Integrated Algorithmic Design in Practice

A Renovation Case Study

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The lack of interoperability and the diversity of required documentation in the development of architectural projects often results in inefficient design processes. Integrated design approaches such as Building Information Modeling seek to tackle this problem, but still require strenuous and time-consuming manual work when it comes to design exploration and the implementation of design changes. Algorithmic design approaches facilitate this process by supporting quick change propagation and exploration of design variations, as well as automating the production of the required documentation. This paper presents an integrated algorithmic design workflow, encompassing all design stages, from conceptual design to fabrication. The workflow is tested throughout the design, analysis, visualization, and fabrication of a classroom renovation project, resulting in a more fluid and efficient design process.

Keywords: *Algorithmic Design , Algorithmic Analysis, Integrated Design Workflow, Digital Fabrication*

INTRODUCTION

Digital technologies have been adopted almost universally as the predominant means of design and production in architectural practices (Kotnik, 2010). This development has also affected how projects are represented and communicated to clients, which nowadays also encompasses photorealistic images, animations, or even Virtual Reality (VR). As technology progresses, the client is given an increasing amount of media to perceive the project in a more realistic and detailed way. Although this provides opportunities for the suggestion of changes that would not be contemplated otherwise, these are not always easily materialized, and the architect may take extended periods of time to modify the geometry in a digital model. This problem can be solved with Algorithmic Design (AD), a generative design approach based on the use of parametric algorithms (Caetano et al. 2020).

Employing AD in architectural projects can positively impact the design process by significantly accelerating the generation of a wide range of model variations. Either through the adjustment of parameter values or through modifications in the algorithms, changes are implemented in a more efficient way than with traditional approaches. Moreover, AD can be used to automate the production of photorealistic images and animations.

Integrating AD with analysis and sophisticated visualization mechanisms further promotes the design exploration, as different designs can be generated and evaluated through the same algorithmic description (Caetano et al. 2018; Castelo Branco et al. 2019). This research proposes an integrated AD methodology endorsing several design stages, from conceptual design to fabrication, including analysis, optimization, and visualization. We further demonstrate this methodology, applying it to a project for the renovation of a university classroom, intended to improve the learning conditions in terms of visual and acoustic comfort.

RELATED WORK

In the development of an architectural project, each field tends to work with their own specific tools that often do not correlate with those used in the other disciplines (Anderson 2014). This lack of interoperability hinders the efficiency of the design process, making it highly susceptible to information losses. Integrated design approaches tackle this issue, envisioning the building as the product of new social relationships amongst architects, clients, developers, builders, communities, and consultants (Moe 2008).

Building Information Modeling (BIM) integrates the conception of building form, system sizing, and construction data management into a single design environment (Eastman et al. 2008). Although BIM is intended to easily communicate with performance analysis tools, portability is still not optimal (O'Donnel et al. 2013; Aghemo et al. 2013). To suit the requirements of these tools, the analytical models often need to be created from scratch, consequently leaving performance assessments to final design stages.

An issue similar to the abovementioned happens while selling and communicating the idea to the client, as visualization is paramount for their comprehension of the project. Technical drawings can be challenging to perceive, especially when it comes to the space's scale or ambience (Chappell and Dunn 2016). To mitigate this hurdle, architects tend to resort to other visualization methods to make projects more comprehensible for clients. Despite many BIM components and plugins already being able to compose appealing renders and/or to benefit from VR [1-3], changes to the building form suggested by the client can still be very time-consuming to apply. This happens because traditional modeling approaches rely on the manual insertion of geometric elements, turning minor changes in large-scale models into lengthy and error-prone editing processes (Leitão et al. 2013).

While some BIM tools also provide parametric capabilities, the degree of flexibility and change propagation achieved with these tools is still limited when compared to an AD workflow (Feist 2016). Using AD as the main strategy for integrated design approaches further connects the design intent to the design outcome, as parameters and constraints link different geometric entities together while maintaining the design logic. Changing a single building element in the algorithmic description will adapt the rest of the model accordingly, considerably reducing the required time for the architect to apply and propagate design changes. Moreover, the generation of analytical models can be done seamlessly from the same algorithmic description, allowing for performance evaluation tasks to transition from later design stages to earlier ones (Aguiar et al. 2017). However, the parametric logic of AD strategies enables the creation of more complex projects, which translate into highly customized building components that are not easily constructed by traditional means. Integrating fabrication in the design workflow is, therefore, crucial for the materialization of these projects.

