A Heuristic Approach for Early-Stage Product Development in Extreme Environments

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Abstract— **This article considers a heuristic approach for developing products for extreme environments. The authors propose a set of heuristics for exploring environment and product features throughout the design probing process. The proposed strategy is exemplified through several cases, with special emphasis placed on a project that considers developing new products for aluminium electrolysis shop floor environments. These heuristics are presented as an approach for dealing with large amounts of uncertainty in an early-stage product development setting.**

Keywords—engineering design; probing; early-stage product development; environment prototypes; product prototypes;

I. INTRODUCTION

Rooted in the early stages of product development, this paper discusses a heuristic approach for early-stage product development for extreme environments; i.e., a delimited space with a combination of external, physical conditions, exceeding the limits of the standard environment conditions, that influence the growth, development, behavior and operational life of products. How we choose to design, build and test may be influenced by the different extreme environmental aspects—extreme parameter values, parameter variations and relations between parameters. Handling the challenges related to these aspects, and the difficulty of setting initial requirements when working under such harsh conditions, have been motivation for the approach to be discussed below. The strategy involves probing both the environment and the product throughout the concept development phase. Probing is referred to as an interdisciplinary development cycle where ideation happens through divergent thinking and open questioning, then subsequently, converging, as the prototype concept is evaluated.

How can we facilitate exploration of relevant environmental aspects to aid determine product functionalities in early-stage product development?

From an overall objective for the project, we apply probing to elaborate on objectives, thus increasing the level of detail toward a concept solution. The approach takes a critical look at revealing causality during testing, and suggests applying environment parameters one-by-one. This should allow designers to identify root causes of environmental effects.

In this paper, we will use contextual examples from concept development of an unmanned unit performing anode covering in an aluminium electrolysis plant environment processing raw aluminium-oxide into aluminium. This case is used as both an example for the different aspects of extreme environment and for exemplifying probing of both the environment and the product. In the electrolysis process, large carbon anodes are placed in electrolysis pots at high temperatures. Inside the electrolysis pots, the anodes are covered with an alumina/sand/gravel mixture (from here referred to as "cover mass") for thermal insulation of the electrolyte bath and to prevent unwanted oxidation of the anode that will occur if exposed to the surrounding air over time (Fig. 1). The carbon is slowly sunk into the electrolyte bath by the attached, current-leading yokes, which are made from copper.

This research is supported by the Research Council of Norway through its user-driven research (BIA) funding scheme, project number 236739/O30.

II. ASPECTS OF EXTREME ENVIRONMENTS

Environment is defined by [1] as the combination of external, physical conditions that affect and influence the growth, development, behavior, and survival of organisms. If one put products in the role of the organisms, much of the definition applies. Gomez [2] relates extreme environments to inhospitable conditions for life, describing it as a habitat characterized by harsh environmental conditions, beyond the optimal range for the development of humans; for example, pH 2 or 11, -20°C or 113°C, saturating salt concentrations, high radiation, and 200 bar pressure, among others. Cressler [3] describes the extreme environment his transistor and electronics systems must cope with as surroundings lying outside the domain of conventional commercial or military specifications. In what Schrage [4] refers to as 'Spec-driven' engineering, this would probably be a rather convenient description.

From these definitions, we define an **extreme environment** as a delimited space with a combination of external, physical features, deviating substantially from the standard environment that influence the growth, development, behavior and survival of products. Typically, these standard environment conditions are set to an indoor workspace with common values, say, staying around 25 °C and 1 atm of pressure, etc.

Fig. 1. Two anodes covered in mass, but with excessive tearing in front after long air-exposure. The front plate is shown in the bottom of the picture, and the current-leading yokes ascend from the mass, on top the anodes. Picture courtesy of Alcoa Mosjøen.

To achieve sound product functionality under harsh operational conditions, and to understand how to maintain this, it is important to acquire what is accessible of relevant environment data. This would typically be measurement data of the different **environment parameters**, e.g. temperature, luminosity, pressure, humidity etc. Cressler [3] exemplifies typical influencing parameters in his studies of electronics for lunar missions as extremely low temperatures (e.g. -269°C or colder), very high temperatures (e.g. 300°C or warmer), very large and/or cyclic temperature swings (e.g., -230°C +120°C night to day, as found on the lunar surface), and ionizing radiation (e.g., aurora). These are examples of conditions ranging between two extremes. [3] also explicitly points out the fluctuation as a challenge in itself.

