Filtering and Informing the Design Space: Towards Design-Space Thinking

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Building on the concept "prototypes that filter the design space," we establish how other kinds of design artifacts and activities (e.g., sketching, tests, concept posters, metaphors, design tools) are equally critical in filtering the design space. We also suggest a parallel term, "informing the design space," to define how design artifacts and activities expand the design space. We focus on a 16-month, full-scale media architecture design project and zero in on seven of its component events, and use design-space schemas to shed light on the dynamics of the design space with respect to informing and filtering the design space. Our concluding contribution is to propose design-space thinking as a sub-discipline of design research. We argue that this research perspective serves to address the creative aspects of the design process, the generative potential of design-space thinking, and the tools that support design-space thinking and research.

CCS Concepts: • **Human-centered computing → Interaction design process and methods**;

Additional Key Words and Phrases: Design space, design materials, design artefacts, design process, design creativity, strong concepts, replication

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1 INTRODUCTION

In a highly influential *ToCHI* paper, Lim, Stolterman, and Tenenberg (LST) coined the phrase "prototyping as filtering the design space" [33], where *filtering* refers to extracting certain aspects of the design space for investigation (Figure 1(a)). The authors illustrated this idea with examples such as using two-dimensional (2D) prototypes as part of the design of a building, arguing that prototypes enable designers to explore and evaluate selected dimensions of the design space while temporarily ignoring others. Another example in the paper involved three prototypes of a digital camcorder—a 3D printed prototype, a screen-based one, and one based on a breadboard—which filtered three aspects of the design space, namely, ergonomics, input feedback, and input layout, respectively. The authors also proposed a set of general filtering dimensions (Appearance, Data, Functionality, Interactivity, Spatial Structure), which were refined into example variables, such as

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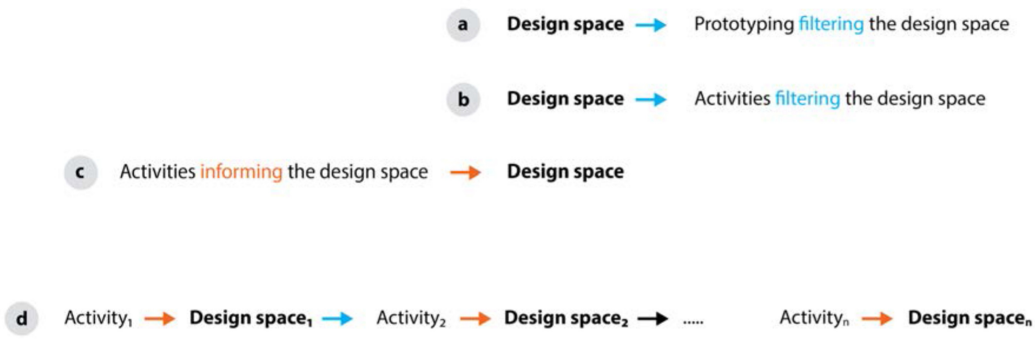

Fig. 1. (a) Prototypes as filtering the design space, (b) activities filtering the design space, (c) activities informing the design space, and (d) dynamics of the design space.

size and color. Understanding how such a design space may be explored and traversed by filtering the design space through prototyping is particularly relevant to this paper.

Of over 500 papers that cite LST [33], only a small percentage mention filtering (e.g., [4, 7, 12, 52]). In our reading, these papers do not seem to further develop the idea of filtering. The only exception is Schilling et al. [45], who propose a Focus Framework enabling to gain important insight into not only what is in focus in a series of prototyping events but also what is out of focus or even neglected.

LST do note that prototypes created from different materials may manifest the same sort of filtering in unlimited ways (Figure 1(a)). We build on this finding, and demonstrate that a design space may be filtered in numerous ways other than through prototypes, for instance, by a sketch on a whiteboard, a digital 3D model, a written scenario, a video scenario, and design tools (Figure 1(b)). More significantly, we build on LST's work by proposing a parallel term to "filtering," namely, "informing," to capture the process of establishing and expanding the design space, including informing the design space with images from field studies, the designer's repertoire, sources of inspiration, funding sources, design tools, and design activities, including prototyping (Figure 1(c)). In other words, the notion of informing the design space is intended to capture in a systematic way what are brought to the design process in order to understand the accumulated designerly knowledge of the design process. Whereas "filtering" the design space is concerned about the process of exploring and testing knowledge available at a particular point in the process, the concept "informing" is concerned about capturing how knowledge is generated through design activities. More notably, we offer insight into the dynamics of the design space as the unfolding of loops of filtering and informing the design space, a particular kind of seeing and moving, in the sense D. Schön [47] described (Figure 1(d)), which visualizes the general flow of activities informing as well as filtering. As the analysis of the case study in this paper will demonstrate, the process of informing and filtering the design space is not linear, but a complex web of informing and filtering. Moreover, whereas Schön theorized *situational* backtalk, we are suggesting that a detailed representation of the design space offers a comprehensive platform for backtalk with previous situations as well. Although LST were interested in shedding light on how prototyping contributes to cumulative knowledge acquisition during prototyping, our interest is broader. Our aim is to contribute to an even more comprehensive, diachronic understanding of design knowledge acquisition around the dynamics of the design space.

At a more general level, the paper may be seen as a response to the call to replicate and validate results of Computer–Human Interaction, called RepliCHI [55, 56]. Our research differs

Fig. 2. Plant a Light.

from earlier replication research [29] by (1) confirming an existing finding in a different or more complex context, rather than replicating a quantitative study; (2) investigating in the wild, rather than conducting a controlled experiment; and (3) studying a design process, rather than human interaction with user interfaces. Moreover, the approach is a particular kind of concept-driven design [51] and elaborate on strong concepts [28] by suggesting that strong concepts may generate ideas related to the design process. Whereas Wiberg and Stolterman [54] proposes generic design thinking as a way to understand the historical development of classes of designs and the design space they populate, we zero in on the development of the design space through which an ultimate particular emerges, and offers a conceptual approach to tracing the evolution of a specific design.

The core concept of this paper, "design space," is commonly used in interaction design, even though there is no single definition of the term. It may refer to the physical spaces in which design activities are carried out, but, more commonly, and of interest in this paper, the term is used in a metaphorical sense, as the space of design possibilities and alternatives that a designer considers, to meet a design brief [27]. Moreover, a design space may be represented in a number of ways, such as a Cartesian space [49], a network graph [58], or a conceptual space [3, 12]. The scope of a design space ranges from a class of technologies, over all accumulated knowledge during a specific design process, to the design space of a collection of designs, ideas, and sketches. In this paper, we address design spaces understood as conceptual spaces [27], and similarly to Biskjaer et al. [3] and Dove et al. [12], we apply a lightweight format, the design space schema, to represent a design space.

Most importantly, the term "design space" enables us to investigate how a design solution emerges and is shaped from a primordial soup of design materials, activities, and ideas.

In order to pursue this endeavor, we present a retrospective investigation of the 16-month design process of a media architecture project, Plant a Light, part of the Aarhus European Capital of Culture program, and operational from November 1, 2017 until December 9, 2017.

Plant a Light is an interactive media facade part of a botanical garden greenhouse where users can "plant a light organism" via physical interaction (see Figure 2 and the enclosed video). Visitors interact by placing a hand on each of the two hand-shaped marks on a pillar in front of the building. The pillar lights up and make a humming sound followed by a visualization of an organism emerging from the bottom of the greenhouse building. Each organism has a size of five window

frames on the facade and its lifespan is randomized from 30 seconds to 2 minutes. The organism also changes color to represent that it goes through different phases from birth to death.

We closely followed and documented the design process with photos of design materials and design activities, notes, and interviews. Initially, we identified over 60 events and activities, and for the purpose of this paper, we zero in on 7 of these events, and apply design-space schemas to visualize the design space at particular points in time, which enables us to shed light on the dynamics of the design space with respect to informing and filtering the design space during the several-month-long project. Hereby, the nuanced understanding of the concept of design space contributes to advancing our understanding of how design processes unfold over time.

This paper's contribution is threefold: (1) generalizing the concept of filtering, (2) suggesting the term "informing the design space" along with a set of strategies for doing so, and (3) demonstrating how conceptual design-space schemas enable the study of the dynamics of the design space. In line with LST [33], we define *filtering* as extracting certain aspects of the design space for investigation and define *informing* the design space as the process of establishing and transforming the design space.

