P+: A Test Fit Platform for Generative Design of 3D Media Architecture

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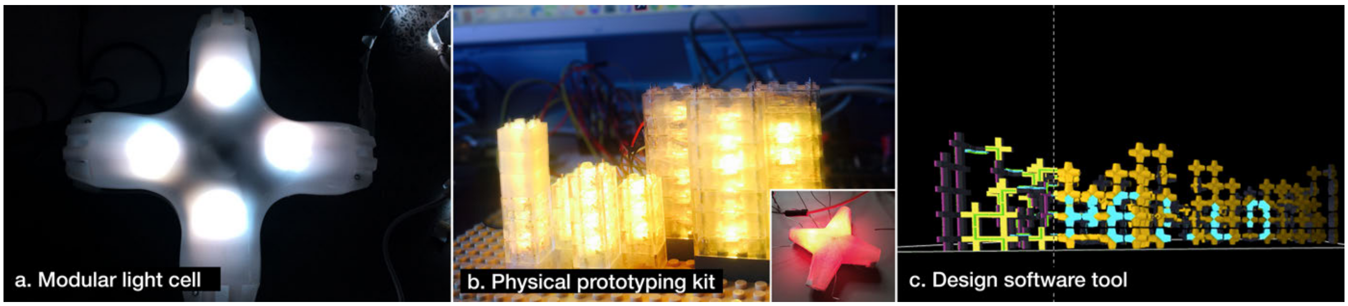

Figure 1. P+ consists of three different parts: (a) the modular light cells to assemble 3D media façades on an urban scale, (b) a physical prototyping kit that consists of LED-Bricks in Lego format [15] and higher-fidelity 3D printed cells (bottom right) to explore content taking into account the lighting quality of LED media façades, (c) the software tool for generation, simulation and execution of design solutions with lower (left) and higher (right) fidelity representations, here with "hello, world"-scrolling text .

ABSTRACT
As media architecture becomes an increasingly popular vehicle for the integration of digital technologies into the built environment, a combination of techniques becomes necessary to overcome challenges regarding prototyping form, content and scale. In this paper, we present P+, an open-sourced test fit generative platform for the design of 3D media façades. It consists of modular light cell components that can be assembled into a larger structure; a physical, 3D printing based prototyping kit; and a software tool for generation, testing and live running of façades fulfilling pre-defined contextual constraints.

Author Keywords
Design tools; media architecture; media façades; urban prototyping; architectural design; 3D simulation.

ACM Classification Keywords
D.2.2 Design Tools and Techniques; I.6.m. Simulation and Modelling: Miscellaneous.

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INTRODUCTION
An interesting phenomenon that can be observed in the 21st century city is cutting-edge architecture increasingly emerging out of algorithmic models, signaling what some have dubbed a 'digital turn' in architecture [2]; conversely, with the emergence of media architecture, Human-Computer Interaction began to integrate architectural aspects such as spatial layout, illumination design and acoustics into a more holistic approach to the design of public spaces with new technologies [12]. The pervasiveness of digital displays and sensing technologies has prompted interaction designers to approach buildings and urban environments as interfaces in their own right. Consequently, conference venues on pervasive displays and the media architecture have fostered researchers from both domains to share various concerns when it comes to designing experiences and services in the city.

Media architecture refers to the utilization of specific categories of media – namely those based on information technologies – in the design of architectural elements that can convey their own dynamic information or prompt transient sensorial experiences. The transient nature of its aesthetic qualities and its potential to incorporate sensors for gathering inputs from passers-by enable the design of large-scale displays and interfaces integrated to environments that not only accommodate people and frame their experience, but also listen and change in response to them. Given its potential to turn any urban surface into a digital display and thus add dynamic content to sections of public spaces [20], media architecture has been increasingly employed as platform of choice for the design of new urban interfaces [21, 22], public art [17] and digital placemaking [10]. Through a series of field and case studies, researchers investigated important aspects for successful deployment of media architecture, such as social implications [11], contextual integration [16], and spatial factors [6].

