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Test Environments in Engineering Design: A conceptual study

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Abstract

Experimenting with solutions and technologies plays an important role in designing innovative products at a fast pace. A number of researchers have investigated the use of prototypes as means for experimentation in engineering design. This paper is taking a broader perspective, considering the fact that a prototype test includes both models of the product (prototype) and models of the real environment (test environment), and investigates how these models are entangled. Using concepts from Theory of Experimentation and Design of Experiments, a conceptual framework for decomposing and describing the prototype and the test environment is proposed. The applicability of the framework is then demonstrated through three select cases from design activities around the development of a flood protection system.

Keywords: prototyping, experimentation, design of experiments, engineering design

1 Introduction

In the search for ways to develop better and more innovative products, prototyping and experimentation are two activities that go hand-in-hand and have proven to be particularly important in the early phases (Criscuolo, Salter, & Ter Wal, 2013; Rich & Janos, 1994; S. H. Thomke, 1998; Veryzer, 1998).

In recent years, prototyping has gained substantial attention in the multidisciplinary engineering design research community. Although the importance of prototyping has been highlighted in numerous studies, researchers tend to focus merely on the concept of prototyping when dealing with the *evaluation* of prototypes. Thus, established research domains such as design of experiments (DOE) and experimentation are often omitted. Since a considerable amount of the knowledge and insight is created in the testing and evaluation stages, bringing perspectives from experimentation and DOE into prototyping research may prove fruitful.

The main objective of this paper is to investigate test environments in a prototyping context. By unifying existing prototyping research with parts from DOE theory and experimentation, we present a framework for decomposition of generic prototype tests. The two main components of the framework are:

- A detailed and expanded design-build-test-analyze model for prototype testing
- A method for structuring different variables and properties in a prototype test

The paper is structured as follows. First, a brief literature overview of prototyping and experimentation is presented. Then our proposed framework is introduced before we finally present several practical examples to demonstrate our framework.

2 Theoretical background on prototyping and experimentation in product development

2.1 Prototyping in product development

Prototyping plays an important role in modern product development methodologies. The prototyping activities and the prototypes themselves cover a wide range of applications. Some of the most common formalized prototypes in the development process are often named *proof-of-concept*, *proof-of-product*, *proof-of-process* and *proof-of-production* prototypes (Ullman, 2010). These prototypes are also referred to as *milestone* prototypes and mainly serve as tools for ensuring progress by verifying and validating aspects of the product and the production process. Less formalized prototypes are frequently built ‘when needed’ in the earlier development phases—often for exploratory purposes. Regardless of the type of prototyping or the timing in the development process, the overall purpose of prototyping can be divided into four categories: *learning, communication, integration* and *milestones* (Ulrich & Eppinger, 2012).

One of the most important value contributions from prototyping can be attributed to the role they play in the design cycle. As stated by Loch, Terwiesch, and Thomke (2001), the understanding of design cycles have evolved over the years. Simon (1969) introduced the *generate-test* cycle and stressed its importance in the evolutionary process of generating new design alternatives. This was further expanded by Clark and Fujimoto (1989) by the introduction of the *design-build-test* cycle to emphasize the importance of building prototypes. Finally, Thomke (1998) proposed a *design-build-run-analyze* cycle to point out that the analysis of a test or an experiment is important in product design. In this context, prototypes can be constructed based on the outcome of experimentation, thus becoming the final outcome of a design cycle, or they can act as an enabling platform on which experimentation can be performed. In either case, prototypes have a great potential for capturing learning in the product development process.

As multiple prototype definitions exists, we will use the wide definition by Ulrich and Eppinger (2012) which states that a prototype is “an approximation of the product along one or more dimensions”, where the dimensions could be functionality, appearance, components or any other product related attributes.

2.2 Experimentation in product development

For conducting complex experiments in science, DOE theory is considered the best practice, and often used as a basis during the experiment design and planning process. DOE is a research area that is statistically founded and confines the experiment planning, the selection of process parameters, and techniques to analyze data, to draw valid and objective conclusions, (Montgomery, 2008, p. 11).