We identify three aspects of extreme environments that should be taken into consideration in the process of early stage product development. First, the **extreme values**—the extreme values of a specific environment parameter. Second, the **variation**—how values vary in both time and space. Third, **relations between parameters and resulting effects**—how different parameters interact and create effects that influence the behavior of products.

A. Extreme Values in the Environments

One can think of an extreme value of a parameter as a substantial deviation from a predefined environmental, technological or physical standard. This extreme value is often the basis for an early characterization of the extreme environment. The extreme value is important when looking at how the extreme environment will influence the product capabilities. The standard represents the norm which is perceived convenient for a respective development project. It could then make sense to relate the extreme environment to a related a priori-known environment, e.g. a marine environment as the standard in relation to an arctic, marine environment as the extreme. Hence, while shifting the focus toward the extremes—i.e., what separates this particular environment from the (known) standard, representing the focus herein. Pahl & Beitz' [5] term of 'overall function of the product' does not usually concern itself with the environment at all—this being extreme or not. However, by identifying discrepancies between standard and extreme environments early on, this represents the first step of understanding of the potential challenges and how it will impact the design as progress is made.

B. Variation in Environment Parameters

By variation in environment parameters we mean the spread of measured values. This might be generally high dispersion in the measurements of a parameter, or when there are prominent deviations between a parameter's mean value and its extreme value. Variation may both be time and space dependent. High variation then makes us ask questions on what context we are going to design for. Designing for the extreme value or mean value of a parameter might seem insufficient. Then testing the behavior of product and environment within the range of limit values is an approach that is further discussed below.

There are several examples of variability in environment parameters in the case of an aluminium electrolysis pot. One key parameter is temperature, where cavities in the cover mass radiate heat from the bath up to temperatures between 600-900°C, sometimes including flames from burning gas. Where these cavities are, how big and how many, vary significantly. IN most cases the anodes are properly covered, thus leaving an average surface temperature of the cover mass at about 200-350°C. This is an example of a major deviation between the mean and extreme conditions within the same environment. It is also likely to have a high variation of measured thermal values due to the variety of the cavities.

An example of an extreme value with low variation is the presence of a 250 Gauss magnetic field caused by the strong, but steady electric current through the pot. This parameter could then be tested for only this value, as opposed to testing for a range of values for high variation parameters.

C. Relations Between Parameters and Resulting Effects

By relations between parameters and resulting effects, we consider the co-occurrence of multiple environment parameters and their resulting effects that might influence the product solution. These effects may obviously differ from solution to solution, and between the product and humans. One example is Palmer & Croasdale [6] who suggests danger and discomfort for human beings in the artic as the combined effect of wind and low temperatures by an analytic wind-chill index [7], which again can be linked to heat transfer models that calculate the likelihood of frostbite. Heat transfer between the air and a human body is plainly complex, and involves factors such as whether one is primarily concerned with an exposed face or with cooling of the whole body. There are also dynamic effects: cooling is most rapid at the beginning of exposure since the skin blood vessels have not had time to contract. This shows how the effect (chilling) sprung from the combination of parameters (low temperature and wind), and how this effect may change as the body (or a product for that matter) adapt its behavior.

The human body could pose as an analogy to complex products where the same phenomenon of effects from combined parameters would apply. All kinds of situations where certain parameters are prominent, certain effects from combining the respective parameters may be prominent. Some examples are applications of E-glass/epoxy composites, where the properties are altered from combined parameters of load, moisture and temperature [8], or the combined influence of temperature and pressure for water vapor transport through textiles at high altitudes [9]. How one divides the environment into separate tests of parameter effects, and thereafter recombine parameters to determine effects from parameter combinations, is explained further in section III.E.

III. Elaborate on Objectives Through Probing Both Product and Environment

A. The Approach of Probing both Product and Environment

Gerstenberg et al. [10], describe a design probe as a prototype where new knowledge is created and tested by deduction, induction and abduction (Fig. 2). In principle, it is an interdisciplinary development cycle where ideation happens through divergent thinking and open questioning, thus stimulating creativeness. Subsequently, convergence occurs as one evaluate the prototype concepts [11].

The concept of probing has earlier been applied as a way of iteratively discovering and changing functional requirements by developing prototypes built on existing functional requirements until a satisfying solution is found [12]. This way, the development team has a dynamic approach towards the design criteria. This is similar to what Schrage [4] describes as 'prototype-driven' development, as a contradiction to 'spec-driven' development. In the latter, prototypes are designed according to predefined specifications. The approach in this article adapts the 'prototype-driven' development form the aspects of divergent and convergent thinking around both the product and the environment wherein it operates.