However, despite its increased popularity and the fact modelling tools and computational design have become standard practices in architecture itself, media architecture – and media façade design, in particular – is yet to fully benefit from those practices. With rare exceptions [8], it is largely still designed in an ad-hoc manner, retrofitting 'digital layers' over otherwise standalone buildings. Consequently, research into tools and methods to support a generative design process combining physical structure and content of media architecture is still very much lacking. In this paper, we present a platform we developed and made publicly available for supporting: (1) speculative generation of three-dimensional (3D) media façades to address a configurable set of contextual constraints; (2) simulation of light effects; and (3) real-time execution of those effects on the resulting façade. In the following sections, we discuss related work in the field and then present our design rationale, case study, solutions and findings from the research, as well as its limitations.

RELATED WORK

Developing prototyping toolkits to address the domain-specific challenges of media architecture [1, 5] received a relatively high interest in the research community in the past. Since media architecture displays have unique characteristics in terms of size, shape, form factors and display technology [9], Gehring et al. [7] developed a generalized *simulation toolkit* to test interactive content for various infrastructures before the final deployment. Wiethoff and Gehring [24] mentioned that *lighting qualities* of LED media façades, and the resulting aesthetic experience, cannot be simulated on a computer screen. In this vein, they introduced the miniature lighting lab *LightBox* [23] for experience prototyping [1]. As a further development, Hoggenmueller and Wiethoff presented the tangible prototyping toolkit *LightBricks* [15] to explore various 3D physical designs along with visual content that is mapped onto electronically enhanced Lego bricks. Further research was conducted on retrofitting existing physical structures with pixel elements [3, 19], using rapid prototyping techniques to build low-cost façade elements [14], and evaluating interactivity with media façades in the wild [13]. Yet, the software and hardware tools presented lacked on a generative design approach that encompassed digital content as well as physical structure, since they were all intended for simulating or augmenting infrastructures that already existed. Therefore, they did not provide a self-supporting structure nor complied with the requirements of *robustness* and *stability* when designing for urban spaces.

Halskov and Ebsen [8] discussed approaches to the design of complex media façades, adopting as subject the Danish Pavillion in the Shanghai Expo 2010, consisted in a double helix shaped building containing 3600 holes on its façade, each fitted with an RGB LED lighting fixture. This produced a curved media façade with pixels arranged in a non-grid pattern and with shapes varying depending on the onlooker's perspective. The authors presented a series of prototype iterations – ranging from a full-size mockup of a section of the façade, a pixel visualization digital tool, wall projection, 3D modelling software, and mixed reality physical model. From each approach, the authors derived insights into different aspects of the design process, and presented the aggregate set of techniques as a framework for the development and testing of media façades. The framework offers a more fine-grained classification of their design tools according to the specific qualities of media architectural interfaces: *scale, shape, pixel configuration, pixel shape,* and *light quality*. Our work presented in this paper leverages on their taxonomy and extends it to include considerations about important aspects in the generation and prototyping of 3D media façades. The design of our modular platform is inspired by the emerging paradigm of LED-cubes consisting of a three-dimensional array of LEDs, which is popular in the maker community and have been explored as a medium for volumetric visualisations [18]. Our work addresses recurrent challenges, such as the seamless integration of data cables into the physical structure, simulation and live testing of visual effects according to different points of view, and support to decision-making on design trade-offs.

DESIGN MOTIVATION AND GOALS

Our main motivation when starting the present research was to apply, in the rather specific field of media architecture (and, in particular, 3D media façades), some recent developments in the broader field of architecture, with the goal of addressing some of the challenges pointed out by Dalsgaard and Halskov [4]. Of particular interest, at this stage, were those challenges not necessarily related to interactive aspects of media architecture, but rather concerning potential trade-offs in the actual physical form and digital content: (a) integration into physical structures and surroundings; (b) increased demands for robustness and stability; (c) developing content to suit the medium; and (d) aligning stakeholders and balancing interests. In that regard, we set three initial design goals, as described below.