OBJECTIVES AND WORKFLOW

This paper proposes an integrated AD workflow, aiming to emphasize architect- client interaction and fabrication. The purpose is to take advantage of the features offered by algorithmic approaches throughout all architectural design stages. To achieve these goals, we extend the workflow previously developed by Aguiar et al. (2017), further detailed in Figure 1.

Algorithmic Description. The first stage comprises the generation of building geometry using an AD tool. The modeled elements have specified design parameters and constraints, which can be manipulated throughout the process of design exploration. Through an abstraction layer, equivalent models for different tools can be seamlessly generated by the AD tool. Thus, the algorithmic description includes the necessary information to follow through with the remainder stages of the workflow.

Analysis. Next, we evaluate the performance of a range of design solutions. The algorithmic description already contains all the necessary information for simulation (e.g., material description and climate data), so that analytical models are generated without additional effort, and only containing the necessary elements and details required by the different analysis tools. This encourages architects to study the impacts of different design choices, and to implement performance-oriented changes early into the design process. Moreover, since the creation of analytical models is automated, it allows for the implementation of optimization processes. This stage can iterate back to stage 1 as needed, until the architect is satisfied with the solution.

Presentation. The AD tool connects with a series of visualization mechanisms that provide a better perception of the model, to showcase the project and engage the client. This stage is linked to stage 1, so that client feedback can be directly integrated into the design. Since the model is parametric, design changes suggested by the client can be performed in a reduced time span, facilitating the adaptation of the project to the client's requirements.

Fabrication. The final stage of our workflow assesses the viability of the construction, when the design starts to undergo a rationalization process for fabrication. The algorithmic description of the project can also be used to automatically generate the necessary elements for fabrication. If the assembly of prototypes proves to be inefficient or unfeasible, we can go back to stage 1 and apply the necessary adjustments. This design rationalization towards construction tests the design's feasibility beyond the elements analyzed in stage 2.

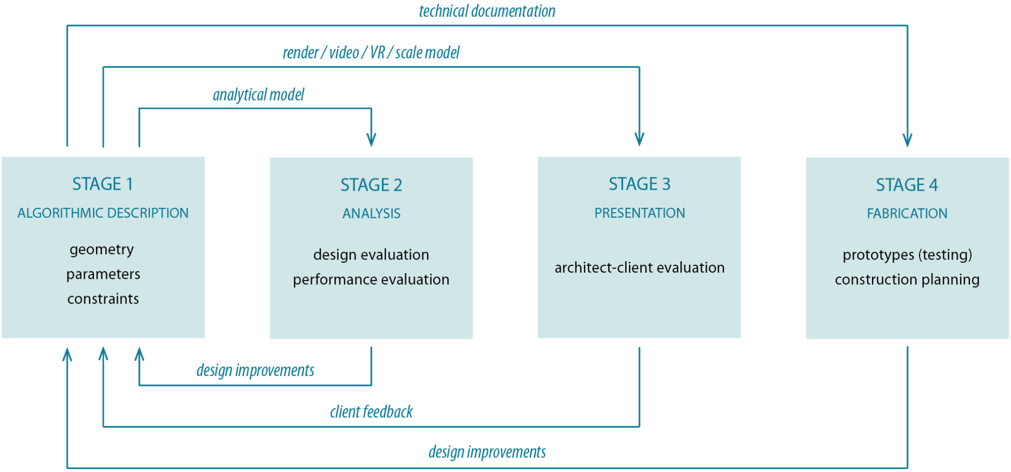


Figure 1
Integrated Algorithmic Design Workflow. Stages 1 and 2 compose the workflow developed by Aguiar et al. (2017).

Figure 2
Classroom. View from the entrance (left) and side view (right).

EVALUATION AND DISCUSSION

Recent integrated AD approaches mostly focus on new constructions. In this paper, we demonstrate the advantages of their application to design problems related to building renovation. Although the latter is a current key societal problem, most decision support tools are limited regarding the generation and evaluation of design alternatives (Nielsen et al. 2016). We evaluate our workflow by applying it to a classroom renovation project, developed at Instituto Superior Técnico, in Lisbon (Figure 2). The project won a public competition towards the improvement of the university's facilities, in which university staff and students voted on the projects they wanted to see implemented.