Design probing is an iterative prototyping of solutions for proving functionality, thus arriving at the best local optimum within the explored solution-space, according to [12]. Similarly, an iterative prototyping of test environments involves creating or utilizing different environments featuring (a set of) common functionalities. The different environments are equivalent to the product's solution-space. As for the product, one may evaluate an environment prototype the same way, and then build on the knowledge for later iterations; hence, revealing parameter relations as the environment prototypes gets more complex.

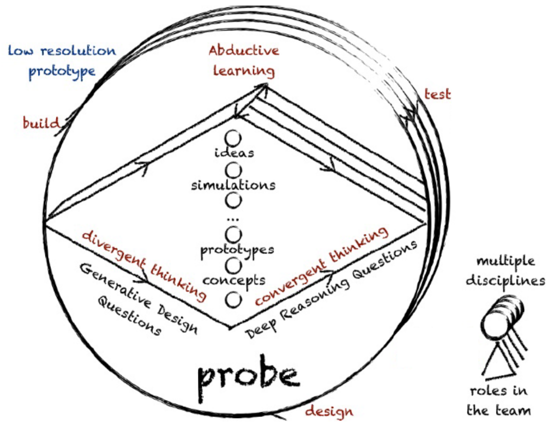

Fig. 2. Probing cycle, adopted from [5].

An example of unclear causations can be found within an aluminium electrolysis pot. The anode covering mass has a certain hardening rate, and one could find the frequency of needed covering to avoid total hardening by looking at the hardness versus the time that the mass lays untouched. From this information alone one might think the mass is hardening over time, due to for instance air-exposure. However, as one acquires more knowledge of the conditions, the pot's air temperature, the thickness of the mass layer and the content of the mass, all do influence the hardening rate. Eliminating the effects of these parameters would cease the hardening, thus eliminating the assumed relation between hardening and exposure time. Failing to uncover root causes may lead to false or incomplete understanding of the environment, which in term may negatively influence the value of the developed solutions.

Having an explicit focus on probing the test environment as a prototype on the same terms as the product prototype, should help the development team test relevant product functions versus relevant effects from the environment. A general rule for developing new knowledge or understanding is to avoid introducing more than one change at the time. This is true for both prototypes and environments. The reason for not changing more than one parameter at the time is to isolate effects that come from specific changes. In the case of extreme environments, extracting the influential parameters into a respective environment prototype by testing their effects separately should establish a clear relation between environment parameter and product behavior. After gaining control over the individual parameters, the design team can start combining them to investigate potential new effects and responses.

The incentive for the approach of probing both environment and product is providing continuous awareness of, and learning about, the environment throughout the development process. This resonates well with the dynamic requirements in probing as new discoveries about the environment is likely to affect and change our view on the product and its objectives. The learnings acquired from environment prototyping is mostly about confirming or debunking our (pre)assumptions of what the critical functions of the product should be, and how our product will impact the environment. Therefore, striving to expose