Design Goal 1: Test Fit Generative Design

We were inspired by techniques characteristic of the 'second digital turn' in architecture, as described by Carpo [2], with particular focus in generative design, i.e. the production of solutions emerging algorithmically and fulfilling a specific set of rules as well as pre-defined contextual constraints in the form of design variables (parametric design). For example, the footprint and height of the public space limit the potential dimensions of the media architecture structure, as does the need of leaving certain areas empty to allow pedestrian movement, or the ability of only visualize the content of the media façade from certain angles. Moreover, it was also important that our design platform only generated solutions that were *test* *fit*. Test fit is a standard practice in architecture to ensure that design solutions fit in a site footprint and adhere to other contextual constraints. The expectation was that, departing from known rules and conditions, we could arrive at a set of design solutions we could not possibly have envisaged upfront, all satisfying the project conditions.

Design Goal 2: Portability and Adaptability

One of the reasons media architecture solutions are often designed on an ad-hoc basis is the fact they tend to be site specific, reducing the likelihood of solutions being reused and relocated to (or recreated for) a different location. Likewise, limitations on budget or the availability of technical equipment may lead to reconsiderations in the design, with consequences often hard to assess. To overcome this challenge, we considered a modular approach to pixel design, in order to support adaptable public media environments that could be easily changed, reframed, expanded or reduced in response to long term variations in contextual conditions.

Design Goal 3: Content Simulation and Live Testing

As pointed out by Halskov and Ebsen [8], the complexity inherent to media façades requires a blend of digital and physical prototyping tools to simulate and assess different aspects of the design, e.g. pixel shape, light conditions and different viewing perspectives. Our design platform should thus allow prototyping, visualization and testing of a 3D structure and its digital content from any angle.

THE P+ DESIGN PLATFORM

Based on the goals outlined on the previous section, we devised a design platform, which we called *Pixel Prototyping and Production Platform*, or *P+* for convenience. It consists of three major components to support the process of designing a 3D media architecture solution demonstrating fitness to contextual constraints, its modular construction and the live running of visual effects on its façades: (a) a modular light cell unit; (b) a physical prototyping tool; (c) a software tool for generation, simulation and execution of design solutions. In this section, we present each of those components; in the next, we discuss how they lead to our proposed design method, as well as their contributions and limitations. To enable others to follow our approach and further develop the platform, the software tool, 3D models and instructions are freely available on github[1].

Modular light cell

To build complex 3D media façades on an urban scale, we developed a modular light cell in the shape of a cross measuring 35x35x10 cm (see Figure 1a). The cell's outer shell consists of two halves (front and back) made of polyethylene plastic using rotational molding techniques. The front side, with the LEDs facing up, is made of translucent material to create a smooth diffusion, whereas the backside is made of white opaque material. The cross-

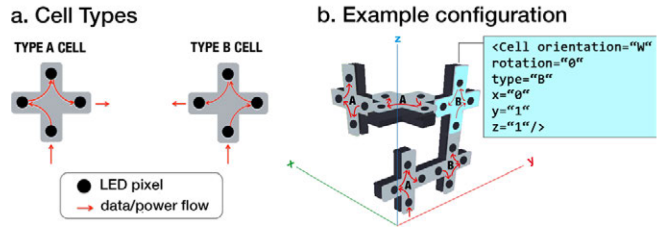

Figure 2. The two types of light cells and how they are assembled into more complex structures.

