Building with Data: Architectural Models as Inspiration for Data Physicalization

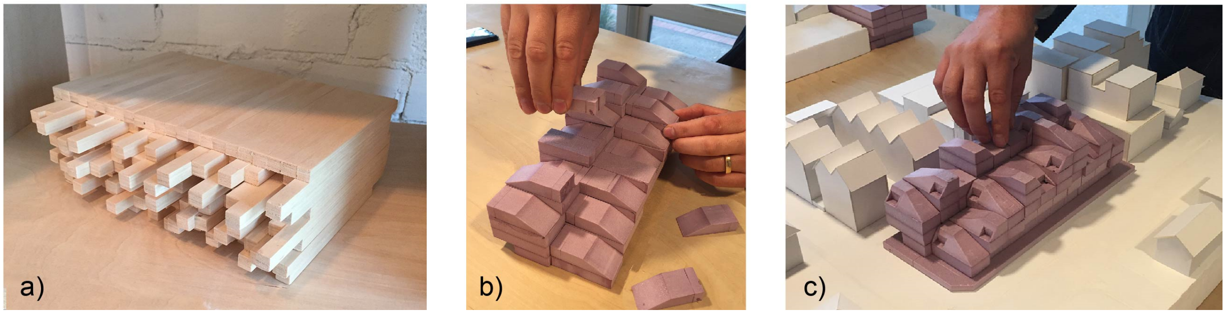

Figure 1. a) Concept Model. b) Working Model. c) Working Model in Context Model. All Images: MoDA Architecture.

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ABSTRACT
In this paper we analyze the role of physical scale models in the architectural design process and apply insights from architecture for the creation and use of data physicalizations. Based on a survey of the architecture literature on model making and ten interviews with practicing architects, we describe the role of physical models as a tool for exploration and communication. From these observations, we identify trends in the use of physical models in architecture, which have the potential to inform the design of data physicalizations. We identify four functions of architectural modeling that can be directly adapted for use in the process of building rich data models. Finally, we discuss how the visualization community can apply observations from architecture to the design of new data physicalizations.

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Data Visualization; Data Physicalization; Architectural Models; Embodied Interaction; Design Process

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INTRODUCTION
The tradition of building scale models has a long and well-established place in architectural practice. Models have immense popular appeal – they invite tactile exploration, facilitate collaboration, and evoke a sense of "delight in the miniature" [24]. Perhaps most importantly, physical models immediately reveal the relationships between multiple dimensions of a structure, relationships that are often not obvious in blueprints or static views. For architects, models are a unique and powerful tool which "sustains a communicable precision without narrowing the delightful cultivation of the imagination" [1].

Data physicalization, by contrast, is a relatively new field of research that has emerged within the data visualization community to find modalities beyond screen-based interactions for viewing and exploring complex data sets [17]. Jansen et al. emphasize that to create effective data physicalizations, we must better understand how they operate in practice [19]. This includes understanding which physical representations work best to engage audiences, how to encode variables in physical form, how to support interactivity, and what types of workflows can best support data physicalization.

Architecture is a rich place to look for inspiration and answers to these questions. Like data physicalization, the field of architecture is facing challenges in addressing the shortcomings of digital modeling and is rediscovering the power of physical models. Computer models lack depth, texture and a sense of materiality, despite the most advanced digital modeling and rendering software [31]. By examining methods used for centuries by architects, and how they have been adapted for contemporary digital practice, we suggest useful observations that can be directly applied to the field of data physicalization.

To explore these questions, we reviewed the architectural literature on physical models, conducted one-on-one interviews with ten architects, and examined the use of scale models in the design process. Based on our observations, we discuss the benefits that physical models provide and identify distinct types of models used for both generating and presenting ideas. In this paper we (1) characterize the process and history of model-making in architecture, (2) identify aspects of the model-making process that are relevant to data physicalization, and (3) suggest four implications for design: Exploring Spatial Relationships and Characteristics, Supporting Comparison and History, Providing Context, and Evoking Emotion.

RELATED WORK

We begin by characterizing the use of models in architecture and its evolution over time, and consider its relationship to recent work on data physicalization.

The History of Physical Models in Architecture

Historically, architectural models have always functioned as objects of critical engagement [27]. The earliest evidence of models is from Egyptian times when they were often buried with the owner of the building as a symbol of wealth or status [31]. The first word used to describe models, *paradeigma*, indicates the representation of patterns or information about an architectural idea rather than a scaled replica of a building [5]. Leon Battista Alberti was the first to document the benefits of physical models for architects in the 13th century – highlighting their value not only for presentation to clients but also as a conceptual device for the architect during the design process. Alberti appreciated how architects could constantly rework and modify physical models as well as iteratively share models in collaboration with builders and craftsman, eliciting their recommendations to produce better designs [21].

