Emerging Architectural Makerspaces: Analysis and Design Strategies

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MAKERSPACES: ANALYSIS AND DESIGN STRATEGIES

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Abstract

This article examines contemporary architectural design strategies being implemented in emerging architectural makerspaces within selected architectural schools. A review of the literature provides three major perspectives for design-build pedagogy in present-day architectural education: engagement with the community, collaboration and learning materiality, along with digital fabrication tools. Corresponding design approaches include building porosity, the use of atria and built pedagogy. A comparative study of seven makerspaces was subsequently conducted in order to identify the challenges and opportunities for applying these design approaches. Showcasing the internal activities on the outside invites the public to engage in the making process. The inclusion of an atrium facilitates visibility and interaction amongst the participants. A careful selection of material and construction methods can raise students' awareness and understanding of materiality and fabrication tools. Finally, these analyses are combined to produce a matrix of comparative studies for design guidelines. This article can serve as an impetus for further research in design-build pedagogy and the design of workshops.

Keywords:
architectural makerspaces; design-build pedagogy; architectural education; built pedagogy; learning environment

Introduction

Over the last several decades, the "design-build" method of teaching has become an important tool used in architectural schools, as evidenced by dramatic increases in design-build content at architectural conferences and in architectural journals (Hinson, 2007). The design-build pedagogy refers to engaging architectural students in both the design and construction of projects (Canizaro, 2012). The purpose is to "extend students' design skills in making a stronger link with material experimentation and construction" (Wallis, 2007, p. 201–202). Most of the architectural schools that incorporate this pedagogy in their teaching make full use of their workshops or makerspaces. An understanding of makerspaces is relevant while implementing design-build pedagogy.

Although each design-build course has various focuses, the overall trend is shifting towards adopting more digital fabrication tools into the process (Storonov, 2017). Many renowned architectural schools have recently constructed facilities to specifically cater for the emerging design-build courses, including the University of London Here East Campus (2017) and the Arch Tec Lab, Swiss Federal Institute of Technology Zurich (ETH Zurich) (2016). Digital fabricated design elements are often used as part of these newly built workshops or makerspaces.

Surveys of students have proven that the physical environment plays a vital role for the learning process (Dovey & Fisher, 2014; Fisher & Newton, 2014; Nasar, Preiser, & Fisher, 2007; Temple, 2008). However, there is currently a lack of understanding with regards to how architectural makerspaces can be designed to best facilitate their corresponding pedagogy. Therefore, the purpose of this article is to identify links between design-build pedagogy and makerspaces where this form of learning occurs.

The article begins with a brief literature review of various perspectives of design-build pedagogy. The key themes of the pedagogy identified include the engagement with the community, collaboration, learning materiality and digital fabrication. Based on this review, three design strategies (building porosity, the inclusion of an atrium and built pedagogy) are discussed respectively with selected cases. The research methodology being used is a qualitative analysis of case studies. Seven architectural makerspaces are used to identify the challenges and opportunities of applying these approaches. Finally, the analysis of selective makerspaces is combined to produce a matrix study for design guidelines. The limitations of the research are also discussed at the end of this article.

Literature Review on Design-build Pedagogy

The modern design-build architectural education originated from the Bauhaus under Walter Gropius in the 1920s (Salama, 2015). In the 1960s, as a reaction to aesthetically driven Beaux-Arts methods, the clash of ideologies between historical and novel architectural methods sparked the growth of design-build programs. In the 1990s, design-build programs were further expanded, likely in response to theory-laden "paper architecture" and stylistic historicism of the 1980s. More recently, access to new digital fabrication methodologies and 3D printing has further expanded design-build programs. Today there are more than 100 educational programs based on design-build pedagogy around the world (Canizaro, 2012). Although the focus of each program varies, the key perspectives are identified, including the understanding of materiality, engagement with the community and collaboration (Carpenter & Hoffman, 1997). The book *Design-Build Studio: Crafting Meaningful Work in Architecture Education*, edited by Storonov (2017), covers sixteen studio case studies accommodating design-build teaching methodology. Authors reiterate the importance of design-build studios by enabling students to better understand the intrinsic relationship between materiality and construction. Moreover, the book argues the proliferation of machines like laser cutters and water-jet cutters has led to an escalation in digital fabrication within universities (Storonov, 2017). The literature review revealed four focus areas of design-build courses, including the understanding of materiality, engagement with the community, collaboration and digital fabrication tools. These are described in more detail in the following sections.