shaped design has evolved from multiple prototyping iterations and was considered ideal for connecting multiple cells and creating a "porous" 3D spatial structure. Further, the LED arrangement within the cross-shaped cell was chosen similar to a seven-segment display, which enables the representation of text with only a few cell units. Each cell houses 4 high-power RGB LEDs (108 lumens each) that can be controlled individually. For that, we used the widespread digital multiplex (DMX) protocol. This comes with limitations regarding (a) its *constructive versatility*, due to the underlying "daisy-chain" network topology of DMX, and (b) the *number of cells* that we can control in one line due to the limit of 30 devices in accordance with the overarching RS-485 standard. However, instead of using purpose-built hardware for autonomous [19] or self-organizing [3] pixel units, we decided to fall back on a widespread standard, keeping the hardware as simple as possible and, instead, solving issues regarding localization of cells and mapping, on the software side. To cater for the continuous flow of power and data through the structure, we figure out that it was sufficient to wire the LED strips within the cells in two different ways, effectively resulting in *two* distinct types of cells, each of them having the LED-chains mounted in the opposite direction (see Figure 2).

Physical prototyping kit

Exploring content by relying solely on rendering-based simulations is not feasible due to the *lighting qualities* that LED media façades produce [8]. However, pre-testing content with the actual modular light cells is (a) time-consuming when it comes to assembling a complex structure, and (b) requires a lot of space that may not be available prior to a planned exhibition. For this reason, we adapted the physical prototyping tool LightBricks [15] for running content explorations on a small-scale model (see Figure 1b). LightBricks consists of transparent LEGO™-bricks, housing a WS2812B RGB-LED. Stacking 'pixels' on top of each other, the tool can be adapted to various structures. To power the LEDs and transfer data, connectors are inserted into the knobs of the bricks. To control LightBricks with our software tool (described in the following section), we connected them to a WS2812B-contoller supporting the art-net protocol, which allows us to simply exchange the miniature model with the actual light cells at a later stage. Using the original LightBricks to simulate P+-structures has limitations, since it ignores (a) the *pixel shape* (cross shape) and (b) the *pixel configuration* (a P+ light cell houses 4 individual LEDs). For this reason,

[1] https://p-plus.github.io

we took the development of LightBricks forward by using 3D printing to produce a unit in the cross-shaped pixel design (4x4x1cm) housing 4 individual controllable LEDs (see Figure 1b, bottom right). The 3D-printed version follows a press-fit design which allows to "wire" the contacts of the SMD-LEDs without soldering. To simulate the diffusion of our actual modular light cells, we 3D printed the front side in transparent and the backside in white polylactide (PLA) filament. In summary, LightBricks serve as a generic tool that allows fast and low cost prototyping of media architecture structures, whereas the 3D-printed complement can be used for further refinement of the representational fidelity.

Design software tool

We developed a design software tool in Processing for generation, simulation and execution of design solutions for 3D media architecture structures using our cross-shaped light cell. The tool has three basic features: (1) individual cell rendering; (2) 3D media façade generation; (3) exporting of structure layout as blueprint for construction; and (4) execution of visual effects, both as simulation on the digital structure and live running on the physical prototyping kit or final 3D media façade.

Cell rendering

For each light cell unit, the tool stores the following data: (a) position in the xyz-coordinate system; (b) orientation of its illuminated face (North, South, East, West, Up or Down); (c) rotation around it's own axis (take on the values 0, 90, 180, 270 degrees), which in turn determines the entry and exit points for its power and data; (d) whether it has type A or B (Figure 2); and (e) the colors assigned to each of its four RGB LEDs. The tool can render the cells accordingly, with a series of toggles enabling different modes: for example, the user can switch between low and high-fidelity renderings (Figure 1c), or choose between displaying the true colors for each individual RGB LED or, rather, having all cells facing a particular direction rendered in the same color, as illustrated by Figure 1c, left side. The green lines through the cells in that figure illustrate another important feature to assist the construction of the structure: rendering the logical flow of DMX data through it, based on the rotation and type of each cell (A or B).