Concept

The proposal covers the acoustic and visual requalification of the classroom, to improve the teaching and learning conditions while making classes more comfortable and productive. To address this issue, the nature and location of the intervention was studied to find an optimal solution that satisfied the project's requirements. The chosen solution entails the application of a rough absorbent acoustic treatment in the ceiling's surface, hidden above a wooden grid structure suspended between the room's transversal beams. The grid design is inspired by the Ripple Effect phenomenon, as shown in Figure 3.

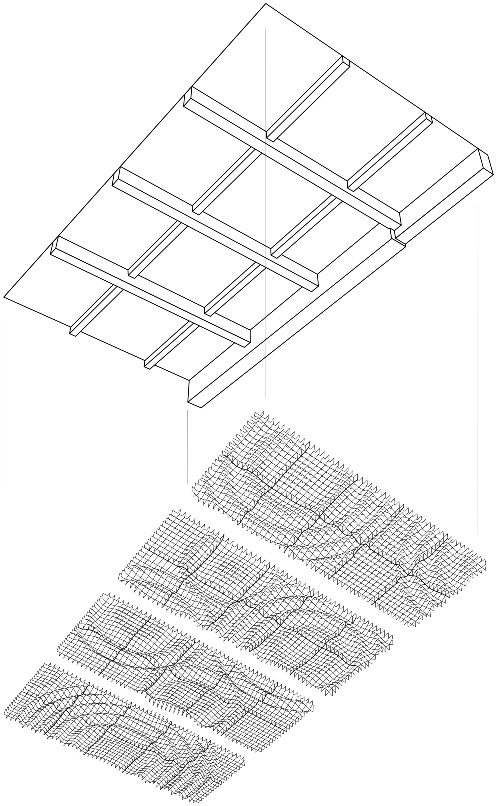


Figure 3
Exploded isometry of the renovation design.

Model Geometry

Both the existing classroom and the intervention were modeled algorithmically, facilitating the exploration of design variations and the quick propagation of design changes. The waves that portray the Ripple Effect were modeled using attractor points with varying attraction forces. The design parameters were (1) the number of attractors and their respective position and force, (2) the height, contour, and number of the profiles, (3) the elevation of the grid structure in relation to the room's existing beam structure, and (4) the materials for the intervention.

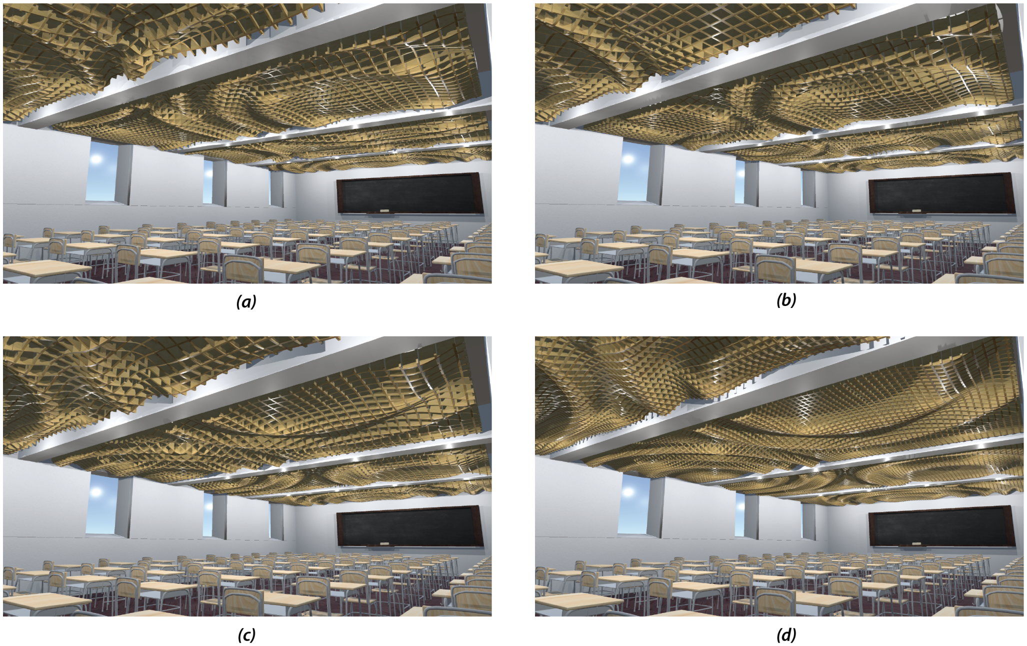
Figure 4 illustrates some of the possible design variations that can be generated, namely by changing the force (a to b) and position (b to c) of the attractor points, or the number of profiles (c to d). Additionally, the developed algorithm changes the shape of the profiles in non-visible areas to avoid material waste in the construction phase.