Understanding of Materiality

The critical feature of design-build pedagogy is to allow students to engage with the materials directly. Design-build is a critique of the common emphasis on theory and drawings (Canizaro, 2012). The design-build courses integrate design, making and building activities and thus encourages participants to question the feasibility and constraints of their imaginations, with the aim of allowing students to gain a deeper understanding of materiality (Abdullah, 2011). Jiao and Tang (2019) documented and analysed the entire process of the Lianhuadang Farm Project, a graduate design-build course in the School of Architecture of Southeast University, China. In this course, bamboo was used as the main construction material. Through material research, process training and on-site construction, this course enabled students to explore bamboo's properties, connections, representations and construction details (Jiao & Tang, 2019). They concluded that focusing on one particular material (bamboo), using a design-build approach, facilitates an in-depth learning of its materiality. Through discovering and solving problems on-site, students also developed their communication skills and social awareness in architecture. Hackel, Gaube, & Lampe (2018) also evaluate the effectiveness of design-build courses, especially the importance of on-site "hands on" experience. They argue that during the construction process, students can explore material properties, construction technique and structure (Hackel, Gaube, & Lampe, 2018).

Engagement with the Community

Design-build courses often have a clear objective to develop outcomes based on community requirements. This provides an opportunity for students to engage in the community planning process and to develop a sense of civic mindedness. Such courses facilitate students to interact with real clients and stakeholders, thus enabling them to have a better understanding of the realities of budget constraints and industry collaboration. This provides a good foundation for students to better equip themselves for real world practice after graduation. Design-build methodologies are suited for the sites in relatively remote areas, enabling students to become more aware of the natural context and the environmental impacts of their work (Canizaro, 2012; Carpenter & Hoffman, 1997; Rice-Woytowick, 2011). For example, in the Lianhuadang Farm Project, students conducted on-site investigations and in-depth interviews with the locals about their needs. Through actively engaging with the local communities for design decision making in every stage, the design solutions can effectively resolve the issues involved (Jiao & Tang, 2019).

Collaboration

The nature of construction requires students to collaborate with one another and work in teams. The conventional architectural studio pedagogy, according to Dutton (1987), has a hidden curriculum of competition that results in a resistance of students towards working as a team. The introduction of design-build pedagogy can serve as a useful tool for bonding students, in order to work towards the same goal. The process of collaboration can also lead students to become more aware of their strengths and shortcomings, which may not be identified when working individually (Canizaro, 2012). Self-awareness is fundamental to the growth and the development of students' self-confidence.

The "Innovative Teaching in Construction Technology" (it | ct) project team in the Department of Architecture, University of Hong Kong, undertook a full-size design and construction project in the curriculum for architectural students. Second-year architectural students worked together in teams to design and build for their "real clients". Amato, Thilakaratne & Jia conducted a follow-up survey to examine students' response to the design-build course. Their research found that students not only discovered the significance of understanding materiality and the construction process to design, but also learned the crucial link between teamwork and management. The teamwork and collaboration aspects were critical during the project. The course helped students design more competently with more collaborations skills to produce excellent designs in a real context (Amato, Thilakaratne, & Jia, 2005).

The hierarchical relationship between students and instructors in the studio setting is considered another example of the hidden curriculum (Dutton, 1987). Since studio instructors in design-build courses also need to participate in the building processes alongside their students, design-build presents a forum through which to break the social hierarchy in the learning environment. During the development of construction processes, architectural students have opportunities to engage with consultants from other backgrounds, such as engineering or mechanical disciplines, fostering multi-disciplinary collaboration.