We first position our research in relation to design-space research, and follow this with a presentation of our research method. For the main part of this paper, we present and analyze the media architecture design process, which provides the foundation for the discussion of contributions 1 through 3. The discussion is concluded with a proposal for a research agenda for design-space thinking research (contribution 4).

2 DESIGN SPACES

The term *design space* is commonly used in interaction design and in other design disciplines, and may take several different forms. In this section, we examine examples from interaction design and a broader range of related design disciplines, in which the meaning of the term has been more clearly outlined. Design space is occasionally used to refer to the physical space in which design activities take place (e.g., [44]). However, it is far more common for design spaces to be metaphorical ([3, 6, 16, 33, 41]), which are the kinds of design space discussed in this paper.

To provide an overview of the multiple ways of conceptualizing a design space, we identity three main categories of the scope of design space: (1) design space of a class of technologies; (2) design spaces as all accumulated knowledge; and (3) design space of a collection of designs, ideas, and sketches. We also address three different ways of representing a design space: (1) as Cartesian space, (2) as a networked graph, and (3) a conceptual space. Based on the various scopes and representations of design space, we argue for our design-space conceptualization and representation.

2.1 Scope of Design Space

2.1.1 The Design Space of a Class of Technologies. The concept of a design space has been used to organize various classes of technologies. Card et al. [6] have mapped the design space for input devices based on selected physical properties, and Nigay and Coutaz [40] have mapped the design space of multimodal systems with a particular focus on concurrent processing and data fusion. A more recent example is Beaudouin–Lafon's research on instrumental interaction, which provides a metric for comparing interaction techniques based on the design space of interaction techniques [2]. Other examples of classes of technologies organized as design spaces include tangible interaction [30] and graspable interfaces [16]. A recent study of the design space of a collection of media architecture displays is particularly relevant to this paper [24].

2.1.2 Design Spaces as All Accumulated Knowledge. The broadest understanding of design space may be the consideration of it as all the knowledge accumulated at a particular point in time.

Heape's design research embraces not only material artifacts but also social relations and activities [27]. The Questions, Options, Criteria approach to design-space analysis emphasizes how options and criteria may be analyzed to capture the decisions regarding an all-encompassing design space [34].

2.1.3 The Design Space of a Collection of Designs, Ideas, and Sketches. Approaching a design space as a collection of designs, ideas, and sketches includes workbooks and portfolios [18]. Understanding how such a design space may be explored is particularly relevant to this paper. LST describe how prototypes are used to traverse a design space and filter a particular area, and as concrete realizations of particular conceptual design ideas [33]. Along the same lines, Hassenzahl and Wessler [26] investigate the Repertory Grid Technique as an approach to gathering design-relevant information on the design space of artifact prototypes.

2.2 Representation of a Design Space

Originally, design space was interpreted as a Cartesian space whose axes represent specific design parameters and associated values [49]. In this way of representing a design space, a particular design occupies a single point in space, assigning each parameter with a specific value, and the formal representation of the design space enables heuristic searches of the design space for a design solution [50]. Representing a design space as a Cartesian space enables parametric design and is used in architecture or computer chip design. Related ways of representing a design space are tree structures [34], and a networked graph where each node is a design representation derived from its parents [58]. Whereas Cartesian and networked graphs are highly formalized constructs, understanding a design space as a conceptual space is subjective. A conceptual design is commonly represented as a number of aspects and associated options considered by the designer, including both potential designs and un-instantiated possibilities [3].

2.2.1 The Design Space as a Cartesian Space. Originally, the emergence of the design-space metaphor was typically interpreted as a Cartesian space whose axes represented specific design parameters, which should be considered against a backdrop of rapid developments in the computer sciences and cognitive psychology, and the associated early successes of contemporary research into artificial intelligence. This background is captured by Simon's characterization of design as a type of problem-solving based on heuristically searching a problem space for satisfying solutions [50]. In this model, a particular design occupies a single point in space, instantiating each parameter with a specific value, and may be one of many ideas that may address the constraints imposed on, and selected by, the designer. Similarly, Shaw describes a discrete Cartesian design space, the dimensions of which represent design decisions, with alternatives being values in those dimensions [49].

2.2.2 The Design Space as a Network Graph. The design as a search metaphor has been applied in computer-supported parametric design. Here, the design space is interpreted as a network graph in which each node is a design representation derived from its parent(s) in some way [58]. Design activity traverses this network to revisit previously represented design ideas, or to search for opportunities to generate and insert new nodes that represent possible design alternatives.

2.2.3 Conceptual Design Spaces. One important aspect of the design space as a search-space metaphor is that it is typically used to conceptualize a collection of possible design alternatives, many of which will not be instantiated. This may also be the case where design is not fundamentally considered as a computational search process, but the design-space metaphor is still used to refer to a conceptual space of possible design ideas. For example, Westerlund uses the design-space metaphor to represent all the possible design solutions [53]. This design space has no fixed

Table 1. Designs-Space Schema

Content	Display	Technology	Location	Interaction
Art	Cells	LED	Near building	Mobile phone
Weather	Canvas	Spots	Out in the city	App
Plants	Sub-cells	Laser		Physical object
Single light				Pillar
Processes in nature				Glowing pillar
Color change				
Plant cells				
Constellaction				

boundaries, and its dimensions need not be strongly defined. In this model, the objective of design work is to gain an understanding of the design space, and activities take place at its currently understood boundaries. Biskjaer et al. [3] describe a *conceptual design space* that is encompassed by particular constraints on creativity, which strongly influence what might (and might not) be part of the final design. This is conceived as a space of opportunities constructed through framing and inquiry, but, again, it is a space of largely un-instantiated possibilities. Dove, Halskov, and Hansen further develop this idea, demonstrating how design spaces may be understood as a particular type of conceptual space, which may be described with reference to important quality dimensions and the possible values by which these dimensions may be instantiated [12].

2.3 The Scope and Representation of Design Space in This Paper

In this paper, we are interested in the dynamics of the design space during a design process, in contrast to understanding the design space of a collection of final designs or technologies. With respect to scope, we address design spaces that are understood as conceptual spaces, which enables us to address not only quantitative information about the design space, as when design spaces are characterized as Cartesian space, but also design knowledge in a broad sense.

As previously demonstrated [12], the interpretation of the design space as a conceptual space enables us to highlight the dynamics of the design space, which change over time, and the way in which a selection in one dimension may send ripples throughout the entire space, and introduce constraints on other aspects.

Like Biskjaer et al. [3] and Dove et al. [12], we apply a lightweight visual format, the design-space schema, to represent a design space. A design-space schema is essentially a table with aspects listed in the top row, and a number of options for each aspect in the columns below them (see Table 1); in other words, the headers of the columns are the design aspects the designer is addressing and options below each aspect are the options or alternatives the designer considers. Here, we visualize selected aspects of the design space at the end of the design process discussed in this paper. These are "Content" (possibilities for narratives and what should be shown), "Display" (how the facade may be considered as a display), "Technology" (types of light sources), "Location" (where it may be possible to interact), and "Interaction" (how users can interact with the installation). Table 2 shows an abstract representation of the design-space schema format with the design aspect (A1, A2, and A3) in the headers of the columns and the options (e.g., A1-O1, A1-O2) associated with each aspect below. When considering design space as a conceptual space, we use the term "aspect" instead of "parameters" to also include non-quantitative elements of the design space, and we use the term "options" to emphasize our interest in the design choices made during the design process.

Table 2. An Abstract Representation of the Design-Space Schema Format

A1	A2	A3
A1-O1	A2-O1	A3-O1
A1-O2	A2-O2	
	A2-O3	

Table 3. Options Informed by the Design Activity in Italics; Options Filtered During the Design Activity Underscored with a Broken Line

Content	Display	Technology
Art	Cells	LED
Weather	*Canvas*	*Laser*
Plants		

Fig. 3. Informing the design space, indicated by italics.

To capture the dynamics of the design space during the design process, for the analysis in the case study (Section 4), we present the design space for each design activity of interest. And, as illustrated in Table 3, we use font style to indicate options informed by the design activity (italics) and those filtered by the design activity (underscored with a broken line). Visualizing the design space in this way enables us to explicitly represent the relationship between the design activates and the design space.