2.2.1 Design of experiments

DOE theory states that a system or a process—in our case a prototype test—consists of different system variables, inputs and outputs. The properties of the system describe the relation between the input, variables and output. The variables could be either quantitative (magnitude, direction, numbers) or qualitative (implemented functions, design alternatives) (Antony, 2014, p. 8). Furthermore, the variables can be controllable (possible to control to optimize the process) or uncontrollable (impossible to control and may influence the process).

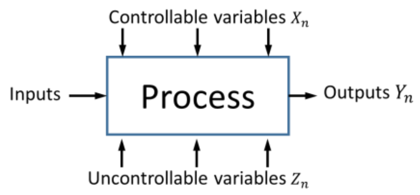

Figure 1 - Relation between process input, output and variables

The three key principles for DOE theory are *randomization*, *replication* and *blocking* (Antony, 2014, p. 9; Montgomery, 2008, p. 12).

These principles are meant to reduce the experimental bias of the test, so that the conclusions will be based upon the result from the process, and not from the structure of the experiment. Randomization is structuring the test cycles so that unstable variables will be displayed as a spread in results rather than a clear tendency. Replication means re-running the whole experiment to target the experimental error. This should also be performed in random sequence so that experimental bias is scattered. Blocking is to identify discrete variables that are difficult to randomize, that could affect the process, and analyze the results accordingly.

As illustrated above, the three basic principles from DOE targets the use of multiple runs of experiments to be able to identify some cause-effect relationship, and display the characteristics of a process according to the variation in variables, including statistical variation. The process could then be optimized by using the optimal variable settings established from the tests.

2.2.2 Prototype experiments

As the design process generally aims for a satisfactory design in contrast to an optimized design (Simon, 1969), it is apparent that prototype tests will often lack a DOE foundation, as optimization is one of DOE's key area of use. The "satisfactory focus" in the design process can be identified by looking at the most common prototype designations: *proof of concept*, *proof of production* and *proof of process* (Ulrich & Eppinger, 2012). These are prototypes and prototype tests made to demonstrate, verify or explore the proposed solutions, and are most often singular test events with immediate positive (compliance) or negative (non-compliance) results. Alternatively, the prototypes go through several iterative cycles to achieve a threshold performance/value. Prototype tests that are within domains that could benefit from DOE techniques, are comparison of different product solutions, treatment of user experiences/statistic, or optimization of production characteristics through techniques as Six Sigma (Goh, 2002).

These activities could be performed in a formal setting, as a part of a prototyping plan for verification and validation, or in an informal setting for generating ideas and exploring the design space. Elverum and Welo (2015) has previously investigated how prototyping and prototype testing facilitated activities beyond the formal means of verification and validation.

3 Characteristics of prototype tests

Experiments for testing prototypes comes in many variations, where the theoretical basis could touch both the area of DOE and experimentation in product development. We therefore propose to start building a framework for prototype testing using only parts of the terminology and models from these grounds, mainly the characterization of a process and the concept of design cycles.

3.1 Prototype test environment

Through our research, we have believe that the design-build-run-analyze description is incomplete, and should include both the real environment and the test environment as a part of the cycle. This change is briefly touched upon by Stefan H. Thomke (1998) as he identified that product developers were using representative models of the product (*prototype*) and models of the environment (*test environment*) when performing iterative experimental cycles.