The invention of perspective during the Renaissance started the primacy of the image over the model and by extension, a lack of esteem for getting one's hands dirty [28]. The model became a tool representative of the lowly world of the craftsman. This professional elitism continued through the Baroque period with the discovery of descriptive geometry and other advancements in drawing techniques, until the geometric experiments of architect Antonio Gaudi in 1882. Gaudi considered ruled surfaces, specifically the hyperbolic paraboloids, to be symbols of divine perfection, but they could not be defined on paper. His hanging wire and plaster forms became the first instance of a self-generating formal system as adjustments of wires and weights could produce a diverse set of similar forms [31]. A short time later, in the first half of the twentieth century, architects such as Frank Lloyd Wright and Walter Gropius reinvigorated the model in practice. Wright credited his early experiences playing with *Froebel's gifts* (physical constructive teaching tools designed by German pedagogue Friedrich Fröbel) for his understanding of formal representation. Meanwhile, Gropius argued that the native intelligence of the hand, with the help of tools and machinery, was essential to design because "conception and visualization are always simultaneous" [27]. Gropius also saw that the abstract representations of plans and sections separated the object from reality, and required specialized training to be understood, whereas models offered an unmediated connection to the schema.

Building on the work of the Bauhaus, Mies Van der Rohe pioneered the notion that the model could serve functional roles outside of the design and construction process. His utopian glass skyscraper model suggested that a model could exist as both political statement and object of desire [27], bringing the model into the realm of a distinct art object. This notion culminated in New York in 1970 with the first exhibition devoted solely to the architectural model. In the same era, the founder of the MIT Media Lab, Nicholas Negroponte, emphasized tactile methods of exploration using models, even as digital design and computation were becoming more common within the architectural pedagogy [25]. In many offices, analog models were phased out of everyday practice in the 1980's as CAD (computer aided design) models became much cheaper and easier to produce and modify. With the introduction of BIM (building information modeling) and parametric modeling, the idea of data as a fundamental driver of the design process influenced a radically different breed of architect.

Despite these advancements, the increase of 'unbuildable' models created by parametric modeling software [31], combined with an abundance of overly 'photoshopped' renderings, has renewed appreciation of the tangible and tactile appeal of physical models [7]. Similarly, the advent of digital fabrication has made model making easier and faster [31]. There has been very little research, however, on the functions of modeling itself as an action. Albena Yaneva has studied the strategy of architects to 'scale' themselves into the various models during the design process with a case study of analog models in the design workflow of Dutch architect OMA [43]. The majority of the current discourse on models in architecture focuses on new fabrication technologies [31] or theoretical critiques of scaling and modeling [9]. However, we are not aware of any prior research that has applied these ideas to domains outside of architecture.

Data Physicalization

Like architecture, data physicalization [19] often involves the creation and use of three-dimensional physical models. Whereas architectural models typically reflect real or imagined geometries that could be manifest in the physical world, physicalizations instead give physical form to abstract data with no direct physical analog. Despite these differences, the two share a variety of common concerns, and devote considerable attention to the physical properties, interactions, and encodings of the resulting models.

While research on the benefits of data physicalization is still sparse, initial studies [2, 17, 31] have shown that physicalizations can provide some advantages over their screen-based counterparts. For example, Jansen et al. have shown that physical 3D bar charts outperform screen-based equivalents for information extraction tasks. Specifically, they identified the importance of physical touch, as well as the visual realism of the physical objects as possible advantages [17]. Other recent research has demonstrated how physicalizations can serve as useful and accessible teaching tools [15] as well as a focus point for data-driven community dialogues.

Although many historical examples of data physicalization exist in other disciplines, researchers have only recently begun to catalog and describe them systematically using terminology from the visualization literature [6]. Vande Moere and his collaborators have categorized and discussed a wide range of emergent and artistic examples – categorizing the different degrees of physicality they exhibit the embodiment model [45] and the degree to which they are classified as symbolic, iconic and indexical [22]. Similarly, White and Feiner [40], Willett et al. [41], and Offenhuber and Telhan [26] have explored the range of ways in which physicalizations are connected to and reflective of the physical world around them. Hogan and Hornecker [13], meanwhile, identify a variety of historical and emergent examples of physicalizations in disciplines including engineering, ergonomics, and virtual reality.

Notably absent from recent discussions of data physicalization is a detailed consideration of the use of physical representations and models in architecture, despite the long and rich history of physical model making in architectural practice. However, architecture and HCI overlap in a number of different ways as information technology becomes more embedded within our existing physical, social and cultural networks. In fact, the design challenge for both fields is ‘fundamentally a matter of embodiment’ [20].

Some recent work on interactive physical displays for dynamic 3D visualizations – including systems like InForm [8] and EMERGE [34] – draws on a historical lineage that includes a discussion of architecture. However, few tangible computing examples after the seminal MetaDesk [36] and Urp [37] systems created at MIT in the late 1990s and early 2000s have applied metaphors or tasks from architecture directly. We address this by suggesting that the challenges faced by designers of data physicalizations are similar to those faced by architects – who also encode meaning into form in a way that allows for others to ‘read’ the mapping without specialized knowledge.