We can now offer a more precise definition of our two key concepts. Informing the design space is defined as the process of establishing and transforming the design space, and is captured by the conceptual design-space schema in terms of adding new aspects considered during the process, and by adding new options (see Figure 3). The design-space schema representation facilitates a more precise and detailed investigation of the very general observation that "design activities expand the design space."

Whereas "informing" concerns the expansion of the design space, "filtering" does not modify the design space, but facilitates the investigation of a selected part of it (see Figure 4). The design-space schema provides a consistent and precise representation for investigating in detail how not only prototyping but also other kinds of design activities filter the design space.

Though filtering and informing are distinct mechanisms, it is import to note that a particular design activity, for instance, an ideation workshop or a prototyping activity, may both filter and in turn inform the design space. For example, a prototype may filter options with respect to one or more options (a1 and b2 in Figure 5), and through the process, the designers may become aware of

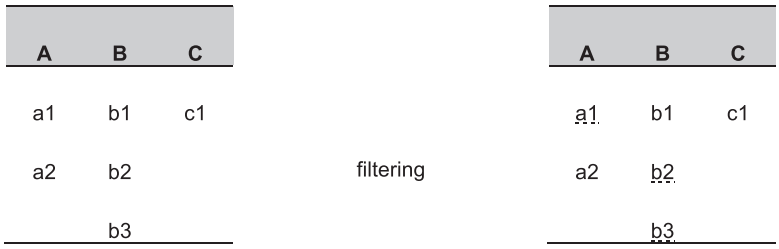

Fig. 4. Filtering the design space, underscored with broken lines.

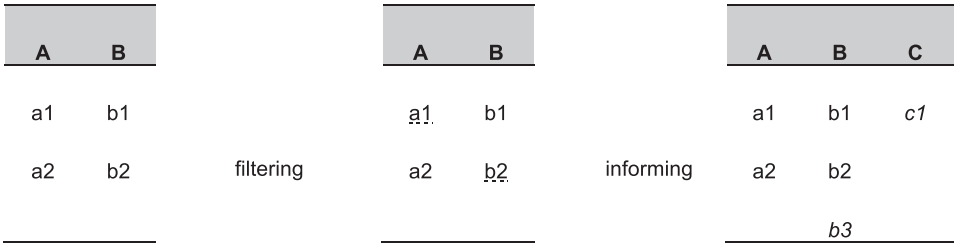

Fig. 5. An activity that filters the design space, and, in turn, informs it.

both new aspects and new options (aspect C and options b3) and that it informs the design space, and, hence, filtering and informing are intimately connected.

It is well-established that the design space is dynamic, but how the design space is established, transformed, and explored is typically expressed only in rather general terms. As we will demonstrate in Section 4, our explicit representation of the design space in terms of a design-space schema enables us to provide a much richer account of the dynamics of the design space. Before diving into the case study of a media architecture design space, we present the research method.

3 METHOD

The investigation into how the concept of design space may advance our understanding of how design processes unfold over time is based on a research-through-design approach. Research-through-design is described as generating knowledge through design [59], and has been investigated with an interest in the knowledge acquired through design objects, as well as with a focus on the dynamics of design interests and research interests as the design process unfolds [1]. The initial research question was rather broad, and actually not a proper well-defined research question, rather a research interest or focus on how design processes develop over time. From the early start, rich data from the process were collected, and based on our research group's broader interest in design-space research, our focus was narrowed down to how a design space develops during a design project. For the initial analysis, we were inspired by LST's research on prototyping as filtering the design space.

As mentioned earlier, the research reported in this paper is based on a large-scale, several-month-long design process of creating a media architecture installation for a greenhouse, and involved interaction designers from our research laboratory, a design agency, biologists from the greenhouse, and the authors (interaction design researchers). In research-through-design, the researchers participate in the design process, and, hence, have the advantages of first-hand access to the design process and being able to regularly document it; in the project described here, we

also had the advantage that our collaborators at the design agency generously documented their process as we went along.

Data from Plant a Light are stored in the content management system of our research laboratory [21], and a rough inventory reveals over 1,500 images, 250 videos, 3 audio recordings, and 40 other kinds of documents from the design process, including email exchanges. The first category includes images of design workshops, meetings, screenshots of the use of a content development tool, experiments, and on-site prototyping (the greenhouse), whiteboards, sketches, and design material such as poster boards and inspiration cards.

The video recordings may be organized into five main categories: video recordings of the key design workshop (an inspiration card workshop), videos of prototyping sessions, video animations of content, videos of content tested on-site, and more general recordings of the process, including the mounting of LED bars at the greenhouse and the final media architecture. Most of the videos are short snippets of less than 1 minute (e.g., tests of content in the laboratory or on-site). Audio recordings document interviews with the production manager of the research laboratory, one of the design heads, and the director of the greenhouse.

For this analysis, the material stored in the content management system was initially organized according to 67 main design activities and design events. For retrospective analysis, we selected seven of the more complex and well-documented design events, and started with the collected design material, and, most importantly, we represented the design space with design-space schemas, introduced in the previous section. Through an iterative process that oscillated between the dataset and a design space for each design activity or inquiry, we obtained insight into the dynamics of the design space.

Caution is important here: Research-through-design in a full-scale, real-world context is not a controlled laboratory experiment, and has limitations, which we will return to in Section 5. In the following sections, we focus on the insights and benefits of the research-through-design process.

4 THE GREENHOUSE DESIGN PROCESS

The object of our study is the process of designing and deploying the media architecture installation, Plant a Light, as part of the greenhouse in a public botanical garden.

Media architecture is the term for installations in which architectural structures integrate displays that use lighting technologies or mechanical devices, and with purposes ranging from advertisement through news broadcasting to engaging citizens [8]. Prominent examples include Rafael Lozano-Hemmer's Body Movies [5], Blinkenlight, BIX Communicative Display Skin, and Kunsthaus Graz [19]. Dalsgaard and Halskov [8] identified eight design challenges that arise when designing media architecture, and in the case presented in this paper, we particularly address the challenges related to the unique kinds of interfaces used, and the content displayed. With respect to media architecture interfaces, Halskov and Ebsen [23] have provided a framework for addressing "the specific qualities of the display of media facade interfaces: scale, shape, pixel configuration, pixel shape, and light quality." In addition to conventional interaction design tools, such as mock-ups and prototypes, a range of more specialized tools, such as projection mapping [9] and virtual video prototyping [25], are available for the media architecture designer who is addressing media architecture's unique challenges [10]. In this paper, we also consider design tools in relation to design space.

The media architecture was developed by our research laboratory, CAVI [21], in collaboration with Kollision, a Danish design office, and staff from the Aarhus Botanical Garden. The project was launched in the summer of 2016 at a meeting between our research laboratory and people from the Aarhus European Capital of Culture 2017 organization, which provided the basic funding for the project.

Table 4. Timeline

1: Project initiation	September 2016
2: Evaluation of tests	September 2016
3: Idea generation workshop	November 2016
4: Interface considerations	November 2016
5: Content development	December 2016
6: Interface design	May 2017
7: Final decisions	September 2017

Fig. 6. Aerial view.

We focus on the seven design activities mentioned in Table 4, as we investigate how the design space is informed and filtered during each of these design activities. In line with LST [33], we define filtering as extracting certain aspects of the design space for investigation and define informing the design space as the process of establishing and transforming the design space.

To highlight the complexity of the design process, we present the analysis as a narrative that references a design-space schema, supported by images of central design materials and design activities.

4.1 Project Initiation

Initially, the project was framed by the contract with the funding source, Aarhus European Capital of Culture, which stated that the goal of the project was to create an artistic light installation and suggested that weather data could be used. The distinctively shaped dome was discussed, based on the Google Earth satellite aerial view of the site (Figure 6). A site visit was scheduled for September 8, 2016, to address questions such as: "Can we consider each window as a pixel?" "Would it be an idea to have the plants cast shadows?"