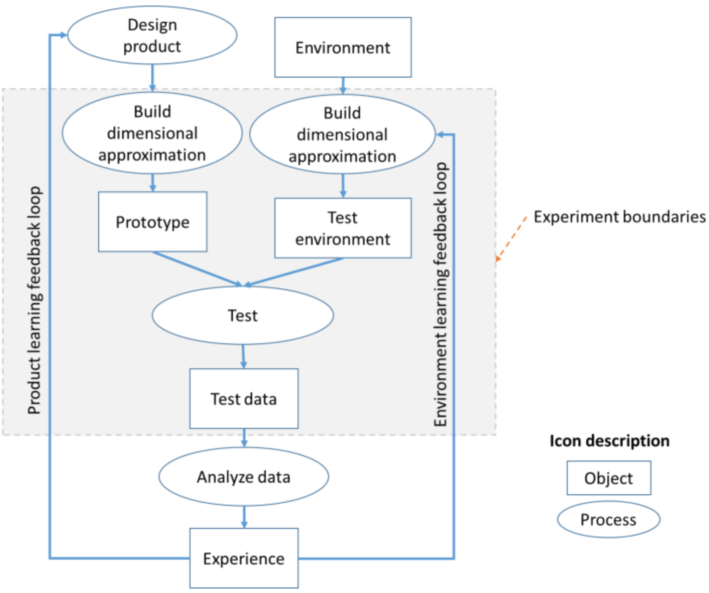

Figure 2 - Extended Design-Build-Test cycle.

As the real environment is the context in which the product operates, the test environment is subsequently the representation of this context in a prototype test. In the same way as a prototype represents the intended product, the test environment represents the real environment, along one or multiple dimensions (*dimensional approximation*). These representations can be a part of an iterative cycle that aims to change and improve both the prototype and the test environment through feedback from previous iterations.

3.2 Classes of properties in prototype testing

The properties of the prototype test environment can be split into three fundamental classes, namely *human interaction*, *environmental characteristics* and *product structure*. Treating the prototype as a separate class gives us in total four individual classes. During the test, properties within a class could either act on, or interact with other properties within its own class or other classes. These interactions is the main reason why product development literature mentions that unexpected results tend to happen when a product, previously tested in a simplified test environment, is tested in a more complete environment (Stefan H. Thomke, 1998), or a more comprehensive (complete) prototype is tested (Ulrich & Eppinger, 2012). This is consistent with DOE literature, where understanding interactions of these would be the key to understanding the performance of a process or a product (Montgomery, 2008, p. 4).

3.2.1 Human interaction

The human interaction class contains the properties of human behavior and biometric data. This could either be the user of the product or other people acting or interacting with the product. The variables in this class can be very unstable and sensitive to differences in other environmental properties. Some of these variables have been investigated in medicine and psychology, e.g. the placebo effect, Hawtorne effect, Genovese syndrome, nervous sweating and numerous of other effects that could introduce unstable results into an experimental test. In addition to the instability, the diversity of human behavior and biometric data is large, and could be attributed to a number of factors as gender, genetics, culture, political view and education. When designing a product, identifying all potential users in advance could be difficult as the product is often sold to a user without stating what behavior or biometric data the user should possess (obvious examples on the opposite are shoe and clothing sizes).

3.2.2 Product system

The product system class are the properties of another product structure not part of the prototype itself, as a manufacturing machine or a structure for which the prototype forms a substructure. In many cases, these product systems are of high certainty, as they are often possible to isolate and investigate without the influence from other classes. Examples of product systems could be a milling machine used as the manufacturing process for a component, or an airplane used to test a proposed prototype wing design. The latter example is often called an integration test (Ulrich & Eppinger, 2012). Especially automotive manufacturers have dedicated platforms for integration tests called mules, on which different prototype components are applied, as in Balaji, Agarwal, Mungi, Babar, and Katkar (2013).

3.2.3 Physical environment

This class include the properties that do not fall into the two previous categories. This will normally comprise environmental loads and characteristics, and could be natural elements as wind, water, gravity, soil characteristics or constructed elements as roads, houses and cargo. The certainty of these properties is extremely dependent on the objective and purpose of the test. The certainty of a test supposed to embrace all environmental loads the product might encounter through its operative life would be a lot lower than a test of a single load at a stated level and certain number of repetitions at a determined duration.