3D Media Façade Generation

The 3D media façade generation relies on a configuration file where a set of properties – mapping a series of relevant contextual constraints – is set as a basis for the design. Core properties are: dimensions and weight of the light cell itself (to future proof the platform for refinements in our modular design); the unit cost of a light cell and total budget available (therefore determining the total number of cells available); the dimensions of the target public space; the minimum height for the structure ceiling; and the maximum number of light cells that can be connected sequentially. Regarding the latter, it is worth noting that connecting cells together effectively creates LED strips, whose maximum length may be dictated by limitations of the data protocol adopted (DMX, in our case) or availability of power supply. Notably, the total number of 'LED strips' in the structure is calculated as *(total number of LEDs)/(maximum length of each string)* and it bears implications for the generative algorithm, as explained below. Another module within the tool gives the user a top down (2D) view of the floorplan and the ability of setting explicit walking paths or obstacles through the space, thus leading the tool to 'carve' tunnels or corridors in the generated 3D media façades. The generative algorithm starts with a number of cells equal to the number of 'LED strips' for the structure (as calculated above), positioned randomly along the edges of the space. It then proceeds with a series of iterations, on each trying to 'grow' the strips by connecting to the end of each a new cell. The actual direction each strip grows is chosen randomly, yet respecting the spatial constraints in place (e.g. cells cannot grow outside the dimensions reserved for the structure, and cannot obviously occupy the same space where another cell has already grown into). If attempts to grow a strip fail to satisfy the spatial constraints, then no more cells can be added to it, the generation is aborted, and the whole process starts over. Otherwise, it goes on until the maximum number of cells is reached, in which case a new solution is recorded, as explained below.

Blueprint for Construction

Whenever the generative algorithm finds a design solution that fits the contextual constraints in place, the corresponding structure is recorded on disk as a CSV file. This file can then be exported to spreadsheets or even 3D modelling programs, and used to guide the placement of each light cell in both the physical prototyping tool or the final, real size 3D media façade structure.

Content Simulation and Live Running

Recorded solutions can also be reloaded into the software tool both for visualization of the 3D structure and simulation of light effects played on it. For our initial purposes, we coded a set of effects including scrolling text (see Figure 1c), fading in and out, a few abstract patterns, and a feature to map arbitrary video sequences on the structure. In addition to simulating the light effects on the digital 3D model, we added a control that, when switched on, would also send the corresponding DMX data signals

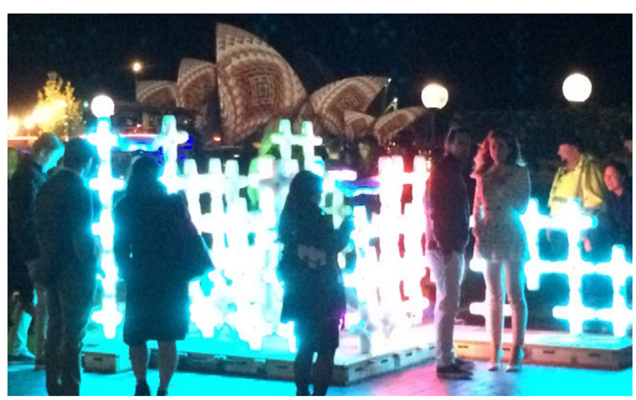

Figure 3. Proof-of-concept installation at public festival.

through the computer Ethernet port, using art-net protocol – thus enabling the live running and testing of effects in both the LightBricks and the final 3D media façade structure.

PROOF-OF-CONCEPT

In parallel to the platform development, we considered its application in the design of a 3D media façade for exhibiton at Vivid Sydney, a large public festival taking place every winter in Sydney, Australia, attracting an audience of over 2 million people. The final installation (Figure 3) helped us to prove the concept for our design platform and address some of the recurrent challenges by Dalsgaard and Halskov [4] that had motivated it, but not all of them. It also delivered some unforeseen issues, as discussed below.

Integration Into Surroundings

Being a public festival, Vivid Sydney makes use of existing public space, with selected installations having to fit into them. However, due to logistical factors, the final allocation of sites across the installations is often not finalized until only a couple of months before the event starts. In that regard, our design platform was instrumental in enabling us to swiftly planning for a range of potential locations, varying the constraints each imposed in relation to dimensions, passers-by circulation and viewing angles.