During the on-site meeting, the director of the botanical gardens and engineers from a lighting company joined the team. An LED fixture was mounted on one of the dome's frames, and the internal lighting was turned off. The team noticed that the skeleton of the dome stood out, shadows of plants were visible, and the placement of the light fixture in a single cell lighted up that single

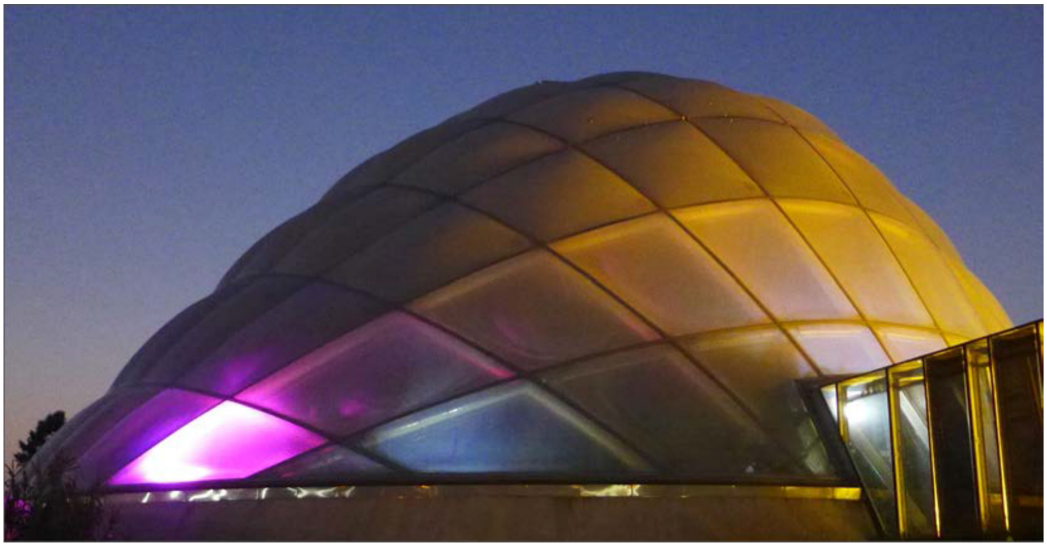

Fig. 7. View of the cell from the outside.

Table 5. First Meeting and Test on Location; Options Informed by the Design Activity in Italic; Options Filtered in the Design Activity Underlined by a Dashed Line

Content	Display	Technology
Art	*Cells*	*LED*
Weather	*Canvas*	*Spots*
Plants		*Laser*

cell almost exclusively (see Figure 7), which supported the idea of considering the windows as individual cells or pixels. Themes for the installation's content were also discussed, and the test generated ideas on-site with suggestions about shadow play and using the plants inside the dome in combination with light sources.

The design-space schema in Table 5 shows the three aspects (Content, Display, and Technology) informed by the two initial design activities and the options considered with respect to each. For instance, the **Content**:Art and **Content**:Weather options stemmed from the contract with the funding source; **Display**:Cells originated from the greenhouse, based on Google Earth images; and **Technology**:LED and **Technology**:Spots are options that were previously applied by the design team. The test filtered the design space with respect to the **Display** and **Technology** aspects, and with respect to these aspects not including all options; for instance, it did not include **Display**:Canvas and **Technology**:Laser. The test activity did not particularly inform the design space, but instead confirmed the potential of pursuing the combination of the **Display**:Cells and **Technology**:LED options. In Table 5, and throughout this paper, we use the convention of having options informed by the design activity in italic and options filtered in the design activity underlined by a dashed line.

4.2 Evaluation of Tests

At an evaluation meeting subsequent to the test on location, much of the discussion revolved around a whiteboard sketch of the dome. The Display aspect was particularly discussed, and the

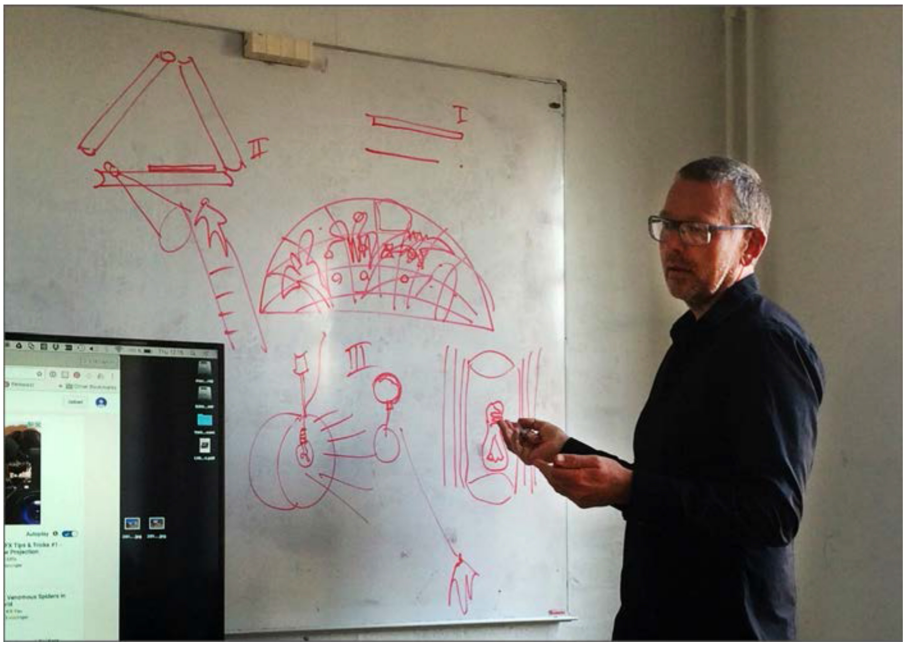

Fig. 8. Sketch of the cells.

Table 6. Evaluation of Tests

Content	Display	Technology
Art	Cells	LED
Weather	Canvas	Spots
Plants	*Sub-cells*	Laser
Individual light		

elements of the dome were consistently referred to as "cells." The main part of the sketch filtered the design space with respect to the **Display**:Cells option, whereas the upper left side of the sketch showed the positions of the LED tubes, that is, filtered with respect to the **Technology**:LED option (Figure 8).

One of the designers speculated whether it would be possible to show more than one color in each cell and create "sub-pixels," thereby informing the design space (see **Display**:Sub-cells in the design-space schema in Table 6).

Regarding the **Content** aspect, one of the designers argued for considering inspiration sources [20], and suggested Rafael Lozano-Hemmer's *Pulse Room* (http://www.lozano-hemmer.com/artworks/pulse_room.php) as an example with individual light sources that in combination create a new meaning. City Bug Report [32] and the artwork *Gong*, by artist Kirstine Roepstorff, were also mentioned as examples that combine two worlds that do not have an obvious connection. One of the designers also presented a Pinterest collection that included various kinds of light and art installations. In this way, the designers' repertoires informed the design space, both with their own cases and others', such as **Content**:Individual light sources (shortened) in Table 6, showing how the design space was further informed by the design meeting. With respect to the Content, it should be noted that the **Content**:Plants option was refined with the suggested option of bringing

Fig. 9. Growth cycles (top) and plant cells (bottom).

the facade to life like a plant, and luring visitors to water the greenhouse building, an option not represented in Table 6. An idea-generation workshop was scheduled to develop the Content aspect and involve people from the botanical garden.

4.3 Idea Generation Workshop

The idea-generation workshop was structured as an Inspiration Card Workshop [22]. The basic idea of the workshop format is that participants collaboratively develop ideas supported by inspiration cards produced by facilitators and workshop participants. Each idea is documented on a poster with selected inspiration cards, comments, and sketches that capture the idea. Inspiration cards are divided into the two categories of "domain" and "technology," and the botanical garden staff provided sources of inspiration from processes in nature, whereas the designers provided examples of media architecture and other technological and light-oriented sources of inspiration. Prior to the workshop, 9 domain cards and 22 technology cards were created, which reflects the complexity of the workshop; hence, for the purpose of this paper, we prioritize to describe the elements that are related to the final result.

The domain cards informed the design space; for instance, the **Content**:Plants option was refined by the Growth cycle card showing a colorful forest informed the design space, leading to two additional options: **Content**:Processes in nature and **Content**:Color change (Figure 9).

Table 7. Beginning of the Idea Generation Workshop

Content	Display	Technology	Interaction
Art	Cells	LED	*Mobile phone*
Weather	Canvas	Spots	
Plants	Sub-cells	Laser	
Individual light			
Processes in nature			
Color change			
Plant cells			
Constellaction			

Similarly, the Plant cells card informed the design space because of the visual similarity of plant cell structure and the cell structure of the greenhouse. Actually, the Plant cells inspiration card was included as one of the design materials, owing to its visual similarity to the **Display**:Cells option. Thus, the Plant cells inspiration card may be seen as filtering a single option (**Display**:Cells) identified earlier in the process, and quite interesting in its connecting or bridging the **Display**:Cells and **Content**:Plant cells options.