Our goal is not to assert that the two fields are identical, or that one maps directly to the other. Rather, we propose that the use of malleable physical representations in architecture and data physicalization share important characteristics – particularly with respect to tactile exploration and problem solving. Our work seeks to identify opportunities where data physicalization may be able to borrow from and adapt interactions and techniques that have long-demonstrated utility in architecture.

	gender	age	occupation	yrs in field	yrs using physical models	yrs using digital models	education	design level
P1	m	35-40	RA	12	16	16	8	senior
P2	f	30-35	IA	6	10	10	7	intermediate
P3	f	30-35	IA	4	4	7	8	intermediate
P4	f	30-35	RA	4	6	5	8	intermediate
P5	f	40-45	RA	20	10	15	8	senior
P6	m	45-50	RA	20	6	15	8	senior
P7	m	35-40	RA	10	10	10	8	senior
P8	m	65-70	RA	40	40	20	8	expert
P9	m	70+	RA	50	50	8	12	expert
P10	f	50-55	designer	30	30	20	8	expert

IA = intern architect RA = registered architect

Table 1. Interview demographics.

EXPLORING MODEL MAKING IN ARCHITECTURE

To better understand the roles and functions that physical models play in architectural practice, we interviewed ten architects from a variety of backgrounds. During these interviews we sought to examine the range of tasks that physical models support in architectural practice. We also attempted to identify specific physical, visual, tactile, and interactive characteristics of these models that make them well-suited to these tasks. Finally, we explored the social role of models and the ways in which they facilitate interactions and exchanges between architects, their collaborators, their clients, and the general public. Throughout, we aimed to identify methods and techniques that might transfer to the design of data physicalizations.

Methodology

We recruited architects who either presently use or have previously used physical models as part of their design practice. We wanted to get a sense of how model making has changed with the introduction of digital fabrication technologies in the last twenty years and sought to survey architects who work with both digitally fabricated and hand-made models. We selected the individuals (five females, five males) based on their specific training and experience with model building. See Table 1 for demographic details.

We conducted each interview at the architect’s workplace, giving us a chance to observe physical models from their current projects. Each interview lasted roughly one hour. The interviewees were all willing to volunteer their time without remuneration. We used a semi-structured interview format, beginning with the following questions:

Q1. What types of models do you use, and how often do you use them?

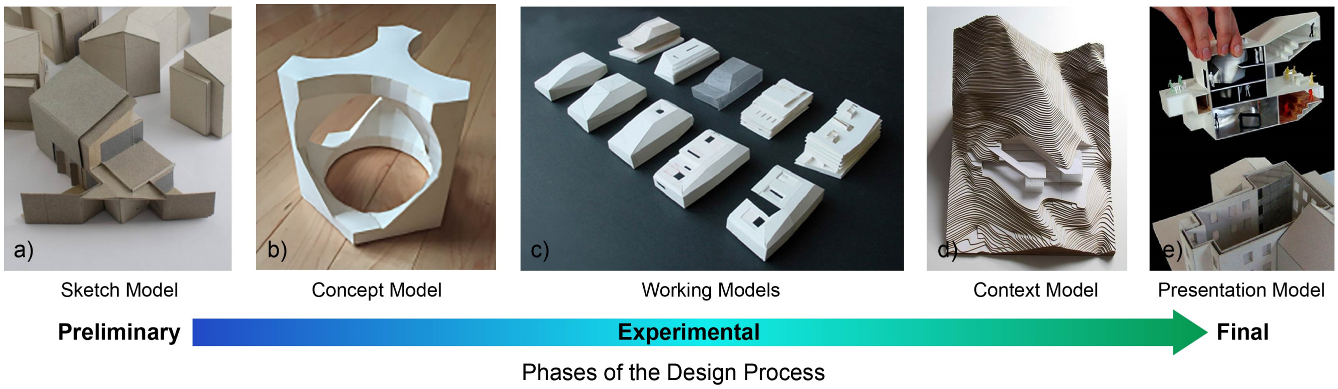

Figure 2. Model types organized according to their position in the design process (left to right): a) Sketch model. Image: Walker Bush Architects. b) Concept model. Image: Noel Heard. c) Working Models. Image: Manifold Architecture Studio. d) Context Model. Image: Buro NY. e) Presentation Model. Image: Saša Randić + Idis Turato.

Q2. What specific functions or roles do physical models play during the design process?

Q3. What strategies do you use to evoke emotion in your models?

Q4. How do models function differently when used for yourself as a design tool versus as a collective tool for multiple designers or the general public?

Q5. How does the architect use scale in physical models? At which scales do architects create models and for what purposes?

Building on these questions, we explored topics in model making based on each architect's individual preferences and experience. Wherever possible, we encouraged the architects to ground and illustrate their discussion using specific examples from their own current and past work. We collected audio recordings and handwritten notes from each interview for later analysis. When feasible, we also collected photos of physical models.

Analysis

Because this study was explorative rather than evaluative, we used an iterative open-coding process. First, one researcher transcribed and segmented the interviews. Then, a pair of researchers worked together to cluster and identify emergent themes based on the physical characteristics, audience, and situations when particular models are used. All themes and functions identified in the paper resulted from this convergent process involving both researchers.