Digital Fabrication Tool

The design-build pedagogy is shifting towards the use of digital fabrication as the main approach to building design and production. According to Allen (2012), digital fabrication has become more seamless, whereby students can design within three dimensional environments that can be directly translated into built form. Although the digital fabrication tools insert an intermediary between designers and materials, the mediation accelerates the iteration process with the possibility of testing ideas in 3D environments at small scales before building at full-scale. Furthermore, digital tools can synthesise construction of the form and the analysis of the design's performance (Storonov, 2017).

Research Methodology

Comparative Study

The main research method of this study involves comparing various architectural schools' workshop spaces in terms of layout arrangement, spatial quality and materiality. Seven makerspaces within architectural departments were selected as primary studies. The case studies were selected on the basis of having been previously published along with associated plans, and gave sufficient diversity to compare and contrast. Most of the selected schools are ranked among the top 100 in the 2020 QS University Ranking in the architectural discipline. These architectural schools shared a focus of implementing design-build pedagogy in their curricula, and most of the selected facilities were recently built, which reflect the latest building technology. Building porosity, atrium design and materiality were analysed and compared in order to have a better understanding of the current workshop spaces and their relationship with design-build pedagogy.

Building porosity describes the spatial relationship of the workshop with its surroundings. Open, semi-open and enclosed are the three forms that the workshop space has, in terms of how they integrate and connect with the surrounding activities.

The typological analysis of atrium is another aspect of the comparative study. The atrium is commonly designed as a focal point of buildings and a place for large gatherings. Atria enable visibility of activities and support social integration of occupants. The study aims to identify different typologies of the atrium and to understand how they influence the social interaction and collaboration among users.

Built pedagogy is generally understood as the role of the physical environment influencing and enabling modes of teaching and learning, as well as teaching behaviour (Monahan, 2002; Oblinger, 2006). In the context of learning materiality, built pedagogy refers to the role of the building to support architectural education by providing an “avenue for reference” as a direct teaching tool (Gardiner, Charing, Mullumby, & Kealy, 2015, p. 7). Students can refer to the details and elements of the building in which they are studying to learn the application of the relevant architectural knowledge. The buildings themselves serve as teaching tools for design and construction by revealing the details and connections, which are otherwise hidden behind finishing surfaces. Given the fact that design-build pedagogy encourages students to better understand materiality through making, it is useful for students to be in spaces that work as built pedagogy. Hence, the materiality of space is another dimension that is linked to design-build pedagogy.

Selected Cases

Seven architectural makerspaces have been selected as case studies (Table 1), including Institute for Advanced Architecture of Catalonia (IAAC), Delft University of Technology (TU Delft), ETH Zurich, Princeton University, KTH Royal Institute of Technology (KTH), Massachusetts Institute of Technology (MIT), and Nantes School of Architecture (Nantes). The selected makerspace facilities were recently built, with the exception of IAAC. All the selected institutes have architectural makerspaces with an atrium that facilitates collaborative learning. Although they possess different construction methods and design intents, the relationship between design-build pedagogy and physical environment can be identified through a qualitative assessment.

Table 1
Selected institutes and their location

Name of Institute	Institute for Advanced Architecture of Catalonia	Delft University of Technology	Swiss Federal Institute of Technology Zurich	Princeton University	Royal Institute of Technology	Massachusetts Institute of Technology	Nantes School of Architecture
Abbreviation	IAAC	TU Delft	ETH Zurich	Princeton	KTH	MIT	Nantes
Location	Barcelona, Spain	Delft, Netherlands	Zürich, Switzerland	Princeton, the United States	Stockholm, Sweden	Massachusetts, the Unites States	Nantes, France

Results

Building Porosity vs Engagement with the Community

The design-build pedagogy often includes the involvement of the community by inviting the public to participate in the making process. Therefore, the architectural quality of makerspaces should possess a level of porosity. Each of the seven architectural makerspaces engages with its surrounding communities differently. These spaces are ordered according to their porosity in Table 2. Three levels of porosity, including enclosed, semi-open and open, are used to describe these spaces.

Located in the city centre of Barcelona, the internal makerspace of the IAAC fabrication workshop is enclosed with bricks, whereby the making process is hidden from the community (IAAC, 2020). This fully enclosed makerspace is more private to its faculty students and staff, but it does not provide much engagement opportunity with its surrounding communities. As seen in Figure 1, the main access point is through the small door at the front, which is not as inviting as TU Delft Workshop (Figure 2). Furthermore, pedestrian engagements are less visible in the narrow walkway setting.