The Constellaction card was a particularly prominent and highly influential technology card that referenced an audio-visual installation that consisted of pyramid-shaped objects that emit light when activated by an external light source as an interaction device, for instance, a mobile phone. The illumination of one pyramid affects neighboring pyramids, creating a wave of light (see http://www.digitalbuzzblog.com/constellaction-the-light-chain-installation/). The Constellaction card may be regarded as filtering the **Content**:Individual light sources option, which develops this particular option, and, in turn, informs the design space with a distinct option, **Content**:Constellaction (Table 7).

Nine design ideas represented by concept posters were developed as a result of exploring, filtering, and informing the design space. Owing to limited space, in the following sections, we focus on the emergence of the Plant a Seed idea, which became the key idea for the subsequent part of the process, and at the end of the project was renamed Plant a Light.

The *Plant a Seed* idea was prompted by one of the workshop facilitators, who picked up the Constellaction card and used it as a prop to mime using a phone to initiate some kind of response. Later, the Plant cells and Growth cycles cards were added, with the suggestion that visitors could initiate some sort of growth cycle, mimicking the process in nature of growing plant cells.

The discussion about this idea was supported by whiteboard sketches of the greenhouse with possible content, and indications of how visitors could interact with the installation, for instance, using a half-dome-shaped physical object to interact. A suggestion about distributing interaction spots around the city received great support, and possible interaction locations were discussed. Hence, the design space was during the development of the idea informed by the inspiration cards and workshop discussion to include a new design aspect, **Location** (Table 8). Inspiration cards, sketches, and annotation were integrated into the final concept poster (Figure 10). A title was added—*Plant et frø* ("Plant a Seed")—together with another drawing of how to display the content, and additional comments about how to interact with it and other inspiration sources, such as *Game of Life*, related to the **Content**:Processes in the nature option. Thus, the various sketches and the concept poster filtered the design space (see Table 8). *Plant a Seed* turned out to be a metaphor, which filtered the design space, and was grounded, shaped, and maintained during subsequent collaborative design activities [13].

Table 8. End of the Idea-Generation Workshop

Content	Display	Technology	Interaction	Location
Art	*Cells*	LED	Mobile phone	*Near building*
Weather	Canvas	Spots	*Physical object*	*Out in the city*
Plants	Sub-cells	Laser		
Individual light				
Processes in nature				
Color change				
Plant cells				
Constellaction				

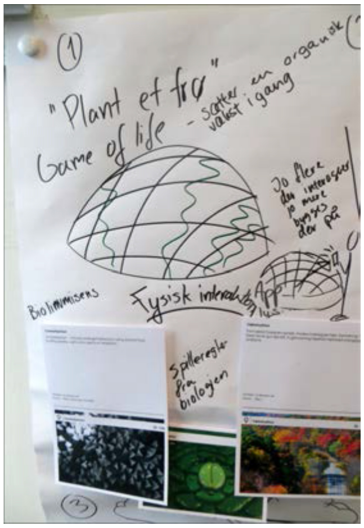

Fig. 10. The Plant a Seed poster.

4.4 Interface Considerations

At a subsequent meeting, the Location and Interaction aspects came into focus (see Table 9). Since the workshop, some of the designers had been out in the town to find possible locations for interaction spots where it would be possible to view the greenhouse. A sketch on the whiteboard (Figure 11) filtered the **Location**:Out in the city, but also informed the design space based on reflection and sights noted while sketching. The designers discussed what might be an optimal solution for interaction spots with a view of the greenhouse; for instance, the rooftop of the local art museum was identified as a popular place in the city with a good view of the greenhouse (see Figure 11, top right). Discussion moved on to address the Interaction aspect, and the idea for a wooden pillar was roughly sketched on the whiteboard. The pillar proposal was a refinement of the **Interaction**:Physical object option that included **Interaction**:Pillar, and an example of swift loops of filtering and informing the design space (see Table 9).

4.5 Content Development

To explore the content aspect, a test simulator was developed to prototype ideas for content. The simulator played a dual role with respect to the design space. On one hand, the simulator filtered

Table 9. Interface Considerations

Content	Display	Technology	Interaction	Location
Art	Cells	LED	Mobile phone	Near building
Weather	Canvas	Spots	Physical object	Out in the city
Plants	Sub-cells	Laser	*Pillar*	
Individual light				
Processes in nature				
Color change				
Plant cells				
Constellaction				

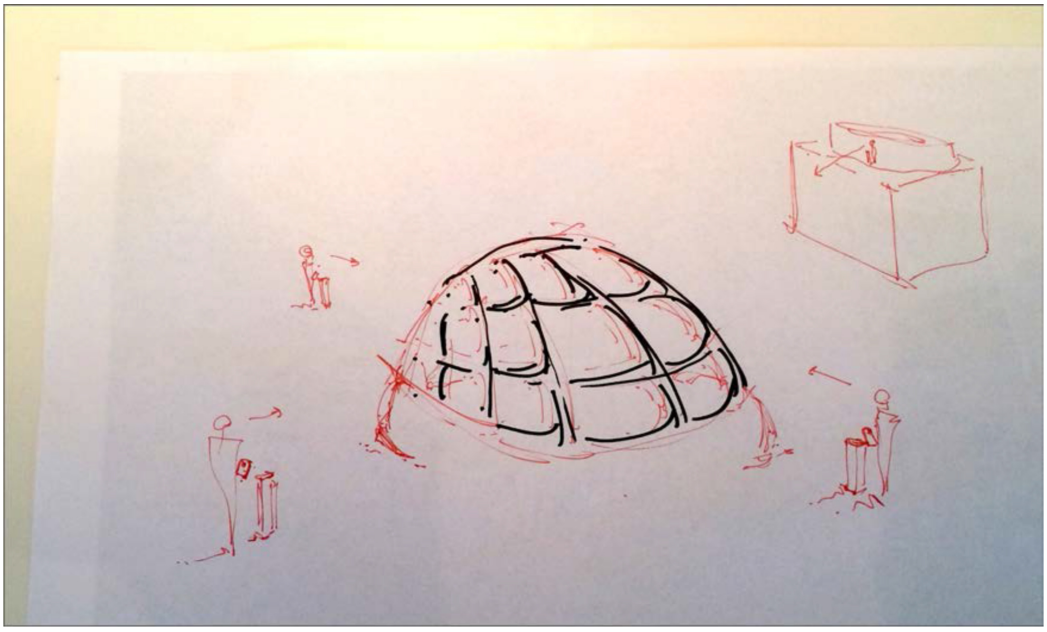

Fig. 11. Sketching location.

the design space with respect to the Content and Display aspects of the design space, and, on the other hand, the simulator offered a number of features that, in turn, informed the design space (see Table 10).

Essentially, the simulator mapped a video stream onto a digital 3D model of the dome with exactly the same configuration of cells as the physical dome. The content simulator forced the team to be concrete about the basic idea behind the "Plant a Seed" metaphor, which was interpreted as the development of an organism, starting with a single cell that evolved into a snake moving across the dome.