ARCHITECTURAL MODELS

To frame these observations, we begin with a detailed description of the different types of models most commonly used by our interviewees, along with standard functions they support during the design process. We also examine the use of scale and physicality in architectural models.

Types of Models

The architecture literature, as well as the architects we interviewed, describe numerous genres of models intended for different points in the design process and various audiences. Here, we focus on a subset of these model types that covers the entire design process from conception to presentation. While not an exhaustive list of all types of models used in architecture, this subset highlights the diversity of models used by architects as well as the functions they serve. We focused on just a few types of models where our interviews and examination suggested clear implications for the design of data physicalizations.

Sketch Models

At the beginning of a project, architects typically do not know yet what they are going to build. To help define and explore the space of high-level design options and ideas, they often use *sketch models* made with inexpensive materials like cardboard, foam blocks, or sheets of paper that can be easily modified by adding or subtracting elements. Architects use these models to quickly materialize an idea in a playful and experimental flow of ideas. For example, one architect (P7) noted using a 'basket of fun objects' or primitive shapes to quickly explore different compositions. The resulting models are intended for an internal design audience, and their rough, unfinished quality helps convey the uncertainty present at this initial stage of the design process.

One common sketching strategy involved starting with just a few known parameters or a "fuzzy approximation" of an idea. Physically elaborating on these initial ideas could then suggest possible directions for further development. As P2 put it, "*These models are very exploratory, messy. They are more 'live'.*"

Our interviewees noted that quick modeling was easiest using materials that already have volume like foam or blocks. Foam can be cut or reshaped easily to adjust the form and can be modified for both amorphous and rectilinear shapes. Several also described paper as a useful medium, noting that it is inexpensive, readily available, and can be quickly folded and layered to produce a variety of different forms. Architects repeatedly cited construction speed and physicality as important characteristics when selecting sketching materials, and critiqued digital tools as lacking these traits.

> *"The feedback from a physical sketch model is quick, more of a visceral response, it's easier to understand the change in the real world than in the digital." -P2*

All of our respondents described sketch models as the primary type of model they use, and many appreciated the responsiveness and flexibility of sketch models during the earliest stages of the design process.

> *"I use the model mostly for myself, to test an idea out. With the model, it's easier to see the whole thing at once." -P3*

> *"[A model] just shows it doesn't work and you have the freedom to change." -P9*

Six of the interviewees emphasized that the manipulations they made in this stage were what provided the most insight and stressed that time spent with sketch models can be a valuable way of generating new ideas. As P10 confirmed, "*The time spent is really important, it gives you time to sit back, rethink your design and get a grip on [an idea]*."

P1 noted that the most valuable aspect within the process of working with multiple iterations of a model is that inevitable "mistakes and failures" will occur. However, "*in those mistakes or failings something really special can emerge that you didn't think of*" which isn't as discoverable in a digital model. Furthermore, P1 emphasized that "*there is something integral about the brain/tactile connection, and the way that we process information.*"

Concept Models

A *concept model* distills the core idea of the project, focusing on its most fundamental formal and material relationships. P3 described her interpretation of the concept model as "*a physical manifestation of an artistic ideal*." It represents "*the essential idea that is taken into material relationships, spatial relationships, across all scales*." Similarly, P10 described the *concept model* as a "*driver for the design.*" P1 uses these kinds of models to express "*the visceral ideas. How you incorporate light, space, or the mixing of two systems*." He also stressed that this step was an essential aspect of his work that allowed him to address critical ideas before thinking about a physical building.

Although differences in materiality exist across all types of models, concept models most clearly emphasize the use of materials and visual variables to evoke an emotional response. The architects we surveyed all noted the choice of materials as the primary strategy they used to influence viewers' response to the model.

> *"The materiality is the most important aspect of a model. Even an amazing plastic 3D printed model doesn't have the appeal of a rich wooden model."-P6*

Several architects even described choosing materials to represent specific feelings and bodily sensations.

> *"Materials have a grounded or heavy feel to them – a visual mass not related to actual weight necessarily, although most people understand this relationship. Concrete can be heavy or light, depending on the treatment. Glass is lightness and clarity."-P5*

All of the architects agreed on the implicit social conventions around certain materials and forms which elicit different emotions. For example, P7 acknowledged that "you wouldn't use a cold material like steel if you wanted people to feel a sense of warmth." Another architect (P2) highlighted the use of illumination which has the ability to "breathe life into the model."

Working Models

As the design process continues, architects often use *working models* to refine and compare variations of the current design. These models can then be used as the focus for discussion with other members of the design team like engineers or investors. Each successive iteration resolves and refines the interplay of all design elements as the model becomes more precise and communicates finer details. P6 described how he would "*make a bunch of little variations and then pick the best two and keep working on those.*" Each time the architects make a decision or change, they instantiate the update via new model and consider the implications of this change on the design as a whole. Each successive model contains and fuses more data within the material and geometric properties, adding more complexity and detail.