The TU Delft Workshop engages the community in two ways architecturally. Firstly, the whole workshop area is enclosed with light-tinted curtain walls to expose their making processes to the outside. This allows people from outside the workshop to be more visually engaged, if not physically engaged. Secondly, the workshop sits adjacent to the library, where people from the library can overlook the making processes, or access it easily (Octatube, 2009). The juxtaposition of programs and showcasing of activities creates more encounter opportunities for the users and the community.

Similar to TU Delft, the ETH Arch Tec Lab also showcases its internal fabricating processes with full-height glazing. Moreover, a bridge and staircases connect the workshop to the nearby teaching building and street (Figure 3). Users can access the adjacent teaching building via the workshop (Schoof, 2017). These features enable the ETH Arch Tec Lab to be an open workshop that is highly visible and accessible to its users and surrounding communities.

Apart from inviting people to enter the workshop, the Princeton Embodied Computation Lab's community engagement approach is to bring their activities to the external environment. A sizeable outdoor construction area directly faces the pedestrian walkway (Figure 4). The workshop building itself is a continually changing living laboratory, where panels can be installed on the external testing frame (Alioto, 2017). Similarly, the school of architecture at KTH is inserted into an existing courtyard space with existing pathways. Pedestrians can easily engage with the ground floor workshop activities through the sunken garden (Tham & Videgård, 2017). Moreover, the sunken garden is in the centre of the courtyard, which symbolises the importance of the fabrication process (Figures 5 and 6).

Although the public cannot access the MIT Media Lab due to management concerns, the architect intentionally positions the public event spaces at the roof level (Maki, 2012). In this way, during the events' period, the public can glance at the making activities inside, as they make their way to the top floor (Figure 7). MIT's internal activities can also be seen through the transparent façade. Similarly, the Nantes's theatre sits adjacent to the workshop area (Figure 8), and the making process can also be seen while attending the public activities inside the theatre (Lacaton & Vassal, 2015).

In summary, responding to the pedagogy of making, the notion of public engagement is embraced inside design-build makerspaces by showcasing their activities to the public and by positioning public programs adjacent to the workshops.

Table 2
Building porosity of selected workshop spaces

Name of Institute	IAAC	TU Delft	ETH	Princeton	KTH	MIT	Nantes
Building Porosity	Enclosed	Open	Open	Semi-open	Semi-open	Semi-open	Semi-open