The tool provided a number of parameters for investigating this idea, which corresponded to aspects that could be used to explore how a single cell may evolve into an organism that would move across the dome, and eventually die. The collection of parameters was a refinement of the Content aspect, and these parameters were additional aspects that informed the design space, and included **Speed**—the speed of adding new cells to an organism, **Color** of the cells, **Direction** in

Table 10. Content Development Tool

Speed	Color	Direction	Number	Noise
1	*#FF0000*	*Up*	*1*	*#000000*
2	*#FFFF00*	*Down*	*2*	*#AAAAA*
3	*#00FFFF*	*Left*	*3*	
4	*#0000FF*	*Right*	*4*	
5	*#FF00FF*		*5*	
6				

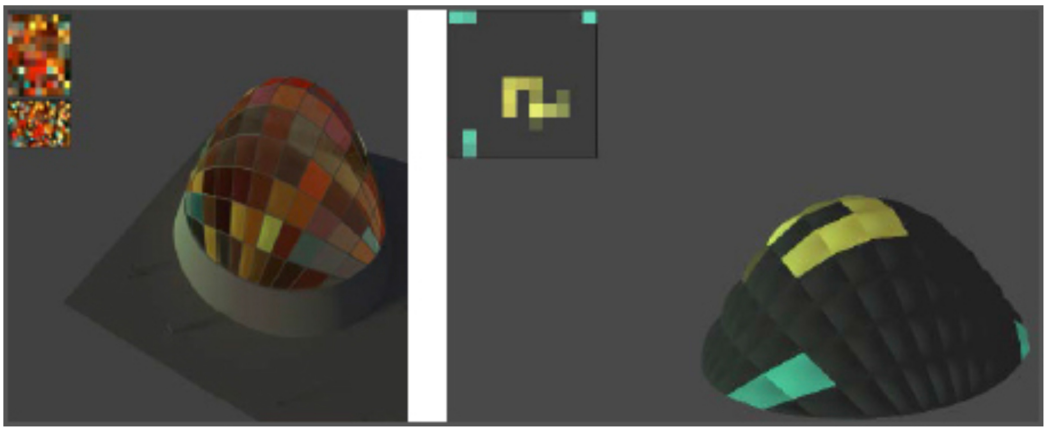

Fig. 12. Content visualizations.

which to add a new cell (Up, Down, Left, and Right), **Number** of cells an organism comprises when it dies, **Noise**—a color to be added to provide variation in the basic Colors, and **Explosion colors**, which cover the entire dome when an organism dies. In design-space terms, the tool not only filtered the Content aspect but also informed the design space with a whole new set of aspects and corresponding options, some of which are shown in Table 10. Numerous experiments based on setting these parameters offered visualizations, each of which filtered the design space (see Figure 12).

4.6 Interface Design

At an interface design meeting, the combination of the Interaction and Location aspects was addressed. An idea filtering the design space was to have several interaction locations around the city, where users could interact with the installation through their mobile phones (a combination of the **Interaction**:Mobile phone and **Location**:Out in the city options), was briefly discussed, but rejected due to complexity. Instead, one of the designers from the design office suggested reusing one of their earlier projects that used a glowing pillar as an on-site interaction device. In design-space terminology, a previous design case of the designer's repertoire informed the current design space by refining **Interaction**:Pilar into **Interaction**:Glowing pillar. The interface ideas that designers settled on filtered the design space by combining the **Interaction**:Glowing pillar option with the **Location**:Near building option. A prototype was made, which in a straightforward way filtered the Interaction and Location aspects with respect to the two options mentioned above.

4.7 Final Decisions and Building the Interactive Pillar

With only 2 months left to the November 2017 launch, and with a change in name from *Plant a Seed* to *Plant a Light*, the next step was a full-scale test on the actual facade, involving numerous combinations of the sub-aspects of content: Color, Speed, and Direction (see Table 10). Tests focused on the speed of the organisms' growth cycles, and their color changes from birth to death. Although time was limited, possibilities for content were still questioned and changed. Some of the possibilities became more specific, new ones were added, and previously used design-space options were revisited, including the use of weather, and a reflection of the seasons (not included in the design-space schemas). The full-scale prototype filtered a combination of the design-space **Content**:Color change, **Technology**:LED, and **Display**:Cells.

The idea of interaction based on touching a glowing pillar was further refined, based on the use of a pillar from an earlier project executed by the design office (**Interaction**:Physical object, Glowing pillar). Tests were conducted with different kinds of light sources inside the pillar, and it was decided that to ensure that users easily would discover where to find the sensors that would activate the installation, hand-shaped marks would be printed on the pillar, which became the final solution filtering the design space (Table 1).

Plant a Light was now ready for launch (see the Supplement Video).

5 DISCUSSION

Our analysis of the 16-month design process behind Plant a Light sheds light on the dynamics of the design space as a conceptual space and demonstrates how design activities both inform and filter design spaces. For the discussion, we start out with the basic definition of the design space of a conceptual space followed by a discussion of the approaches to filtering the design space and ways of informing the design space form the case study. The discussion of informing and filtering constitutes the foundation for the subsequent discussion of the dynamics of the design space through loops of informing and filtering. Finally, we reflect on our research-through-design approach and discuss it as a response to the call to replicate, validate, and advance results of Human Computer Interaction (HCI).

5.1 Design Space as a Conceptual Space

Our analysis builds on LST's [33], and extends their work in several ways. They define five filtering dimensions, and although we acknowledge that these dimensions are core aspects of interactive systems, we suggest an open-ended model that includes the possibility of incorporating aspects specific to a given design situation, for instance, "Location." It should be added that LST do note that, "This list of dimensions is not meant to be complete..." [*ibid.* p. 13], but do not elaborate. At the same time, we acknowledge that a number of standard aspects are relevant to most HCI systems, for instance, Interaction (see Table 7), and that specific domains or applications of technologies involve a number of shared aspects, for instance, the media–architecture display-specific aspects discussed by Halskov and Ebsen [23] (also see Table 5).

The dimensions on which LST focus are the "dimensions corresponding to the various aspects of a design idea that a designer tries to represent in a prototype" [33, p. 11], whereas our approach also includes the aspects (corresponding to LST's dimensions) that are not filtered; for instance, none of the options that are part of the Display aspect (Table 8) are filtered by the concept poster (Figure 10) during the ideation workshop.

The systematic representation of the design space as a conceptual design-space schema that also includes the options (corresponding to values) considered enables us to address filtering not only at the aspect level, but also in greater detail at the option level. For example, when the Plant

Table 11. Kinds of Filtering the Design Space

Filtering	
Prototypes	Concept poster
Test	Design tool
Sketch	Experiment
Technology card	Idea
Metaphors	The final design

a Seed idea filters the design space with respect to the Content aspect, the options Processes in nature, Plant cells, and Constellaction are included, whereas options such as Art and Weather are not. In this respect, we also extend LST's work, who in a few cases also identify values for their variables that correspond to our options; for instance, with respect to Spatial Structure they note that "relationship among interface or information elements [—which] can be either two- or three-dimensional." Moreover, the design-space schema (see Figure 3 and Figure 4) enables us to more precisely address both filtering and informing the design space, as we will discuss next.

In summary, the conceptual design-space schema captures the aspects the designers are addressing and the design options they are considering, and in this way the design-space schema, and the notions of informing and filtering, is of value for understanding design processes in general.

5.2 Approaches to Filtering the Design Space

The fact that prototyping filters the design space is well-established, and LST's research takes a broad view of prototyping that also includes mock-ups. As a first step forward, we observe that the initial tests of technologies (Activity 1, see overview in Table 4) also filter the design space with respect to the Display and Technology aspects, and, moving forward, we see several instances where sketches filter the design space, for instance, the whiteboard sketches in Figure 8 (Activity 2) and the sketch of the pillar (Activity 4). Also, each idea visualized on concept posters while using the inspiration cards filters the design space (Activity 4), but ephemeral suggestions that are materialized also filter the design space, for instance, using mobile phones for interaction in Activity 3. Table 11 provides an overview of the kinds of design-space filtering that this paper addresses.

Perhaps the most complex design-space filtering and informing (which we discuss below) occurred during the inspiration card workshop (Activity 3), where each of the nine concept posters represented an idea, and where one of the labels, "Plant a Seed," became a generative metaphor that Dove et al. [13] discussed at length, and that also filtered the design space.

The design-space analysis supported by our design-space schemas also reveals not only what was filtered, but, equally importantly, also what was not filtered through prototypes, and instead temporarily set aside, ignored, or perhaps forgotten, for instance, visualizing shadows of plants on the greenhouse dome, an early content option considered (Activity 1), the **Display**:Sub-cells option (Activity 2), or mobile phones as interaction devices, one of the interaction options (Activity 3).

Previously, prototyping was thoroughly investigated as design-space filtering [33], which is further supported by this paper (Activities 4, 5, and 6), and our case study presents a novel contribution by drawing attention to prototyping tools—and design tools in general—as design-space filters (Activity 5). More specifically, the content development tool filters the Content and the Display aspects. Finally, the concluding tests and the final installation filter the design space (Activity 7), as illustrated in Table 12, where the filtering of the final design is indicated by broken lines beneath the specific options.