Aligning Stakeholder and Balancing Interests

The provision of budget by the festival limited the number of modular light cells we could produce to a maximum of 500 units. However, unexpected delays in the manufacturing of the units' plastic shells via injection mold by our industry partner reduced that number, only weeks before the festival, to a maximum of 160 units. Juggling such a variation in the availability of materials would have seriously compromised the viability of the project under normal circumstances; yet, the ability to play with quantities and quickly redesign as well as visualize the potential new solutions allowed us to deliver a suitable version of the 3D media façade in time.

Content to Suit the Medium

However, the small quantity of light cells available for the proof-of-concept meant that we had to design it to have a relatively small scale – which, naturally, brought a direct impact on the resolution of the media façade. Content prototyping became thus of vital importance, and for that we adopted the combination of initial tests with the software design tool, followed by refinement with the physical prototyping kit (LightBricks). Both had pros and cons. The LightBricks were suitable for testing and refining ambient light effects – such as wave animations, and firework particles – but not for testing text due its low-resolution. Also, although high fidelity 3D-printed models of the actual cross-shape light cells could have allowed us to investigate readability of text, it would have been costly to produce (in time and money) enough units for adequate testing. As with previous media façade prototyping studies [8], scalability of producing a high-fidelity model proved to be an issue, even with our relatively small proof-of-concept. The design software tool, conversely, failed to simulate the glare emitted from neighboring cells as observed on the final installation, which compromised readability. Likewise, the final light cells presented other unforeseen lighting issues derived from our choice of materials: for example, the opaque back plastic section allowed more light through than expected, impacting the visual appearance of light effects, particularly text readability.

Robustness and stability

Assembling a complex, freestanding 3D structure from many individual modules brings several challenges regarding robustness and stability. We partially addressed them by including in our simulation basic structural constraints (e.g. maximum weight load on each light cell) and working closely to a structural engineer for preliminary analysis of selected structures. Yet, other more complex aspects were not anticipated by our simulation nor the physical prototyping tool. For instance, we only realized the extent of the cumulative impact of minor looseness in the joints between cells while actually assembling the work, when we noticed the occasional lack of stability of units cantilevering from the main structure. Since our software did not support the tweaking of sections of a structure after it had been generated, we managed to make ours more stable at that very late stage by adding to it a few dummy cells, not connected to any of the existing 'LED strips' and playing a purely structural role. Another issue with media architecture installations in public spaces, also reported by [4], is that they might be subjected to vandalism and theft. In our case, while the work was not wantonly damaged, the low height invited children to climb the structure. There seems to be a common presumption that urban installations, being easily accessible and authorized for public exhibition, are necessarily stable and robust. Due to safety reasons, we

x	*Design software tool*	*Physical prototyping kit*	*Modular light cell*
Scale	Small (monitor size)	Small (table size)	1:1
Shape of display	3D	3D, but low level of detail	Actual
Pixel configuration	Actual	Poor approximation	Adjustment
Pixel shape	Poor/good approximations	Poor/good approximations	Actual
Light quality	Not simulated / 3D simulated	Simulated	Actual
Part of display	Whole structure	Small section	Whole structure
Content	Focused (developing content)	Explorative	Adjusted (for readability)
Data flow	Partly simulated	Not tested	Adjusted
Physical pixel placement	3D simulated	3D simulated	Actual

Table 1. Analysis of design platform against the framework proposed by Halskov and Ebsen [8].

thus had to fence the installation after just a few days, ensuring that people watch it only from a safe distance.

CONTRIBUTIONS AND LIMITATIONS

The report above of our proof-of-concept implementation highlights some very relevant contributions from our research, while also pointing to some shortcomings and consequent opportunities for future work. In addressing the core challenges for the design of media architecture proposed by Dalsgaard and Halskov [4], it proposes an open-sourced platform that also advances the framework developed by Halskov and Ebsen [8] for the design of complex 3D media façades, as showed by Table 1. In addition to addressing the design aspects pointed by their research – (a) scale; (b) shape of display; (c) pixels configuration; (d) pixel shape; (e) light quality; and (f) content and its perception from different angles – our platform also addresses two new categories: (g) simulation of data flow; and (h) ability to prototype physical pixel placement, rotation and orientation. In doing so, the tool generates not only a set of design solutions, but also a blueprint for their physical construction.