Analysis

Not originally designed as a classroom, the space's interior surfaces are composed of reflective acoustic materials, namely, ceramic tiles and plaster finish, which translate into a poor reverberation time that hinders the room's acoustic performance. Moreover, it is located below the ground level and has very thick walls, limiting the daylight availability. The challenging room configuration complicated the prediction of the effects of design changes, and the limited budget available restricted the option of consulting with experts in the fields of acoustics and lighting. To mitigate these problems, we employed validated simulation tools for acoustics, namely CATT [4] and Pachyderm (Van Der Harten 2013), and for lighting, namely Radiance (Ward 1994) and POV Ray (Plachetka 1998).

We defined the best strategy for the intervention by testing different design variations and materials. With the proposed workflow, the entire classroom and proposed intervention were defined algorithmi-

Figure 4
Design variations for the ceiling intervention.



(a) *(b)* *(c)* *(d)*

cally, so that analytical models could be automatically produced from a very early design stage (Figure 5). As the design parameters were changed, their corresponding acoustic impact was evaluated in the acoustic simulation tools to provide informed feedback for each design variation.

Initially, we observed that the sole application of a set of wooden panels in any of the classroom's interior surfaces would return a negligible acoustic impact, which could be fixed upon adding a layer of absorbent material between the panels and the surfaces. Afterwards, we studied different placements for the intervention and compared their simulation outputs. The ceiling was determined to be the location in which the acoustic treatment would have the most significant impact, particularly regarding reverberation time and speech intelligibility. Preliminary results show that the classroom's acoustic performance is more dependent on the acoustic treatment than on the Ripple Effect design of the panels.

Upon settling on the placement and design of the wooden panels, we studied the effects of the intervention in the classroom's lighting conditions, and observed that they were not adequate to ensure the

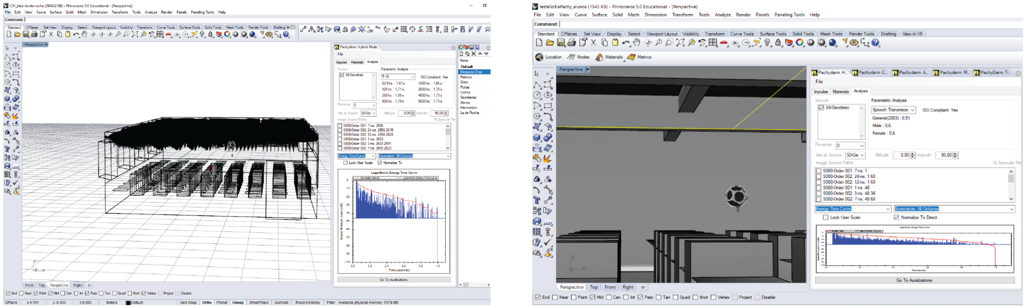


Figure 5
Acoustical simulation model in Pachyderm Acoustics plugin for Rhinoceros.

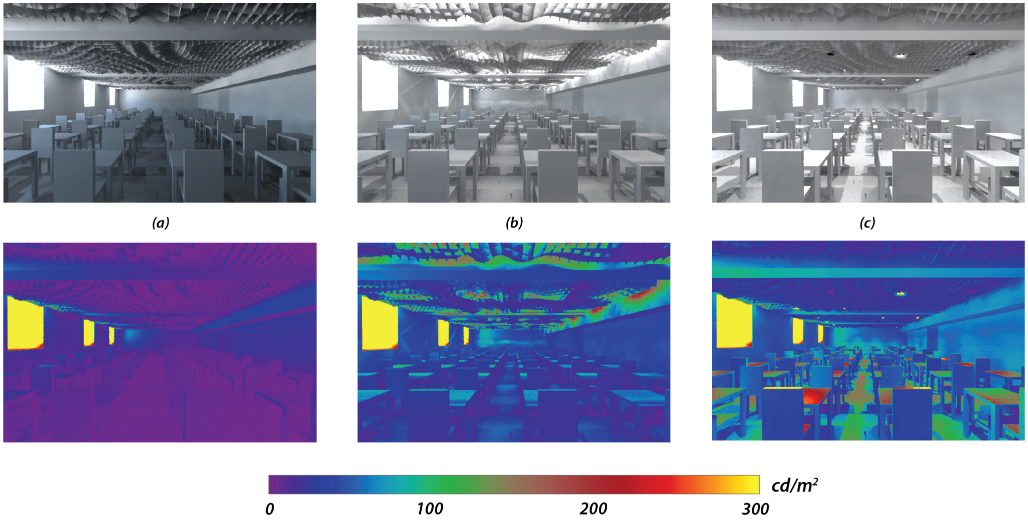


Figure 6
(a) Natural light study; (b) Natural + artificial light study, solution 1; (c) Natural + artificial light study, solution 2.