Working models are typically constructed from malleable materials like foam or balsa, allowing architects to make changes by physically cutting or adding to the model. This malleability supports rapid exploration and iteration of a design. However, more dramatic changes may require the construction of entirely new models that can be compared directly to the previous versions. Generally, the level of detail included in working models increases over time as the architects' focus shifts from the overall structure to finer grained aspects of the design. Models will often increase in size as a result, allowing greater resolution and detail.

As work progresses, the collection of working models produced by the team serves as a visual record of the process. Each model exists as a snapshot of a particular moment, or as a record of a particular line of inquiry that can be referenced later. Architects often reported physically placing models within their studio or office to support comparison and recall. These design alternatives could be grouped or analyzed together or used to compare different examples of design modifications. Ultimately, collections of working models create a physical and visible record of past decisions and design options that support both individual reflection and coordination within a design team.

Architects also reported that working models played a social role, supporting collaboration within their studios and with outside stakeholders. P9, an architect with 50 years of experience, indicated that he showed working models to show his clients on almost every project. stating that:

> *"Most people, even geotechnical engineers, will understand the model only. The models are the common language. The people are part of it; they are all over it. They can move stuff around. They are with you instead of against you." -P9*

Several mid-career architects (P1 and P6) made similar points, noting that working models provided concrete checkpoints that were accessible to both to their clients and to their collaborators.

> *"It is easy to hide mistakes in a digital model when you are presenting to the client, and so the physical reality of the model is a sort of forcing function to resolve the design fully. The details get lost on the computer, but when it is all out in front of you it is easy to catch errors." -P6*

P5 also noted that she felt models played a major role in supporting a collaborative culture within her studio.

> *"Working on a computer is a solitary event and people don't interrupt. When I am working on a model, my colleagues will come up to me and talk about the project, which almost always results in a change for the better. There is a distance to virtual things which isn't really a good thing" -P5*

Context Models

Architects also discussed creating *context models* to study the relationship between a design and the surrounding landscape or urban conditions. A deeper consideration of context will include an analysis of the external systems that a project taps into – be they social, cultural, environmental, economic, technological, etc. The context model describes the relationship of an object to its environment on all of these levels.

Several of the architects stressed the importance of using physical context models, rather than drawings or digital designs. In particular, they emphasized that physical models can make the shape and profile of the surrounding terrain clear, allowing viewers (and even the architects themselves) to accurately assess variations in slope and elevation.

> *"Even contour lines don't really show the terrain. You get a stronger reaction because of the materiality. Our brains still focus on form. Even in our office we see immediately if it works or not." -P9*

Architects also emphasized how context models can provide an overview of the totality of a site that is hard to achieve even from an in-person visit. In fact, context models can often provide a unique bird's eye view of the site, allowing architects to physically examine sight lines, symmetries, and spatial relationships that may be impossible to see from on the ground. Moreover, context models can visually encode information about the surrounding environment –such as the age of surrounding buildings or the presence of affordable housing – that is simply not available in-situ.

Context models can also serve as a platform for physical design explorations and experiments, in which architects interactively test possible designs by placing them at different locations on a site model (Figure 1c). P7 described a modeling exercise where his team used blocks representing different programmatic functions (for example, the administration, classrooms, and services for a school). They could test relationships between the context and the general locations of each activity before designing the building itself.

Finally, as one interviewee (P3) noted, context models can be necessary for international and remote projects, where the architects have limited and infrequent access to the actual site. In these situations, detailed models can serve as a stand-in for the actual site, providing architects with much of the contextual information they need in order to situate their designs.

Presentation Models

In contrast to *working models*, which have lower fidelity and support iterative discussions throughout the design process, *presentation models* are intended to showcase the final design to an audience of primarily non-designers. As a result, the craftsmanship of these models is much more refined, using high quality materials and finishes. In contemporary studios, presentation models are often made with digital fabrication tools that can cut or shape precise geometry with clearly articulated details at all scales.

Because of their high cost and complexity, presentation models are almost exclusively a tool for public engagement. Surprisingly, we found that presentation models were the type of model least used by the architects we interviewed – as they found these detailed models costly and time-consuming to build, even with digital fabrication. Only one architect (P10) continues to make a final presentation model for her projects noting that, "*if the project is less than $1 million, it just doesn't make sense economically*." Despite this drawback, every architect we interviewed marveled at the power these models had to engage people – noting that they produced a sense of fascination that drawings could never achieve.

> *'The clients feel as though they have a part in the project when we show them a model that doesn't occur with drawings. It makes the project seem more real to them, and more connected to them, they immediately want to touch it. -P9*

Scale

Generally, the size and complexity of models tend to increase as designs become more fully defined. However, architects still described creating models at a variety of different scales – even within the same phases of the design process. The appropriate scale for a model was often determined based on a number of factors, including the scope of the project, the available workspace to construct the model, and time and money available. The level of detailing also determined an appropriate scale since smaller models tend to focus on basic geometric forms, while larger models are more useful for exploring fine details. P5 mentioned that scale is also determined by the "*inherent characteristics*" of the modeling medium. For example, wood with a large grain is poorly-suited for small models, as it can "*distort the sense of scale*."