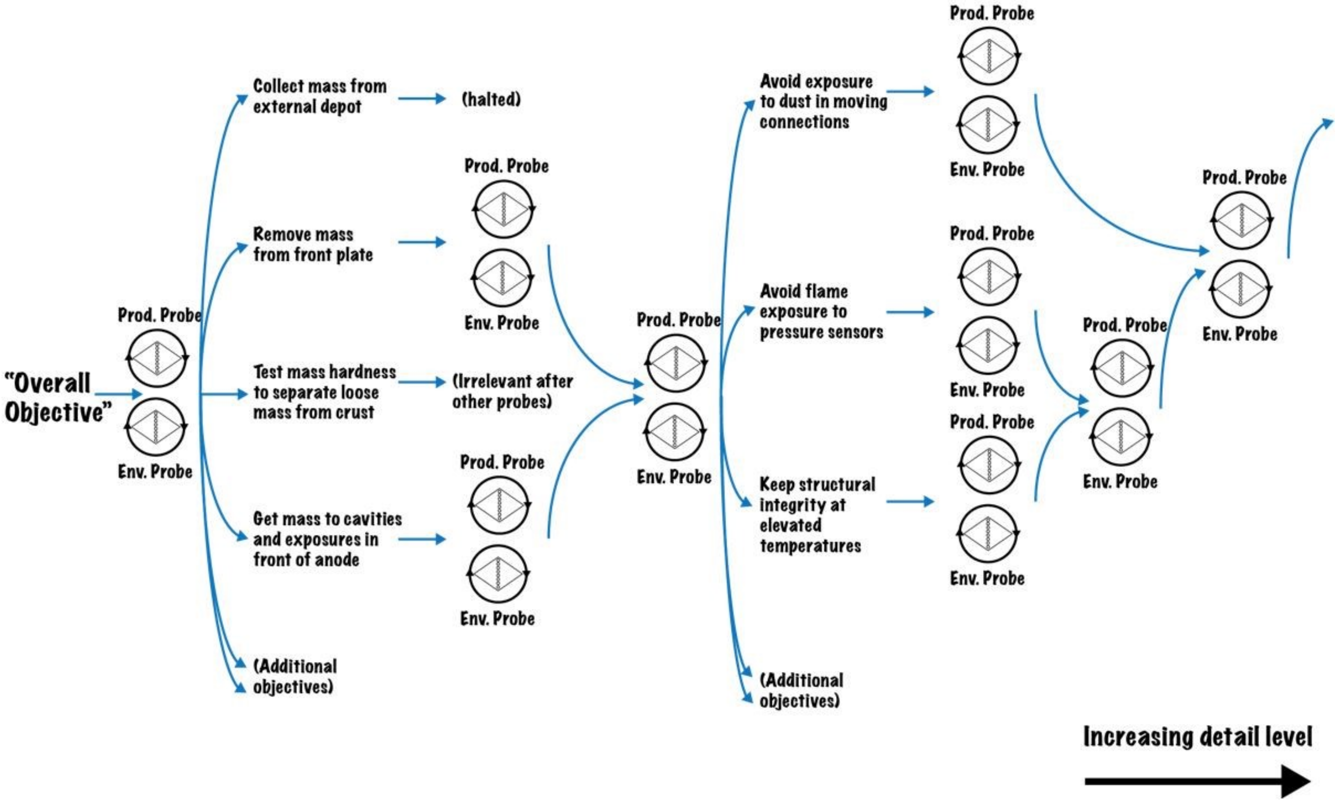

Fig. 3. Example from the 'elaborating objectives' of the the anode covering unit. Probing product and envronment for different objectives generates knowledge to elaborate further objectives and functions as a way of detailing our concept. As the detail level increases, product functions and relevant environment effects for different objectives are combined in new probing cycles.

causes by stepwise testing and adding parameters, and converge towards the actual environment, is essential.

B. *Establish the Overall Objective*

Initially, the product developer's focus should be on establishing the overall objective. This objective may not necessarily be directly determined by the product's operating environment. For instance, much of the core functionality of both soft- and hardware of smart clothing for arctic environments could be evaluated under more regular conditions [13], as indoors, to demonstrate functionality, e.g. equipped clothing and electronics.

The overall objective is similar to what Pahl & Beitz [5] refer to as the overall function. The reason *objective* is used instead of function is to reduce solution-bias when working toward objectives rather than defining functions—even though the latter term is common. This is especially true in early stage product development where the focus lies on staying open minded in terms of what the end-product might be. Pahl & Beitz then further evaluate the complexity of the overall function. By complexity they mean the transparency of the relationship between inputs and outputs of a product. They break the overall function down into less complex sub-functions to describe the functionality less ambiguously and facilitate the subsequent search for solutions. They call this establishment of additional sub-functions a "function structure", and has commonly a main flow to focus our attention of development. In this article, the analogy to establish such a function structure lies in the *elaboration of objectives*.

The overall function is according to Pahl & Beitz governed by initial requirements. However, for extreme environments we may concern ourselves with high variation in the environment parameters and obscure parameter relations, which makes it harder to define clear requirements to begin with. A more dynamic way of setting these requirements is using probing. One can elaborate on one's objectives through probing, rather than establishing a structure that is prone to continuous change from new understanding of the interaction between the product and environment.

C. *The First Product/Environment Probe and Utilizing Existing Prototypes*

Getting an initial understanding of the objective (and potential challenges) through interaction, benchmarking and gaining general information about the operating conditions. The initial interaction with the environment may be viewed as a first environment probe. This may be a physical interaction with the actual environment, or something just resembling it. We are then utilizing existing conditions for acquiring knowledge.

An existing product prototype in such a setting might be a previous version of the product, or simple tools or goods helping to recreate aspects relevant to the overall objective. For automatization of anode covering in our aluminium electrolysis plant case, this existing product prototype is typically the current

Fig. 4. Probing rake and pot environment. Picture courtesy of Alcoa Mosjøen.

raking-tool for shoveling mass. By testing the rake, and the raking operation in the pot in person, we physically interact with an existing product prototype and environment prototype (in this case the actual environment). Seeking out realistic environments early is a good opportunity to get invaluable information from experts and experienced personnel.