continued classroom use. Therefore, we explored a new lighting solution that could be integrated with the grid geometry, to ensure that our intervention not only did not aggravate the room's lighting conditions, but also benefited the learning environment. The goal was to find a solution that maximized the visual comfort, while minimizing the aesthetic impact of the lighting equipment on the ceiling structure.

To understand which arrangement of luminaries would better complement the natural light that entered the room, we conducted a set of lighting analyses to study the placement of the new lighting equipment in the grid and evaluate the different design solutions in different weather conditions. Again, AD was used to automatically generate the corresponding analytical models. Figure 6 illustrates the original lighting conditions of the classroom (a), along with two alternative lighting solutions (b, c), through renders and luminance falsecolor images generated for the 20th of July at 11AM. In the end, it was decided that the new lighting equipment would be placed with at least one light per panel, at the height of the grid, and the minimum distance between profiles was fixed at around 15 cm to fit the new fixtures.

Presentation

After gathering a set of design solutions with acceptable appearance and performance, the corresponding renders could be generated and presented to the client, in order to receive feedback. Equivalently to the analysis stage, the production of renders was automated by specifying the intended visualizations in the algorithmic description of the intervention. This way, the client's suggestions could be immediately implemented and tested in the AD tool by changing the model's parameters, and new images could be generated seamlessly. However, even with a highly-optimized rendering process, this does not provide an instant preview of the new design solution, due to the high computational cost of render generation.

To shorten the time needed to see the implemented model alterations and to improve the experience of the renovated space, the client was invited to see the digital model within VR (Figure 7). Particularly for our intervention, this visualization method helped the client to grasp the visual effect of the placement of attractor points in different areas of the classroom. The possibility of navigating freely through the model enhances the perception of the space, allowing to see details that, either in technical documentation or renders, would not be noticeable. Furthermore, it is not always necessary for the client to exit the virtual environment where the model is inserted to apply design changes, as some of them can be implemented by the architect in real-time.

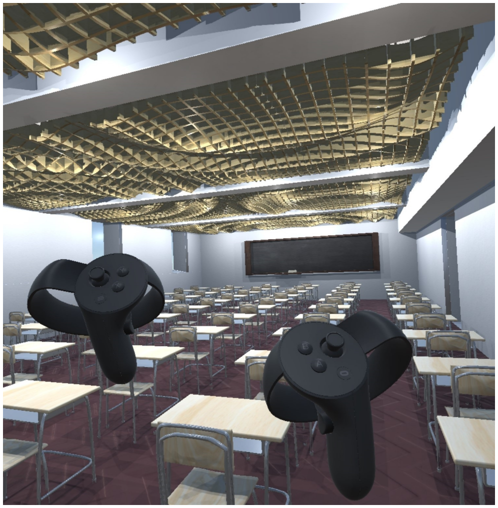


Figure 7
View of the project through VR.

Fabrication

Once the architect and the client settled on a design solution, the fabrication strategy to materialize the project could be defined. The main goals for this task were the reduction of material costs, as well as the simplification of the assembly process. Following that line of thought, a reduced 1:1 scale model was built to assess the distance between the wooden profiles. As mentioned before, this distance would need to be large enough to fit the new lighting equipment but also small enough to maintain the visual perception of the Ripple Effect pattern. This scale model also helped define the assembly strategy. The final disposition for the intervention grid comprises 40 self-contained panels, each composed of 10 longitudinal profiles by 10 transversal profiles (Figure 8).