Table 12. The Final Media Architecture Filtering the Design Space

Content	Display	Technology	Location	Interaction
Art	Cells	LED	Near building	Mobile phone
Weather	Canvas	Spots	Out in the city	App
Plants	Sub-cells	Laser		Physical object
Single light				Pillar
Processes in nature				Glowing pillar
Color change				
Plant cells				
Constellaction				

Table 13. Ways of Informing the Design Space

Informing	
Field studies	The designers' repertoire
Images	Workshops
Sources of inspiration	Domain cards
Funding sources	Technology cards
Contract	Project team
Design tools	Previous case
Prototyping	Competitor studies
Tests	

The numerous forms of filtering, as they occurred during the process (Table 11), raise an interesting question about whether they have any systematic relationship to the design space (Table 12). Most obviously, the technology cards filter the Technology and the Interaction aspects, and the test filters the Location aspect. In the greenhouse case, the simulator tool filtered the Content and Display aspects, but other kinds of design tools may filter other aspects; for instance, 3D visualizing tools such as UNITY and Maya may filter the spatial aspect such as Location or large-scale spatial aspects [25]. Caution is important here, since it is not possible to draw any general conclusions about which kind of filtering is relevant to which aspect, based on a single, though complex, large-scale case.

5.3 Ways of Informing the Design Space

Significantly, we have built on LST's work, proposing a parallel term to "filtering," namely, "informing," to capture not only new ideas (see Figure 3 and Figure 4), but also the knowledge that emerges during all kinds of design activities.

One may argue that a design process always occurs in a design space: Nothing comes from nothing. Table 13 provides an overview of the ways of informing the design space that are addressed in this paper. We have learned that the design space is not only informed by what we generally consider design activities, but also by more general circumstances, for instance, the contract between the funding source and the project team (Activity 2 and Table 5). Our analysis does not address in detail the fact that the selection of participants affects the design space: Imagine how the design space would have been informed if an artist appointed by the funding source, The European Capital of Culture organization, had participated in this design process. There is no doubt that the designer's repertoire, including her or his as well as others' previous projects [47], profoundly

informs the design, as clearly demonstrated by the role played by the Constellaction case (Activity 2). Other resources known to inform the design space are Pinterest collections (Activity 2), inspirational archives such as *Digital Experience* (Activity 3), archives of physical materials from previous projects, as known from IDEO [31], studies of competitors' websites, and the design agency's previous projects. We speculate that the domain experts' repertoires similarly inform the design space.

In the case of some of the technology cards that profoundly informed the design space, the collection of inspiration cards was accompanied by a short video. To manage complexity, and because of the space restrictions of a research paper, we omitted many options related to content, display, and interaction, and aspects such as Temporality, from the analysis presented above. We also focused on what people said during their presentation of the cards, and, paid little attention to an analysis of the entire collection of cards. Furthermore, it is important to note that the role played by the various elements is unique to the specific situation in the process, and not an inherent quality. For instance, a technology card such as Constellaction, displaying a pyramid shaped object, may inform the design space in a different way in another design process.

The way the content simulation tool informed the design space with a whole new set of aspects and corresponding options is particularly important, as this radically expands the design space, and offers digital support for exploring and traversing the design space. This finding has strong parallels in LST's noting that, "Three dimensional *prototypes* open up a new design space to explore" [33, p. 9]. This tool may be regarded as a prototyping tool for content, and calls for a systematic investigation of how prototyping tools both filter and inform the design space. Tools as filters of the design space have parallels in the role of materials, one of LST's manifestation dimensions, and we argue that selecting a specific material also filters the design space. Not only tools, but also methods—for instance, use of personas, mood boards, card sorting—inform and filter the design space.

Just as one may consider the relationship between the design space and filtering, one may ask whether there are any systematic relationships among the many ways activities inform the design space (Table 13) and particular aspects of the design space (Table 12). In the greenhouse case, the field studies informed the Location aspect, which seems to be a typical role played by field studies, whereas images are a much more general source that may inform multiple aspects of a design space. In contrast, almost by definition, the two kinds of inspiration cards—domain cards and technology cards—specifically inform the Content and Technology aspects, respectively.

Comparing the filtering elements (activities and artifacts, Table 11), and the informing elements (Table 13), it is evident that some elements, for instance, the designer's repertoire, either filter or inform the design space, and that other elements, for instance, the design tool, both inform and filter the design space. On the other hand, the contract only informs the design space, and does not filter it.

5.4 The Dynamics of the Design Space

We have studied the design process as it develops over time, based on a 16-month design project that acknowledges the importance of the activity- and time-driven nature of design in general, and in particular, ways of traversing, exploring, and understanding the dynamics of the design space.

LST discuss whether to address each aspect in isolation, or in relation to one another—"It is obvious that the relationships between these dimensions are intricate and dynamic" [*ibid.* p. 13]—without going into detail. The design-space schema visualizes the design-space representation, and thereby encourages us to address its dynamics, and to mention creativity mechanisms, for instance, the inherent constraints of the design task at hand [3, 39] or the role of inspiration. Gaver [18] pursued a similar kind of inquiry, and in his discussion of how design workbooks work,

notes that, "Design creates the spaces in which it operates" [*ibid.* p. 9]. Gaver also argues that ideas emerge slowly over time, and he pursues his line of inquiry through workbooks as representations of design spaces, whereas we use design-space schemas, which provide an explicit representation of the design space, which facilitates much more concrete and specific insights into how the design space is established, transformed, and explored. As pointed out earlier, whereas filtering *per se* investigates a selected part of the design space, but does not modify it (see Figure 4), informing concerns the expansion of the design space. In this way, informing and filtering are related to divergent and convergent thinking [42], and our analysis demonstrates that divergent thinking is not limited to the early part of the design process, but also to much later phases, when the content simulation tool drastically expanded the design space by introducing a whole new set of aspects (Speed, Color, Direction, Number, and Noise, Table 10), each with a set of options.

We suggest that the kind of design-space analysis we have presented may help to shed light on Schön's concept of design as a process with loops of seeing–moving. A very simple example would be the situation where a whiteboard sketch filters the design space with respect to the **Display**:Cell option, which, in turn, informs the Display aspect of the design space with the **Display**:Sub-cells option (Activity 2, see also Figure 5). The plant cell inspiration cards are particularly interesting design material, which filters the existing **Display**:Cell option during the selection of inspiration cards, and, subsequently, during the workshop informs the design space with respect to the Content aspect. Similarly, as noted earlier, the content simulation tool filtered the Content aspect, and, subsequently, informed the design space with a whole new set of aspects (Speed, Color, Direction, Number, and Noise, Table 10), and followed this with numerous experiments based on setting these parameters, which offered visualizations, each of which filtered the design space. A similar case, which may be an instance of a recurrent pattern, concerns the Constellaction inspiration card, which may be regarded as filtering the **Content**:Single light sources option, which, in turn, informs the design space with a distinct option, **Content**:Constellaction. Keep in mind that it is recommended that inspiration cards be selected for a workshop based on their having some relationship to the design task at hand, and, simultaneously, stimulate creativity by originating in a near or distant domain. Another recurrent pattern is that of swift loops that filter an option for a particular aspect, for instance, a sketch, which, in turn, informs the very same aspect by refining it, for instance, the refinement of the **Interaction**:Physical object option of including **Interaction**:Pillar (Activity 4). Such in-the-moment loops of filtering and informing at the micro-level complements the macro-analysis of the dynamics of the design as represented by the design-space schemas (Table 5, Table 10, and Table 12).

5.5 Research Approach

This paper may be seen as a response to the call to RepliCHI. The growing interest in replication is motivated by the observation that the HCI community "often take the significant results of a single user study on 20 users to be true" [56], and by the opportunity to not only confirm results but also advance research on a solid foundation by more clearly and explicitly building on previous research. This was discussed by an CHI panel in 2011, and led to the proposal of a RepliCHI Special Interest Group (SIG) in 2012 [55]. In this context, prototyping as filtering the design space was confirmed and refined by a research-through-design approach to investigating a large-scale, "in the wild," several-month-long design process of creating a media-architecture installation, documented with over 1,500 images, 250 videos, 3 audio recordings, and 40 other kinds of documents from the design process. The research project not only confirmed the well-established insight that prototypes filter the design space, but also directly extended this by establishing how other kinds of design activities filter the design space. For instance, the current study also established that the selection of inspiration cards, the development of the 'Plant a Light' metaphor, and the use of the

design tool also filtered the design space. Moreover, the research project further advanced interaction design research by suggesting a parallel term to "filtering," namely, "informing the design space." Our research differs from earlier replication research in HCI surveyed by Hornbæk et al. [29], which focused on (1) quantitative data, (2) an experiment, and (3) human interaction with user interfaces, whereas our research focuses on (1) qualitative data, (2) "in the wild," and (3) the design process. More generally, our approach to replication includes three elements: (1) confirming an existing finding in a different or more complex context [29]; (2) generalizing how also other kinds of activities than prototyping also filter the design space; (3) suggesting a parallel term to "filtering" and "informing." This paper offers a model that may inspire other researchers to "RepliCHI" by replicating and extending previous research findings.

