 months). This sprint will start at the end of year one, and the selection will be based on the results from fresh and 6 months testing.
Duration: Varying/ Sprints of different size and duration.
Products: Special products that allow for observing degradation within the duration of first sprint. Products that include but also fall out of the widest range as represented in batch 1. Products that may be sensitive to climate exposure. Other products that may become interesting after the first test results.

Outcome: Knowledge about very different products exposed to very different conditions. Continuous evaluation of the validity of the assumptions forming the basis of Batches 1 and 2.

5. Conclusions

The traditional Design of Experiments (DOE) methodology is based on waterfall principles implying a sequential and linear life-cycle process where the setup is selected and fixed before the experimental trials starts. The success of the experiment and usefulness of the results are highly dependent on this fixed initial experimental setup and its assumptions, and does not allow to go back and change something that was not well-documented or thought upon in the design stage. This lack of agility poses a challenge to select the most optimal DOE during the design stage, especially for cases where prior information is lacking, experiments will be conducted on new products, or the variability of the products is too large to be accommodated in a cost-efficient setup.

This paper proposed the hybrid-agile DOE methodology – a methodology that incorporates agile principles in traditional waterfall DOE methodologies – to design effective experimental layouts that allow for improvement during the experimental trial process. The iterative improvement process in the proposed methodology is already accounted for during the experimental design process and is explicitly part of the experimental process. The methodology is suitable to both long- and short-term experiments if the duration of the experiments can be divided into sprints whose results can provide relevant info for the rest of the experimental design, and hence can iteratively improve the rest of the experiments. This methodology can be regarded as a way to run sensitivity analysis about effectiveness of the experimental design during the experimental trials, to understand better the effectiveness of experimental design during the process, and subsequently, allow for its update and improvement based on acquired incremental outcomes. This methodology can overcome traditional DOE, by adding agility in the whole process, especially in cases where the investigated products lack prior information and are characterised by large variability. Incorporating agile principles in traditional waterfall DOEs – the hybrid-agile DOE – has the potential to enable a more holistic knowledge creation by optimising the application of each methodology and maximising the volume and value of the experimental output through continuous and planned incremental updates and improvement.

References

[1] Leprince V, Moujalled B, Litvak A. 2017 Durability of building airtightness , review and analysis of existing studies. *AIVC TightVent.* Brussels.
[2] Litvak A, Allègre F, Moujalled B, Leprince V. 2019 Assessment of the durability of airtightness products in laboratory controlled conditions: development and presentation of the experimental protocol. *40th AIVC Conference*; Ghent, Belgium.
[3] Antonsen U. Slutrapport: Lufttäta klimatskal under verkliga förhållanden (In Swedish, Final report: Airtight building envelopes under real-life conditions). 2017 RISE Research Institutes of Sweden.
[4] Rasmussen TV, Hansen TK, Nielsen JK, Steenstrup FR, Ottosen LM, Petersen LG, et al. 2020 Materialeegenskaber- Test af polyethylenmembraners egenskaber før og efter accelereret ældning. BUILD, Aalborg Universitet.
[5] Sall J, Stephens ML, Lehman A, Loring S. JMP start statistics: a guide to statistics and data analysis using JMP: Sas Institute; 2017.
[6] AgileAllience. 2020 [Available from: https://www.agilealliance.org/.
[7] Fufa SM, Labonnote N, Frank S, Rüther P, Jelle BP. Durability evaluation of adhesive tapes for building applications. Construction and Building Materials. 2018;161:528-38.
[8] Sletnes M, Frank S. 2020 Performance and Durability of Adhesive Tapes for Building Applications. From Product Documentation to Scientific Knowledge (and Back Again). DBMC.

Acknowledgments

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