Figure 1
IAAC workshop entrance.
SOURCE: GOOGLE

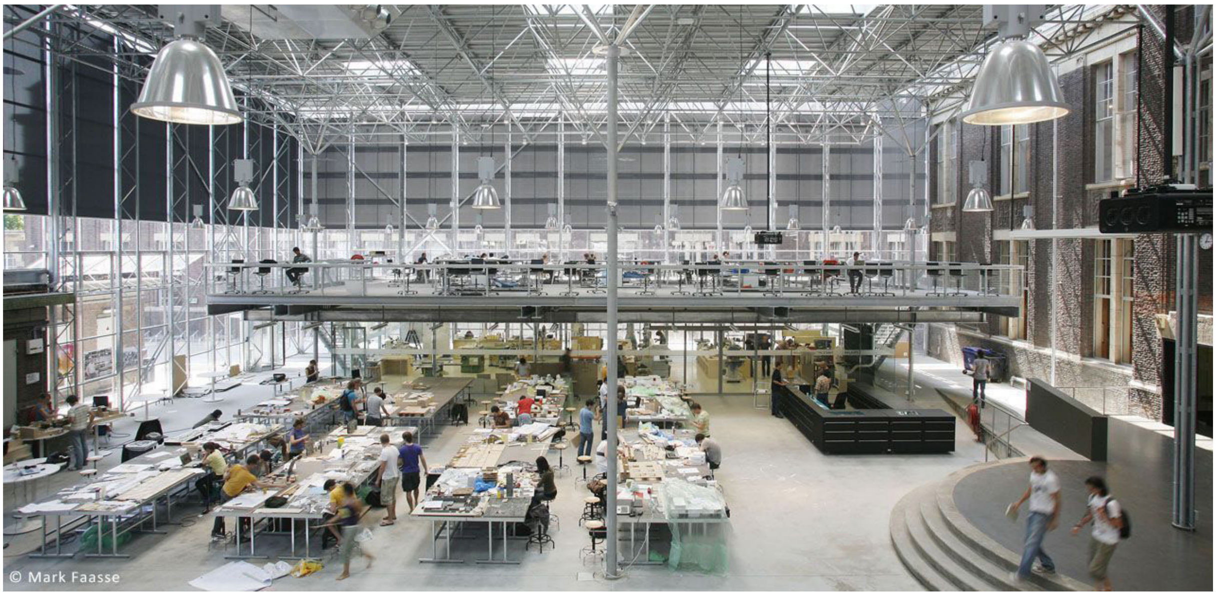


Figure 2
TU Delft workshop: greenhouse glass & adjacent to library.
SOURCE: OCTATUBE (2009)

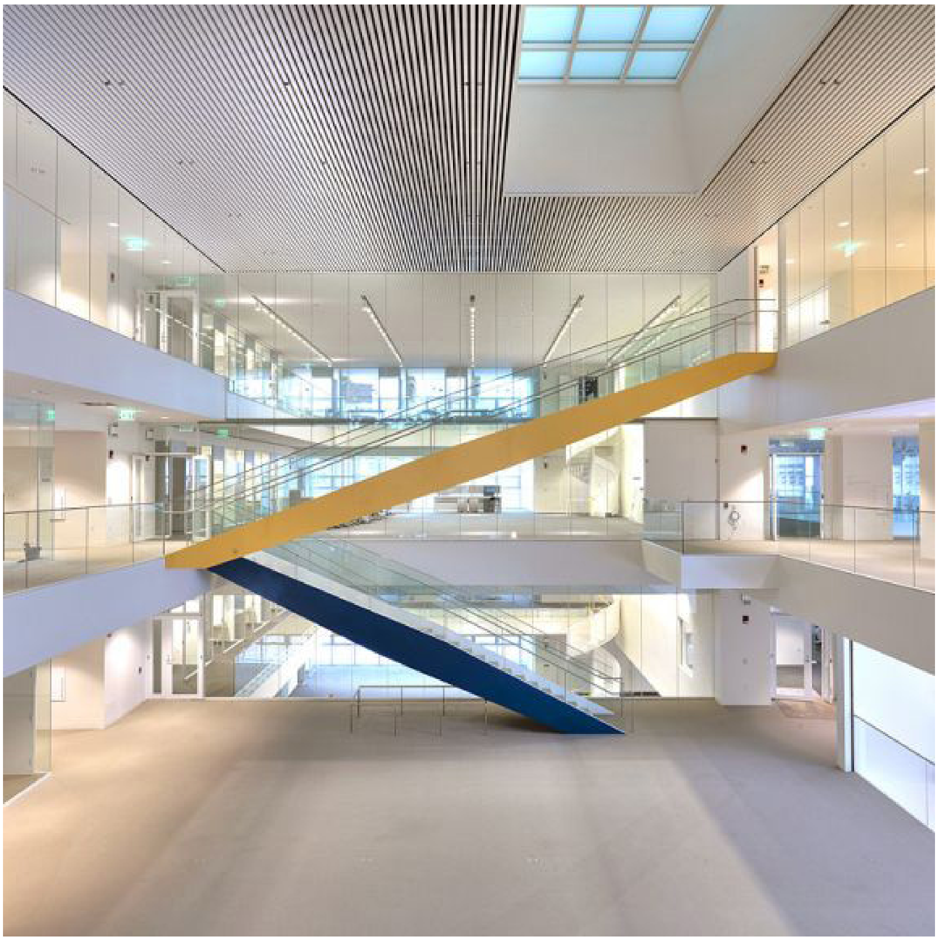
Figure 3
ETH Arch Tec Lab: external bridge and staircase.
SOURCE: SCHOOF (2017)