Architects also noted a relationship between scale and formality. Small models tend to be considered more casual or abstract, whereas a larger model with finer detailing implies a more finished product. This aspect can be substantial when presenting ideas to clients or stakeholders.

> *"The client will see a more polished and refined model as a finished product, so we would never make the model more detailed than necessary in the beginning stages of the project to make it clear that this was a work in progress." -P5*

Reiterating this notion, P2 remarked that "*a higher level of detail makes things less abstract, less open to imagination*." Similarly, P3 commented that "*larger models have more impact – it makes people really excited*" while P4 noted that, "*it's easier for the layman to understand a larger model because it's closer to their size*."

Physicality and Tangibility

All of the ten architects interviewed highly valued physical models because of their tangible characteristics, which they believed made them easier to understand than drawings or on-screen models. Most also praised physical models' accessibility for large groups in collaboration.

Several specifically noted that the three-dimensionality of physical models make them well-suited to illustrate the complexities of a project to non-designers.

> *"Models are only abstract to one degree (shrinking) whereas drawing was abstracting in two degrees (size and dimensionality)." -P4*

P7 explained that his clients also preferred 3D physical models because they removed technical barriers implicit in 2D drawings and on-screen renderings. Clients examining physical models do not need to understand the language of blueprints, or the interactions necessary to examine or manipulate a digital model.

> "*Models have a lot of the information stripped away that refines an idea to a salient point – simplification helps people to understand the kinds of spaces. You might simplify it down to surface areas and transparent areas, focusing on openings in the building. Textural qualities, very simple and refined down to the basic idea. A hierarchy of materials within a project." -P7*

Two intern architects, who both have artistic backgrounds as well as industry experience making models for clients, remarked on the ability of the model to engage the imagination of their clients. P4 noted that, *"It's the intermediate step between the abstract ideas of a building and the reality. They can still project their own ideas on how it's going to be."*

In the same vein, P8, an architect with over 40 years of experience building models, notes that with digital models, "*there is almost invariably a disconnect. There is no interaction. With physical models, it's the tactility. It's real, and you shrink yourself to fit in the model*."

The second most mentioned advantage of physical models was the ability to circumnavigate the model freely to view the project in its' entirety. P8 and P9 both highlighted models' accessibility to large groups:

> *"A model is accessible to everyone equally, unlike a monitor or paper drawings. In a physical model, you move around to see the angle you want to see, you're in control. Clients would often move back and forth around the model, leaning in for a closer look and then taking in the project as a whole." -P8*

> *"[Groups] jump on it. Even a walkthrough video did not have the same impact." -P9*

Some of the most engaging models are those made to be investigated by an audience, with movable parts that can be lifted off or moved to the side so as to see the interior spaces of a project. Several interviewees speculated that the viewers' enjoyment of the model may be linked to childhood and the pleasure of learning through play.

> *"There is some connection to childhood. You want to grab the little car and drive it." -P8*

Interviewees also speculated that the physicality of the models might improve their memorability.

> "*In every school in [region] there was a relief map of the province - 8 foot, huge, painted plaster. Once you touched that mountain you understood it and remembered it your entire life." -P8*

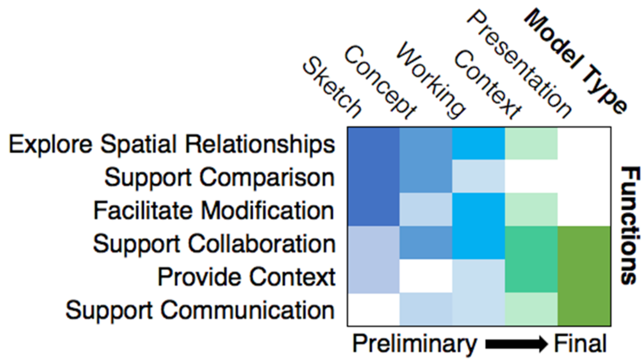

Table 2. Types of Models and Related Functions. The color scheme is the same as the one used in Figure 2.

This suggestion aligns with recent work by Stusak et al. [32] which indicates that physicality can improve the memorability of data representations.

DISCUSSION

While architects use a number of distinct genres of physical models as part of their craft, each of these types can still serve multiple and sometimes overlapping functions (see Table 2). These common, low-level functions underscore the specific points during the process of conceptualizing and designing a structure where physical models are particularly valuable. Moreover, each of the shared functions highlights material properties, manipulation strategies, and use cases that we believe can prove useful for data physicalizations more generally.

Building on the models and applications discussed in the previous section, we outline a set of four specific functions of physical models that can serve as inspiration for the design and development of future physicalization systems.