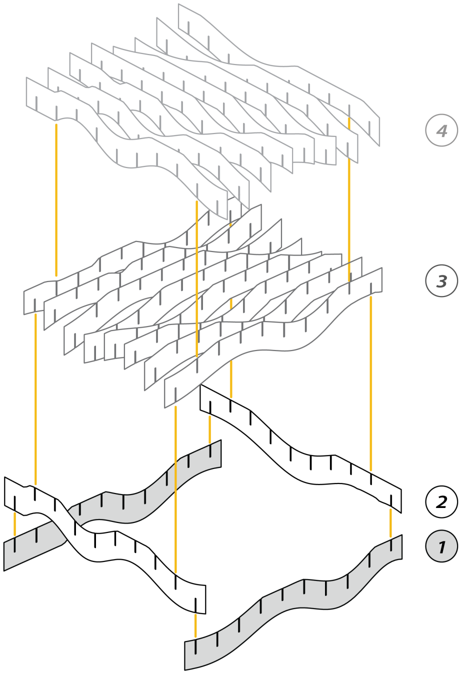


Figure 8
Diagram for the assembly of the ceiling panels. The numbers represent the order of assembly, and the support profiles are highlighted in grey.

The profiles have carved indentions which identify the locations where they fit together to form a panel. These indentions were designed so that, once assembled, the weight of the profiles is fully supported by two of the four exterior profiles, which are the ones that will be directly attached to the ceiling with metal rods. Subtractive fabrication techniques were determined to be the most suitable to faithfully reproduce the designed 3D pattern of the intervention, as it allows the production of larger objects in a fairly short time. Therefore, we chose CNC milling to cut through the materials to be tested (Figure 9). The 2D cutting profiles were extracted from the algorithmic model used in the previous stages, and labeled in numerical order to aid the assembly process.

Although the design process is not yet finalized, it was already possible to test the feasibility of the assembly strategy and to provide a materialistic feel of the finished product. Two prototypes, one in plywood and the other in MDF, were built and shown to the client. (Figure 10) These materials, however, are not the most appropriate for a classroom, as they are easily damaged by the milling process. This results not only in an unfinished, scrapped look, but also in the release of small particles that can harm the space's air quality. Moreover, it is important to reduce the flammability of the intervention, which emphasizes the need for additional research on materials and finishing techniques.

Figure 9
Prototype fabrication through CNC milling.

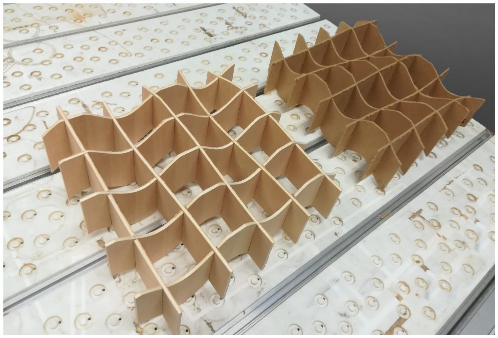


Figure 10
Panel prototypes.

CONCLUSIONS

Building form is no longer a sole concern while developing an architectural project. There is a strive to achieve improved performance levels, a justified use of components and materials, and decreased production timings and costs. Integrated algorithmic approaches promote an interdisciplinary design exploration of sustainable and efficient solutions through intertwined modeling, analysis, visualization, and fabrication stages. This research presents an integrated AD approach that comprised these stages in a seamless workflow.

Modeling an entire project algorithmically is a considerable initial investment, both in terms of required knowledge and programming effort. However, this investment will be returned in the succeeding project stages and in the reiteration of the design process, as it facilitates the exploration of design variations and a quick propagation of design changes. Instead of implementing these changes manually in a laborious and time-consuming process, the architect simply has to change a set of parameters in the algorithmic description or change the algorithmic description itself. We showed the applicability of the proposed workflow in a case study, and demonstrate how the same AD tool can easily handle the ensemble of tasks that compose the design process, making them less time-consuming and, therefore, allowing the design team to focus on the development of architectural solutions.

To evaluate the application of our AD approach, we developed and tested a ceiling intervention for a university classroom. We started by developing an algorithmic replica of the room that is being studied, which rigorously reproduces its current conditions and features. Through this algorithmic model, we can simulate and compare the impact of different interventions before applying them to the actual space, which would be very challenging to predict otherwise. This replica also facilitates the design experimentation at a practical level by automating the planning of prototypes, which vastly reduces the error-proneness of fabrication at different scales. Furthermore, if any of the fabricated components need to be repaired or replaced, their geometry can be easily extracted from the algorithmic model and promptly fabricated with identical preciseness.

Although the final design solution of the classroom intervention is not yet settled, its benefits regarding the acoustic and lighting performance of the interior space can already be discerned. Future developments will focus on the material study of the proposal, as well as the enhancement of design and assembly schemes.

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