Figure 4 (top)
Princeton Embodied Computation Lab: external workshop area.
SOURCE: ARCHITECT MAGAZINE

Figure 5 (below)
KTH pathways.
SOURCE: ARCHDAILY

Figure 6 (top)
KTH sunken garden.
SOURCE: ARCHDAILY

Figure 7 (below)
MIT Media Lab: Atrium.
SOURCE: MIT



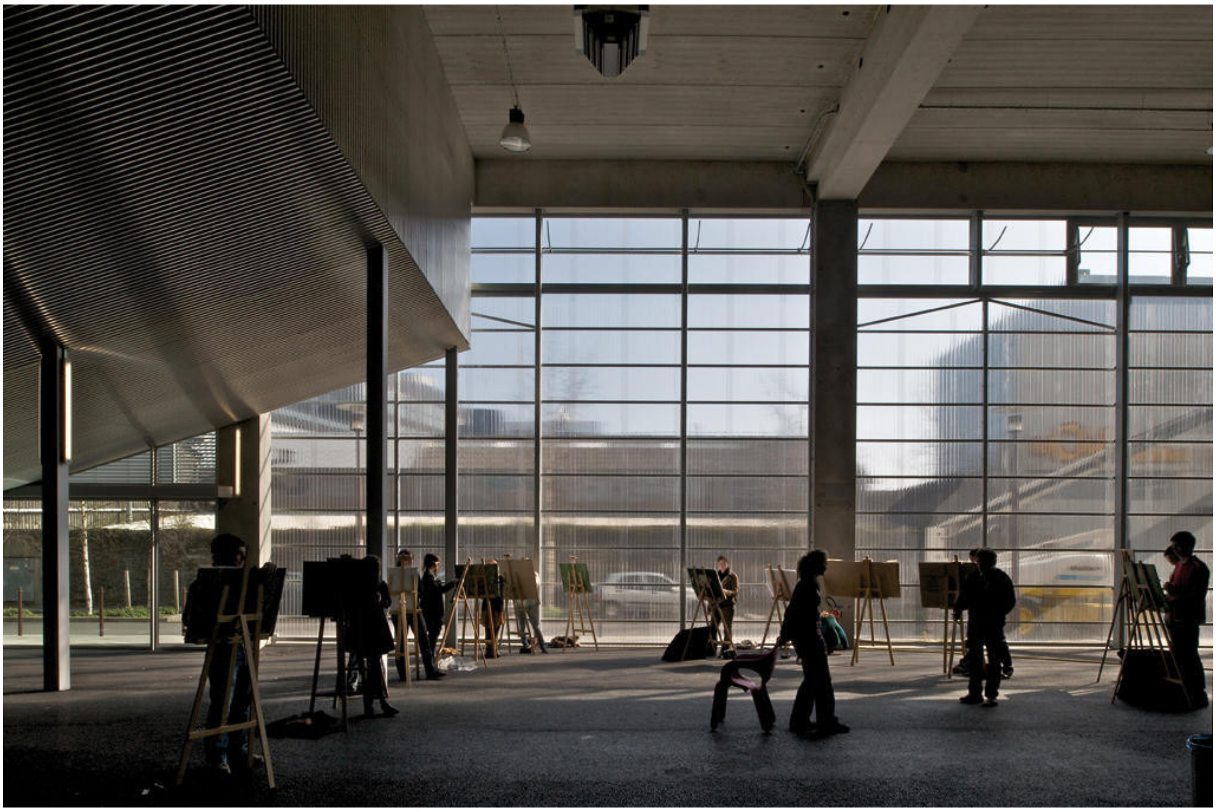


Figure 8
Nantes theatre and workshop.
SOURCE: ARCHDAILY

Atrium vs Collaboration

The design-build pedagogy has a focus on the collaboration process. Thus, the workshop environment needs to facilitate internal interaction. One of the most common architectural approaches is to use an atrium as a catalyst for encouraging collaborations. The four main atrium typologies are centralised, semi-enclosed, attached and linear (Figure 9).