1. Exploring Spatial Relationships and Characteristics

Early stage sketch and concept models provide architects with a physical means of testing, exploring, and iteratively modifying the physical characteristics of a design, often via manual construction and manipulation. Architects often use these kinds of models early in their design process because they provide a quick and adaptable way of creating and comparing design alternatives.

This need to rapidly create and assess possible design alternatives is analogous in many ways to the challenges faced by visualization designers and analysts early in the data analysis process, as they seek to understand and craft appropriate representations for new datasets. While both visualization experts and novices often use "data sketching" [38] as a way to make sense of data on paper or in 2D tools, few mechanisms exist for supporting this kind of rapid, iterative data exploration in the physical world.

Recent work on "constructive visualization" – in which authors manually assemble representations of data using discrete physical tokens or building blocks [15] – provides one potential model for facilitating this kind of exploration. Like many approaches to sketch modeling in architecture, constructive visualization can be playful, accessible, and supports dynamic refinement of representations. However, this line of research has tended to emphasize the pedagogical, rather than practical, benefits of construction – in part because the process of additively assembling physicalizations token-by-token can be an arduous affair.

Architectural sketch modeling, by contrast, often employs non-additive and non-discrete construction methods like subtractive construction using foam and other easily-manipulable materials. Purely manual subtractive techniques may be less valuable when creating data physicalizations, where the resulting physical representations generally need to reflect a precise encoding of the underlying data. However, computer-assisted tools for handheld subtractive fabrication like Zoran and Paradiso's FreeD [46] suggest that simple data-driven tools could easily enable these kinds of physical data sketching or "data excavation."

Similarly, early-stage model-making in architecture often leverages assembly techniques like bricolage in which models are created by piecing together existing objects and physical components. This practice, sometimes called "junk prototyping," is also common in product design and interaction design [10]. Bricolage is valuable because it provides a fast, accessible, and social mechanism for exploring new ideas, while building on the existing complexity and texture of the component objects (rather than simpler primitives like tokens). We believe that bricolage-style techniques may also have value for data physicalization, particularly in social settings where their tangibility and composability can help ground discussions. For example, a collection of simple physical time series could serve as composable building blocks for examining and comparing possible forecast models or concretely illustrating and discussing imaginary policy scenarios. In contrast to the simple tokens used in constructive visualization, these components might include more realistic variability, trends, and other data features (peaks, outliers, etc.) that could be readily assembled to create plausible time series and facilitate deeper conversations.

2. Supporting Comparison and History

Physical models serve as forms of external memory for architects throughout the design process, and their physical nature often permits rearrangement and reconfiguration to support various design tasks. For example, architects may place sets of working models alongside one another to support direct comparison between several design choices or possible building materials. In a studio setting, architects may also position or distribute models on shelves and tables, creating a physical record of the design process that can prompt continued awareness of past experiments and possible alternatives.

Work in information visualization has long recognized the importance of visual representations as forms of external memory [3]. To this end, both visualization and visual

Figure 3. SweatAtoms artifacts support the physical comparison of a series of different athletic activities. Image: R.A. Khot.

analytics research has explored the value of visual histories of the analysis process [12] and visually organizing analysis results to support efficient sense-making [42]. However, mechanisms for comparing on-screen visualizations and analysis histories are limited by the amount of screen real estate. Only a few tools support direct interactive comparisons between multiple representations [16] or attempt to recreate the sense of a large, persistent work environment that supports shared spatial memory and analysis history [14].

Data physicalizations, on the other hand, lend themselves readily to the kinds of direct, physical comparison and rearrangement we see with architectural models. Early research has demonstrated that small handheld physicalizations can be easier to compare and manipulate than their on-screen counterparts [18]. However, our experience with architectural models suggests that the ability to sort, order, and organize larger numbers of physicalizations across a workspace may bring additional benefits – improving awareness of previous exploration and making it easier to revisit and juxtapose analyses. Increased use of persistent data physicalizations as part of their everyday analysis practice could eventually allow knowledge workers to reclaim some of the spatial and tangible value often attributed to more traditional architecture and design studio spaces [30]. For example, Stusak et al. [33] discuss how collections of SweatAtoms– 3D printed physicalizations showing athletes' activity over individual workouts – can be arranged to create "memory landscapes" highlighting longer-term activity (Figure 3).

The idea of spatially distributing analytic views and markers of analysis history also has promising implications for the design of virtual- and augmented-reality analysis environments [4]. While not strictly physical, augmented reality visualizations created with modern headsets could easily be rendered at unique and reconfigurable locations relative to a viewer or their surroundings. Such systems could potentially capitalize on many of the benefits of physical models, without the cost or complexity of physical fabrication or mechanical actuation.

3. Providing Context

When designing a structure or environment architects always need to consider the interplay between structures and their surrounding environment. While it is valuable to visit a site and examine the physical landscape in person, the vast majority of the work exploring the relationship between the design and its surroundings happens in the studio. Context models that include not only the structure being designed but also its surroundings provide a valuable tool for contextualizing new designs. Physically modeling the surrounding environment at smaller scales allows architects to more readily examine and manipulate buildings, topography, and environmental conditions in ways that are difficult or impossible in the real world. Similarly, when creating models, architects can select and emphasize important elements of a scene like nearby buildings, vegetation, property boundaries, or rights-of-way, while de-emphasizing less important details.