By using DOE terminology, we split the variables into two categories: controllable and uncontrollable. All test environment classes can obtain such variables, and all classes can obtain an output. The properties of the class dictate how it processes input variables to change interactions with the other classes and create outputs. One way of displaying these variables and outputs is by using the cause-effect or fishbone diagram (Montgomery, 2008, p. 14). However, this method does not deliberately categorize the outputs to a property class, they are only collectively treated as a "common output". The model does not display the relationship between the classes. A proposed model building on the fishbone diagram, which to a further extent display the interaction between and output from the classes, can be seen together with the fishbone diagram in Figure 3 – Fishbone diagram and proposed model of classification of properties and variables

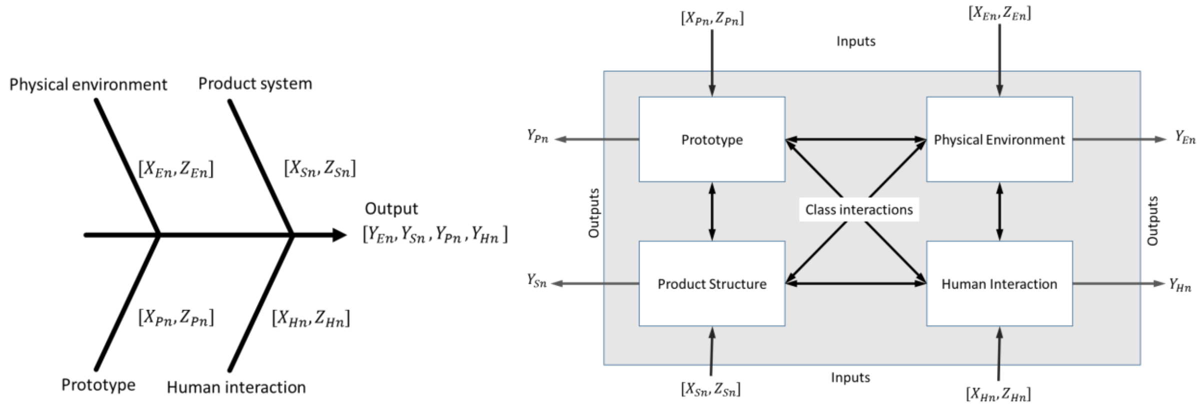

Figure 3 – Fishbone diagram and proposed model of classification of properties and variables

It is important to mention that the output of a class does not necessarily depend exclusively on the input variables and properties of the class, but due to interactions, could potentially be dependent on all classes. Depending on the purpose of the test, the data acquisition should sample the output of interest.

3.3 Replication of class properties

The properties of the test environment and prototype could be introduced to the experiment using three main types of replication, or a combination of these:

3.3.1 Physical replication

This category embraces all types of replication where property is recreated by connecting to the real physical property or a simplified physical version. Examples of the two respective types when testing the aerodynamics of an airplane are field testing in air or isolated in a wind tunnel.

3.3.2 Analytic estimation

Analytic estimation describes use of numbers in form of equations, regulations, legislations or computer algorithms to replicate the dimension. This includes, but is not limited to: finite element/volume analysis, FRF equations, hand calculations and CAD interference checks.

3.3.3 Reflective estimation

This includes use of common sense, rule of thumbs or tacit knowledge to introduce the dimension. Often when a trained metal worker/machine constructor is presented with a proposition of a machine drawing or a CAD model he would sometimes point out those features that will be difficult to make, what welds seems too small and mounting problems you might encounter. This would often be without taking correct measures, doing calculations or trying to construct the part, by using knowledge about previous work and rule of thumbs.

4 Conceptual study of framework

As a part of improving and developing new products for flood protection, four prototype tests have been performed. Each of the tests had their own objectives, prototypes, and test environments. The product system consists of multiple “bookstand modules” connected together with waterproof canvas and sealed to the ground with a semi-watertight seal underneath the modules. The product is meant to be deployed in case of a flood forecast, creating a temporary water barrier.

The cases are selected to demonstrate the extended design-build-run-analyze model, decomposition of test environments, and investigate apparent attributes of test environments for prototype tests.

4.1 Test bench experiment

This test was done to verify two proposed modules according to ANSI/FM standard, where the scope was to ensure that the modules could withstand hydraulic and hydrodynamic loads acting on the product after deployment. The prototypes that were used was 1.80 and 2.10 m high modules without canvas, and were tested in a custom-made hydraulic test bench.