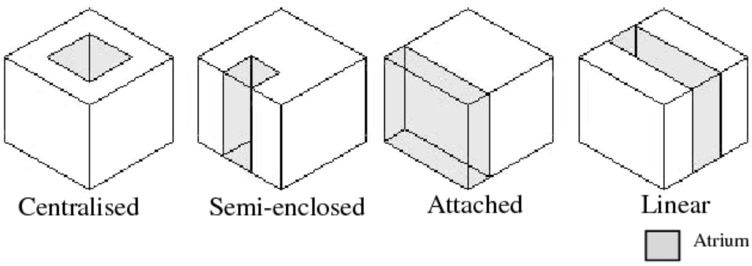


Figure 9
Typology of atrium.
SOURCE: YUNUS, AHMAD, & ZAIN-AHMED (2010)

The IAAC Workshop follows the attached atrium arrangement (Figure 10). Its major workshop occupies a long-span, double-height space. Several classrooms, seminar rooms, equipment stores and offices are attached on one side overlooking the workshop. The visual connection between these areas encourages collaborative activities. Students can access or exit these classrooms and seminar rooms via the workshop, so the curated circulation path facilitates the collaboration processes. Similarly, the Princeton Embodied Computation Lab's classroom is attached to the double-height workshop overlooking the fabricating activities (Figure 11). This type of atrium design can foster collaboration opportunities among students by increasing visual contact. During the making process, activities in the atrium can be easily seen by other students in the building. IAAC and Princeton provide an excellent example of an attached atrium arrangement.

The ETH Arch Lab consists of an attached atrium and a semi-enclosed atrium. The double-height gallery space is stacked on top of the workshop area, which creates a double layer of collaboration meaning. The idea is to showcase not only the process but also the outcome. Student's work is often displayed in this space. Similar to IAAC and Princeton, the fabrication process is overlooked by the offices. On the other side, the production from the workshop is exhibited on the gallery level, which can also be seen from the offices (Figure 12). In contrast, the MIT Media Lab, Nantes Workshop and TU Delft Workshop follow the semi-enclosed settings. Instead of overlooking the atrium from one side, the semi-enclosed atrium consists of two or three sides. These arrangements enhance visibility and emphasise the notion of collaboration (Figure 13). As seen in Figure 9, semi-enclosed spaces enable an atrium to have more visibility to the public, in comparison to an attached one.

Another type of atrium typology is the centralised atrium. Instead of incorporating double-height indoor space, due to the limited site area, the KTH makerspace is organised by a centralised layout. The outdoor atrium becomes a focal point for interaction for the workshop, as well as the adjacent programs, including seminar rooms, exhibition space and atelier (Tham & Videgård, 2017). The atrium is large enough to accommodate outdoor model construction.

In summary, due to the functionality of the workshop in design-build makerspaces, they usually require a column-free, double-height area. The double-height space can be integrated into the design of various typologies of atrium, which all contribute to the notion of collaboration (Table 3). In some cases, like KTH, restricted by the site, the outdoor atrium acts as a key social interaction zone.

Table 3
Atrium type of selected workshop spaces

Name of Institute	IAAC	TU Delft	ETH	Princeton	KTH	MIT	Nantes
Atrium Type	Attached	Semi-enclosed	Attached and semi-enclosed	Attached	Centralised	Semi-enclosed	Semi-enclosed

Figure 10
IAAC atrium.
SOURCE: IAAC

Figure 11 (top)
Princeton. Overlooking the workshop from classroom.
SOURCE: ARCHITECT MAGAZINE