Based on the work of Gerstenberg et al. and Kriesi et al. [10, 12], we note that a central part of the learning process of prototyping comes from building the prototypes—to observe the different components come together and understand their relationships. After the first probe, it may be sufficient to recreate/build parts of the features for some tests when comparing time and effort to the potential learning output. As you then elaborate on your objectives, the utilization of 'existing prototypes'—something that resembles the functionality you want to achieve, is an important tool to learn fast during probing. For products, this might be high-end existing products, such as industrial robots or computers, or low-end hand tools. An existing environment might be a landscape with certain features relevant to the real test environment, such as a crater landscape hosting lunar analog terrain in the rover example.

D. Elaborate Objectives Through Probing

The process of 'elaborating the overall objective through both probing the product and the environment' is best explained through exemplification (Fig. 3). In the case of automation of anode covering in aluminium electrolysis plant ovens (as described in section I), the overall objective would be to "cover potential cavities or anode exposures". Full automation and mobility of the unit performing this covering is desired, and the concept system rapidly becomes complicated. Thorough background research on the facility was done, gaining input from technical personnel, and technology analysis, before new objectives were set for the early-stage concept generation phases. These objectives were: 1) Acquire available mass; 2) Move mass to potential cavities or anode exposures; and 3) Cover potential cavities or anode exposures.

Note that the initial probe involved visiting the actual environment and testing the raking procedure in the production facilities, as mentioned in section III.C. From this initial probe on the electrolysis pot environment (real environment) and rake-tool (existing product) (see Fig.4), further objectives could be elaborated. Here, the designers first diverged by asking themselves what can be learned from this opportunity of interaction, before converging by using the insights from testing.

Establishing the objective on acquiring mass was particularly important. However, the mass accessibility is an uncertain aspect of the environment due to the uneven hardening in the pot and busy infrastructure outside. Other newfound objectives (e.g. the 'remove mass from front plate' and 'get mass to cavities and exposures in front of anode') were also crucial to the overall objective, and had certain functions that unified well with a mass acquisition objective of transporting existing, loose mass along the mass surface. Further elaborating on the objective of mass acquisition from outside the pot was then put on halt.

The designers had now progressed to objectives concerning direct interaction between the cover mass surface and an automated unit. The next design probe concerned recreating the cover mass material, specifically mechanical properties. A product prototype could then be introduced with the task of distributing the material on a surface. The actual cover mass contains condensed toxins, unsuited for a regular workshop or working-space. Prototyping a resembling mass for testing mass-movement functionality in our objective was necessary, due to the hazardous. The other incentive was, as previously argued, to materialize the designers' idea of the environment (the mass) and evaluate it, thus 'calibrating' the designers' understanding of the environment. Various product prototypes were then tested for moving mass. Probing how to move mass up in front of an anode led to a test of the purely mechanical function of moving mass in that manner. An environment prototype based on dimensions and resembling topography of the anode-front was then built. Firm, bulk materials beneath the loose mass was an important effect in the environment prototype, resembling uneven hard crust. A combined environment prototype of the mentioned probes is shown in Fig. 5.

After building an environment prototype (Fig. 5), the designers could then test different product prototypes in the environment prototype. A combination of several product functions tied to these objectives are shown in Fig. 6. One of these combinations involved damage protection and calibration objectives. The designers originally did not perceive these as relevant before initial solutions for mass-moving tools were tested. These solutions were respectively built on the 'clean plate' and 'move mass' objectives.

Fig. 5. Prototyping (aspects of) the anode covering environment.

Given the overall objective, and that electronics (including actuators) and moving parts are particularly vulnerable to the heat and dust, the designers had up to this point considered the solution space to be mostly mechanical. From testing, basic electronics and microcontrollers, such as an Arduino board [14] controlling blinking LEDs and small servo motors temporarily malfunctioned when stationed by the pot's entrance. Solutions where these elements could be withdrawn from the extreme environment, or less exposed, have been favored. Further emerging objectives might be 'avoid exposure to dust at moving connections'; 'avoid flame exposure to pressure-sensors'; 'attain structural integrity at elevated temperature' etc.