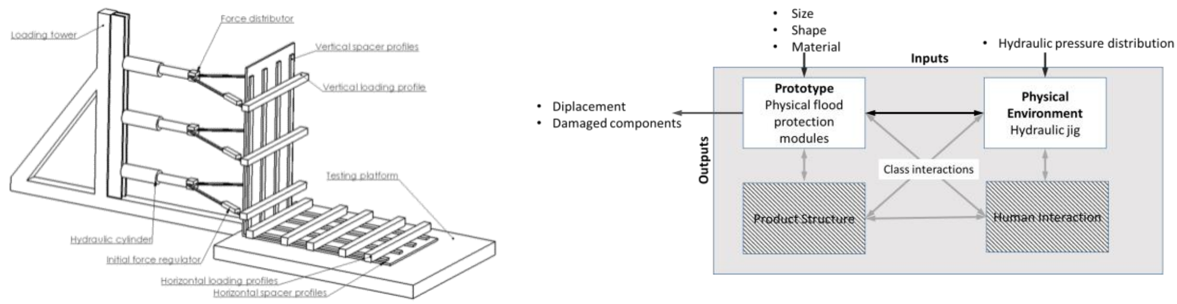

Figure 4 – Test bench test characteristics

In this scenario (deployed/stationary module) there is not supposed to be any human interaction, so all properties depending on this class were neglected. The product is supposed to be mounted together with other similar modules, creating a product system. However, this was neglected as well since each module is designed to translate a minimum of loads to neighboring elements. The physical environment was recreated using a combination of physical replication and analytical estimation. Wave pressure loads from construction guidelines (analytical estimation) was applied to the elements using hydraulic cylinders and beams (physical replication).

The test-bench concept also allowed experimentation with loads much higher than what would have been possible using water. This allowed investigation of loads beyond hydrodynamic wave loads, and enabled targeting the system safety factors to collapse. This did prove valuable in the process of achieving FM approval, which was the main objective of the experiment. Having constructed such a jig for replicating a physical environment it is possible to perform the same type of tests for similar constructions in less time, and therefore enabled a rigorous testing of two different proposed modules. This reusable physical asset can be compared with the non-physical project-project knowledge transfer, as described by Thomke and Fujimoto (2000), which can shorten product development lead-time. However, the design of the test bench requires that the plates of the tested module are plane, which limits exploration of other alternatives using the same test bench.

4.2 Computer simulation

The purpose of this test was to investigate the possibility of changing from an existing plywood-rod design to injection molded plastic elements. The main objective was to identify target thickness and material stiffness for such a module. The investigation included a CAD model and finite element analysis with two thicknesses and two types of material stiffness.

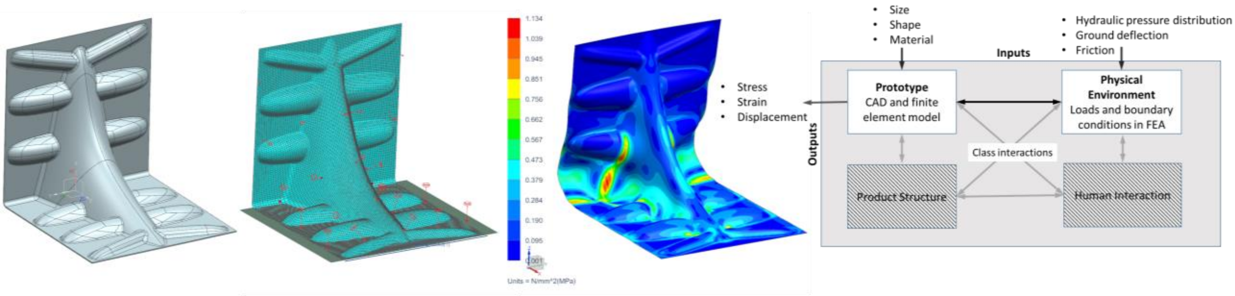

Figure 5 – CAD, FE model, results and test characteristics

As in the previous case, no human interaction is anticipated at this phase of usage and product system influence should be minimal, and was therefore neglected. The physical environment was introduced as loads and boundary conditions in the simulation, adding hydraulic load (corresponding to maximum still-water level), ground anchoring and soil/module friction.