The design research presented here is concept-driven [51], which is reflected in the term "conceptual design space," and shares similarities with concept-driven interaction design in its conceptual and historical grounding (see Section 2), but whereas concept-driven interaction-design research targets concrete designs, our research into design space targets the design process by suggesting how design-space concepts may manifest in the design process.

With regard to conceptually driven design, Höök and Löwgren [28] have proposed "strong concepts" as a kind of intermediate-level design knowledge that is generative and conveying a core design idea. We argue that each aspect and its associated design-space options may act as a strong concept; for instance, location aspects include the options, "near the building" and "out in the city," but ideas for other kinds of location could also be generated, for instance, "inside the building" and "from locations outside the city." Each aspect and option may be manifested in the concrete design, and in cases where an aspect or an option is historically and theoretically grounded, the aspect or option may become part of concept-driven interaction design. An example of such an aspect is Situation, which is grounded in McCullough's work on situational types in urban spaces [37].

Originally, strong concepts were restricted to generating design ideas, and we would like to suggest that a similar kind of strong concept may generate ideas related to the design process. In this sense, both filtering and informing, together with the design-space concept, are generative concepts with respect to the design process, generating ideas for how to expand the design space by informing it in various ways (see Section 5.3), and by identifying kinds of filtering the design space (see Section 5.2). As touched upon in Section 5.1 and further discussed above, "conceptual space schema", "informing" and "filtering" are general concepts at a high level of abstraction, but, on a critical note, the concepts are not rooted in a single particular theory, but in a diverse set of design space theories (see Section 2).

Our research-through-design approach not only contributes to research-related knowledge with respect to the development of the design process through a sequence of informing and filtering the design space, but suggests opportunities for design practices that we address in the next section as part of a design-space thinking research agenda.

6 TOWARDS A RESEARCH AGENDA FOR DESIGN-SPACE THINKING

With respect to future work, our research into the dynamics of design spaces suggests four items for a design-space research agenda.

(1) We see great potential for further developing design-space thinking as a new platform for understanding the development of the design process over time, focusing not only on the individual design artifacts but also on the primordial soup they are part of. In our research, we have shown how a selected set of design artifact methods known from design research may be further investigated from a design-space perspective.

LST have addressed how the designer's choice of materials has direct implications for the users' perception of the prototype and, hence, also for which aspects of the design space may be filtered

by the prototype. More generally, design-space thinking may contribute to design research by providing the foundation for understanding which design aspect may be productively explored according to not only the kind of material but also the design method. For example, large-scale spatial aspects of the design space may productively be explored with 3D visualization tools and platforms such as UNITY, or virtual video prototyping, as suggested by Nielsen and Halskov [25]. In other words, not only prototyping and prototyping materials are important to consider but also the prototyping tools. We have only scratched the surface with respect to methods and scenarios, and a number of design artifacts, such as mood boards and personas, have not been addressed at all, but our case study has indicated a potential for generalizing the finding in relation to design methods and materials in a broad sense. Without explicitly using the term "framing," we have indicated that design-space schemas have the potential to illuminate the designer's framing of a design situation. Moreover, we propose that the conceptual design-space schema has a strong potential for the study of the dynamics of the co-evolution of problem space and solution space [57], as an alternative to formalized methods for design-space exploration [35]. Last but not least, we have not explicitly considered collaboration, and, for example, have not addressed the fact that participants may have different perceptions of what the design space is at a particular point in time.

(2) Related to (1), we suggest applying design-space thinking as a strategy for advancing the understanding of the development of the design process as a creative process. We have touched on a few of the core factors that drive creativity, for instance, inspiration [15, 20, 43], constraints such as low-resolution displays [3, 23], combinations of aspects and options [11], divergent thinking [42], and creativity tools [17]. Moreover, we have shown how design-space thinking, including the conceptual design-space schema, may provide a more nuanced understanding of the divergent and convergent nature of creative design processes. Creativity research has extensively studied such factors, and in interaction design, the creative potential of design methods has also been studied [38]. However, little of interaction design has investigated the development of the creative interaction design process, and we have found promising evidence that research into design-space thinking may help to shed light on how a design solution emerges and is shaped from a primordial soup of design materials, thoughts, and ideas, including ideas that are disregarded, or elements of ideas.

(3) This case study is a design-space investigation into a design process following the completion of a project. In an ongoing project, we are documenting the design space as it develops over time, and, related to (2), we have started to look into design-space schemas as generative artifacts, in line with D. Schön's generative metaphors [46], which acknowledge that design-space schemas capture a space of opportunities.

(4) Tools are needed to capture and document a design process from a design-space perspective. We have used pen and paper, whiteboards, text-editing tools, spreadsheets, and photocopiers. Motivated by all the hard work needed to document and analyze the design space, we are currently developing a design-space tool based on design-space schemas, and with a feature for adding notes concerning aspects and options, capturing how the design space is filtered and informed. In this context, a particular avenue worth pursuing is how to visualize design-space schemas, to investigate their dynamics over time. We are happy to share our tool with researchers interested in points (1)–(3), which in the future may offer open-data and open-source opportunities for RepliCHI [14].

Beyond design research, our research also has implications for design practice. At the most general level, the design-space schema representation offers designers a platform with an overview of "all accumulated knowledge" at a particular point in time (see Section 2.1), which includes not only the knowledge of the current understanding of a design vision, design idea, design concept, and so on, but also those design options that were set aside or rejected, for instance, the use of

mobile phones for interaction in the greenhouse case. In other words, the representation of a design space offers designers the opportunity to revisit previous design decisions, and to identify design options that were disregarded earlier in the design process, or options that were not considered. As discussed above, design-space research, including the design-space schema, also offers design practitioners a framework that supports a choice of methods for expanding and exploring the design space by informing and filtering it. Furthermore, and as briefly touched on above, design-space thinking specifically supports the creative part of the design process, for instance, by organizing sources of inspiration, managing constraints, or facilitating combinational creativity.

7 CONCLUSION

In this paper, we have expanded the idea that prototypes filter the design space to also include other design artifacts that filter the design space, for instance, sketches on a whiteboard, concept posters, design tools, and on-site tests. We have also suggested a parallel term to "filtering the design space," "informing the design space," to define how design artifacts, design activities, and the designers' repertoires expand and refine the design space. We acknowledge the importance of understanding how filtering of the space happens, and have argued that it is also essential to investigate what informs the design space that is being filtered.

To understand how the design space is transformed throughout the design process, we have employed the design-space schema format to capture the dynamics of the aspects and options of the design space. With respect to the dynamics of the design space, we have identified a tentative list of strategies: refining both aspects and options, combining options, and loops of filtering and informing as particular kinds of seeing and moving.

We have applied a research-through-design approach to address the call for replicating and validating results of HCI and advancing replication by focusing on (1) qualitative data, (2) design "in the wild," and (3) the design process. Moreover, the aspects and options of a design space have been interpreted as strong concepts, and our research has been related to a concept-driven research.

We have suggested four areas of research as parts of a design-space research agenda: (1) design-space thinking as a sub-discipline of design thinking, (2) applying design-space thinking as a strategy for advancing the understanding of the development of the design process as a creative process, (3) design-space schemas as generative artifacts, and (4) tools to capture and document a design process from a design-space perspective. We have also indicated a number of areas with implications for design practice.

It may sound clichéd, but it is truer than ever: Additional studies are needed to challenge, critique, and develop design-space thinking. Macro-studies of two or more projects offer an opportunity to understand the development of designers' repertoires, and to identify strong concepts that target both the design object and the design process, in an effort to pursue concept-driven design. With this paper, we have only planted a seed.

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