While designing media façades has often meant to retrofit architectural structures with a layer of digital media, we argue that our platform may offer a more integrated approach to their design. The combination of the software tool, prototyping with the LightBricks and pixels embedded into modular light cells enables a highly agile method for the investigation of design trade-offs, as illustrated by Figure 4. As observed by our proof-of-concept implementation, this method can equip designers not only with the ability to play with the contextual constraints in support to planning and feasibility analysis during the preliminary stages of the project, but also to quickly adapt to shifting conditions during implementation and construction, producing variations of potentially complex yet feasible solutions to the target context.

Of course, there are also still practical limitations with our design platform. Significantly, neither the current software tool nor the LightBricks prototyping kit managed to avoid certain scalability issues. In that regard, we can formalize two particular categories of scalability challenges, namely the simulation of the compound effect of multiple pixels on (a) the overall lighting conditions; (b) the structural integrity of the generated structure. We can formalize those two scalability challenges, respectively, as *cumulative glare* and *cumulative robustness*. Upcoming versions of tools for 3D media architecture will need to take both challenges into account for greater fitness of the design solutions generated.

Our particular implementation of the media façade adopted a modular cross-shaped cell, connected to others in a grid-like pattern. Naturally, more sophisticated media façades would require the redesign of the light cells and their mutual connections to suit the aesthetic requirements of specific projects. Yet, we argue that the overarching design approach adopted here can still serve as a roadmap for the

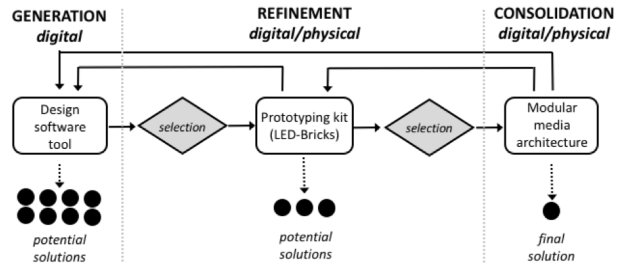

Figure 4. The iterative design method.

implementation of generative 3D media façades responding to a set of predefined contextual constraints. Likewise, although the modular light cells are made using professional moldings procedures – costly and hardly accessible to laypeople – the P+ platform can still offer a framework for nimble design of media façades through the combination of the 3D models generated by the software tool and rapid prototyping techniques such as 3D printing.

CONCLUSION

When it comes to designing complex tri-dimensional media façades, striking a satisfactory balance between expressiveness and functionality of the physical structure and the aesthetics of the digital content requires a level of foresight hardly achievable without extensive prototyping. Yet, research into prototyping frameworks for 3D media façades, while existing, is still incipient, and many design challenges have being left unaddressed. With recent academic and industry practices moving the fields of architecture and digital technologies closer towards each other, it makes good sense for designers working in the field of media architecture and pervasive displays to get inspired by architectural approaches that have employed algorithms to assist the design of urban environments.

In this paper, we presented P+, an open-sourced test fit generative platform for the design of 3D media façades, aimed at addressing some of the core challenges previously identified in the literature [4] – particularly those related to the integration of form and content. In that regard, we proposed a modular light cell component that allowed designers to approach architectural structure and digital content in a more integrated manner. That, in turn, is coupled with simulation and prototyping tools to support generation and tradeoff analysis of potential solutions against pre-defined contextual constraints. While this particular branch of digital design remains a complex undertaking, we argue that our framework deepens its understanding, widening the range of potential approaches to design briefs, and offering new insights into valuable strategies – and also recurrent challenges – to watch out for.

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