Multiple iterations around the prototype and the environment was performed while establishing a suitable CAD and FEA model. For example, adding Y-shaped stiffeners on top and bottom of the geometry, adding friction between modules and ground and considering non-linear behavior of the module. Three different reasons for iterations were identified; improving product performance, improving confidence level for the results and achieving computability (making the simulation work). The obvious limitation of using a virtual (analytical replication) prototype is that it prohibits the use of physical replication of any of the test environment properties. The use of analytical estimation of both prototype and test environment did prove efficient when changing product and environment characteristics, which is in accordance with Ulrich and Eppinger (2012) who state that analytical prototypes tend to be more flexible than their physical counterparts.

4.3 Tub test experiment

The purpose of this experimentation was to identify possible solutions for sealing between the modules and the ground. The mechanisms for sealing, effect of leakages and the effect of geometry were considered. The tests were conducted in a plywood test tank, using a replication of the modules made out of acrylic plates connected with rubber sheets and strings. The physical environment was introduced using physical replication. Water loads were first recreated using a plastic tub with water. This was found unsuitable to the task due to insufficient structural strength, and therefore replaced with a plywood test tank. The ground was recreated using both flat ground (plywood) and pebbles attached with bed liner paint. The rest of the flood protection modules were recreated using aforementioned acrylic plates, which were equipped with a variety of prototype seals. There are many variables in the product system that might change the result (e.g., size and shape), though none of those were explored, and neighboring elements were also neglected as in the previous cases.

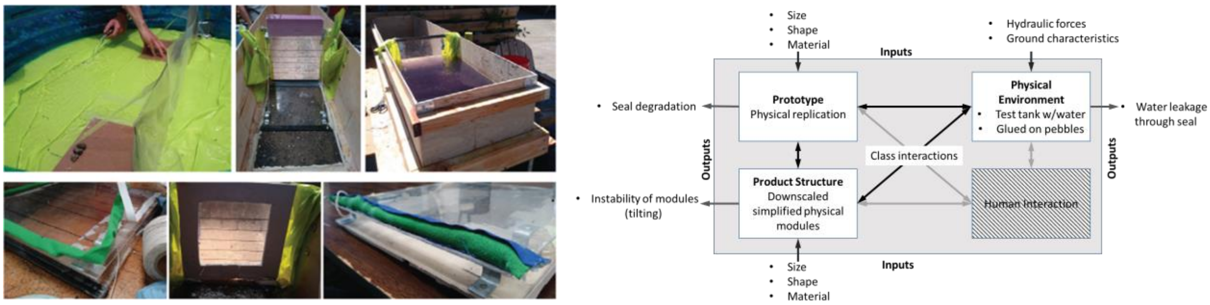

Figure 6 – Pictures of the tub test setup and test characteristics

As in the computer simulation, this case had iterations around the prototype (different seals) and the test environment through the replication of the physical environment (plastic tub to plywood tank). The simple construction of the physical environment and the product system allowed for rapid change of prototype seals. As there was no data acquisition of the water leakage (only estimation by visual references of “more leakage” as opposed to “less leakage”), the experiment did not gain any explicit knowledge of sealing performance. However, the developers gained a thorough understanding and tacit knowledge of the mechanisms involved.

5 Concluding remarks

This paper shows that iterative cycles when performing prototype tests do not only evolve around the prototype, but also the around the test environment. The iterative design-build-test-analyze cycle does not only aim for improving product performance, but also improving the test environment and for increasing the confidence level of the test results. Some test environments are built for reuse together with multiple prototypes, while others are tailored for single events.

The model for characterizing prototype tests, influenced by DOE concepts, did provide a clear graphical description of the process, and the demonstration displayed two types of replication (physical replication and analytical estimation) and three types of property classes (prototype, physical environment and product structure). The cases provided did however not identify elements testing human interaction, or the use of reflective estimation. For filling in these conceptual elements through further research, this should be targeted by *theoretical sampling* of cases, as described and justified by Eisenhardt (1989).

Further studies should in addition to investigate test environments that includes human interaction and reflective estimation, investigate whether, and in what way, the attributes of the test environments affects the prototyping and product development strategy.

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