A growing body of visualization work has also begun to recognize the value of context when presenting and interpreting data. However, this work has tended to emphasize the value of situating visualizations in real-world environments [40], embedding data representations in close proximity to relevant people, objects, and locations [41], or altering environments to make important phenomena visible in-place [26]. As a result, much of the work has focused on using augmented reality tools to render representations of data directly at relevant locations.

Our discussions with architects, however, suggest that embedding or situating data within small-scale physical facsimiles of real environments may also have considerable value for data analysis. For example, by providing context about the area, physical scale models of a large field site could help analysts more easily examine and make sense of relationships between samples or specimens collected there. In contrast to on-screen GIS tools, more detailed physical context models could allow analysts to use physical locomotion, tangibility, and direct manipulation to explore the data, while also providing rich information about the original environment.

Tangible computing systems like Urp [37] and Piper et al.'s Illuminating Clay [29] have demonstrated how dynamic physical models and projection can be combined to support planning and urban design tasks. Despite this, tools that would allow data analysts to quickly create and utilize context models as part of their own data analysis practice remain largely unexplored. Fortunately, recent advances in 3D scanning and digital fabrication [44] seem poised to streamline the process of creating models from existing objects and locations. Widespread interest in content capture for virtual reality headsets also promises to make it easier to create virtual context models for a variety of visualization applications.

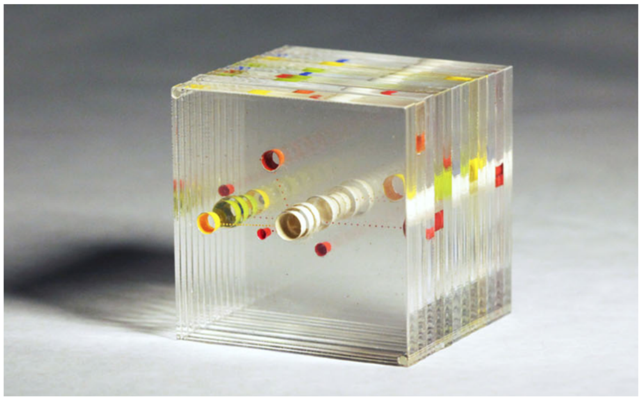

Figure 4. Blip: A Year of Travel. Image: Cemre Güngör.

4. Evoking Emotion

Architects rely on a rich palette of materials when constructing models. This is particularly true for concept models and presentation models, which – like the buildings they envision – are often intended to evoke an emotional response. In practice, aesthetic, material, and construction choices can have a strong influence on how viewers perceive, react to, and choose to interact with models.

For example, Cemre Güngör's 'Blip' (Figure 4), uses transparent acrylic to represent the feeling of '*looking into one's past*' and to allow for viewing from all angles [11]. In this case, the designer used his choice of material properties expressly to influence the emotional response of the viewer in a way that suited his feelings about the data set.

While information visualization has long considered the perceptual implications of low-level visual encodings such as shape and color in data graphics [3], the perceptual characteristics of the materials used in data physicalizations remain unexplored. Moreover, very little work has sought to systematically characterize the emotional impact or visual appeal of different information graphics [23]. In practice, the question of aesthetics is often treated as a distraction by much of the visualization research community, where discussion of extreme aesthetics and visual embellishments [2] are often rebutted with appeals to Tuftean minimalism [35]. However, for data physicalizations – which must ultimately be constructed from real-world materials rather than pixels – these questions of aesthetics become more difficult to sidestep.

Many informal social conventions exist around the use of material and light (brushed metal implies seriousness, foam is "sketchy", LEGO is playful, etc.). However, little practical guidance exists for designers looking to create either perceptually affective or emotionally provocative data physicalizations. While initial perceptual studies of physical variables like size are ongoing [20] more work is needed to develop a nuanced understanding of the practical and aesthetic tradeoffs associated with different construction techniques. There are no de facto 'style guides' for architects to guide material choices, however, existing work on model-making and materiality in architecture [39] could provide a practical starting point for physicalization designers looking to understand the interplay between material form and emotional response.

CONCLUSION & FUTURE WORK

Architectural models are a versatile visual and physical tool for exploring complex spatial relationships. By identifying the characteristics and functions of physical models in architecture, we highlight opportunities for new kinds of physical representations that support the analysis, exploration, and presentation of a much wider variety of data. Specifically, our work details four functions of physical models that can serve as inspiration for building physical data systems. We describe low-level functions that underscore the specific points during the process of conceptualizing and designing a structure where physical models are particularly valuable. Our initial discussion also highlights material properties, manipulation strategies, and use cases that each point to potentially valuable research areas for physicalization. As the field of data physicalization grows, we hope that the traditions of architectural model-making can provide inspiration for imaginative and precise representations of data that inform the mind as much as they engage the senses.

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