This example highlights how some objectives may be temporarily halted, because some other objective is more crucial to explore further (much like Pahl & Beitz's 'main flow'), or it might simply be proved irrelevant by other probes. How one can combine probing of product prototypes and environment effects relating to certain objectives one-by-one is shown in the right-hand part of Fig. 3.

E. Heuristics on Learning From Environment Probing

It is first when combining parameters and see their resulting effects that one understands what is truly causing the behavior between the product and the extreme environment. Decomposing the extreme environment first should facilitate this insight. We then have experience with testing product versus single environment effects, interacting on several levels of combined functionality. This way, it is easier to reveal what is causing different (unexpected) behaviors when parameters are combined. Continuous evaluation, both of product and environment probing, from relevant stakeholders should be included throughout the process. This is especially important for the environment probing, since it is likely to be the most difficult to evaluate for the developers.

Ultimately, testing in the real environment is needed to uncover discrepancies between the environment prototype and the real environment. This should both work as verification of understanding and estimates of the environment, as well as reveal potential relations of parameters and their true effect.

IV. Future Considerations

When designing for extreme environments, a very common question is whether the product's materials and technology is sufficient to cope with the conditions or not. As mentioned in section II, extreme environment is likely to pose more challenges than the extreme parameter values do alone. What is sufficient under very varying values and types of parameters is hard to say when also relevant data is hard to acquire. Utilizing good product benchmarks is then important to have some beacons in the solution-space. For example, if rubber is known to do its job well when sweeping cover mass, but it also has a short lifespan, then making solutions based on simply changing the rubber throughout operation might be a more wanted solution than finding more expensive alternatives. In other cases, we do not have this luxury, or the stakes of insufficiency is simply too high to go for anything but the "best".

In his work on researching fundamentally adaptable electronics, Cressler [3] points on the "warm box" solution for lunar rovers, a common approach of shielding prone technology from the environment (in this case from cryogenic conditions), as crude at best. He points on how this "warm box" design-approach critically limits the designer's ability to create a truly distributed system for such rovers, resulting in excessive point-to-point wiring, increasing system weight and complexity, lack of modularity, and an overall reduction in system reliability. We see how these drawbacks also apply to heat and magnetic shielding of electronics and actuators brought into an aluminium electrolysis pot. However, a consideration of stakes and accessibility should of course be taken when evaluating sufficiency of material and technology. Failure on the moon is likely to have way higher stakes than failure in an automated unit in an aluminium plant in the unfortunate case of insufficient or malfunctioning machinery. Based on this, we consider the level of coping technology and material to not necessarily correlate with the environment's hostility alone, as this will depend on stakes and accessibility.

In the case of high variation for certain parameter values, it is more convenient to uncover a certain threshold of what we can expect to be sufficient of material and technology—especially if the material or technology needed to withstand the extreme value has a way higher cost, restriction or sophistication than materials or technology required for more nominal conditions. Having possibility to tune these conditions in environment

Fig. 6. Product prototype for ultimately performing anode covering autonomously. Several solutions for different functions are here combined.

prototypes could be a good facilitation for maneuvering toward the respective 'sufficiency threshold'.

V. CONCLUSION

In this paper, we describe an approach for early stage product development in the context of extreme environments. It emphasizes our finding that environments should be prototyped with a similar approach as products before testing environment and product together. The prototypes of both products and environments are generated with specific environment parameters or product functionality in mind. Knowledge on product behavior is developed through testing solution principles versus single environment parameters and their corresponding effects. When we then later combine parameters for testing, we may assume a potentially new product behavior to be tied to the relation between the parameters and their new effect. We then already have experience with the individual parameter effects and the respective product behavior, to make such an assumption. Eventually, testing in the real (or close to real) environment is crucial for validating our assumptions regarding the environment and the testing.

We base our approach of probing (iterations of divergent and convergent solution thinking) the product and environment together where environment parameters affect product functionality. 'Existing prototypes' may be used, but focus has to be placed on the right factors that are causing product behavior. The way we choose to test, the materials and the prototype's resolution, may all be influenced by the different extreme environment aspects—extreme parameter values, variation in parameter values and relation between parameters.

It may be hard or not necessary to set strict, initial requirements for our product concept, due to the extreme environment aspects stated above. We suggest an approach to work towards objectives, and elaborate them through probing both the product and the environment. This way new objectives may naturally evolve as some may become redundant along the way, while keeping the critical functionality of the product in mind.

ACKNOWLEDGMENT

The authors would like to direct special thanks to Alcoa Mosjøen for providing support and context during the project. The close cooperation with M.Sc. student Even Jørs has been greatly appreciated in this project.

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