Figure 12 (below)
ETH Arch Lab Gallery & parametric roof ceiling.
SOURCE: VELUX

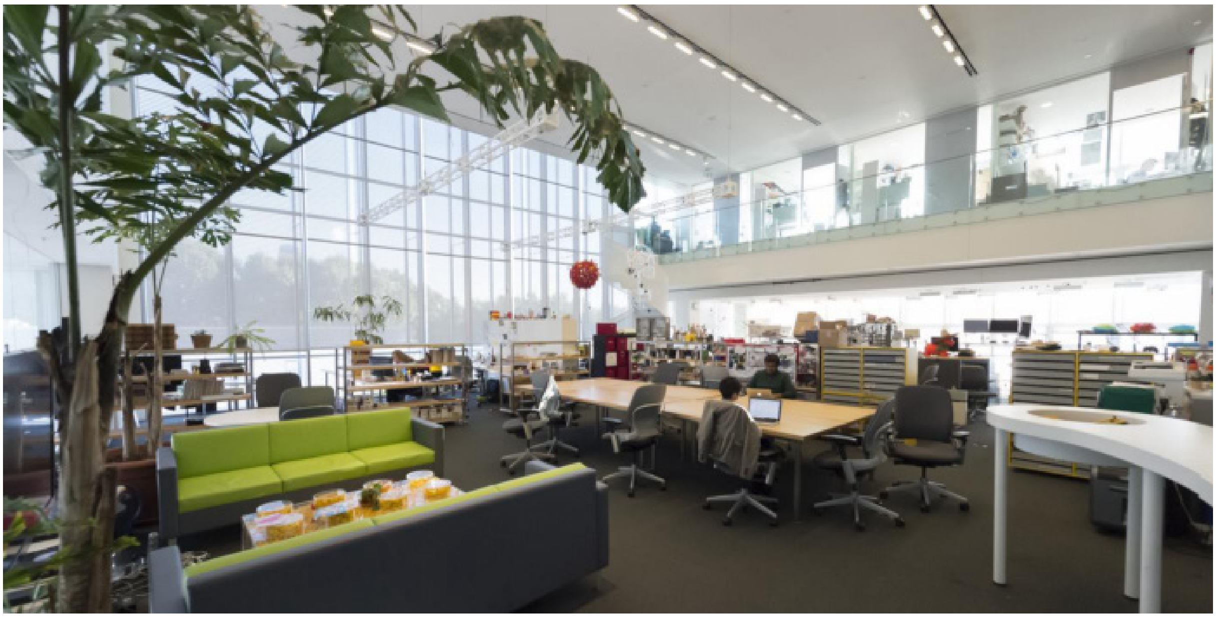


Figure 13
MIT Media Lab semi-closed atrium.
SOURCE: MIT MEDIA LAB MEDIUM

Built Pedagogy vs Learning Materiality

The design-build pedagogy encourages students to better understand materiality through seeing, touching and making. Following this pedagogy, students are often within an environment where tangible outcomes of materials are in reach, enabling testing and experimental approaches to how materials perform and look. As an alternative to making by hand, the pedagogy is shifting towards adopting more digital fabrication tools. As a result, the corresponding learning space serves as a pedagogical tool that allows students not only to identify and learn from the materials and building process, but also to reflect on the emerging digitalised fabrication technologies. There are only a small percentage of architectural schools that currently incorporate digitally fabricated elements in their learning space design. However, as digital fabrication technology becomes more advanced and accessible, it will benefit students' learning by integrating digital fabrication into the construction of the makerspaces.

Princeton's workshop is designed as a continually evolving building. Students studying there have opportunities to learn from building components and systems as they are upgraded over time. This approach provides students with more learning possibilities of materiality and technical knowledge. Moreover, the building itself incorporates several cutting-edge construction techniques; for instance, the 5-ton gantry crane is the first in the United States made of timber instead of steel (Alioto, 2017). By using cutting-edge construction techniques in the faculty building, students are encouraged to be more innovative while designing their studio projects.

Similarly, the ETH workshop is covered by a parametric timber roof ceiling, which was designed and scripted by designers before being prefabricated by a single gantry robot, to embrace the advanced digital fabrication technique (Figure 12). The ETH workshop provides a valuable opportunity for students to be exposed to steel, glass timber and digital fabrication construction techniques, which reflect their design-build pedagogy.

For the KTH workshop space, design in harmony with the surrounding environment was duly considered. The newly invented, large, curved-glass panels and rusted steel are applied to the external façade of the KTH workshop's exterior to establish a complementary relationship with adjacent red brick buildings (Tham & Videgård, 2017). The striking contrast between bricks and rusted steel raises the students' awareness of materiality and the process of making.

Different from the high-tech design features at other schools, Nantes and IAAC workshops share a low-tech construction. Steel and concrete or bricks are used respectively in response to different functional requirements (IAAC, 2020; Lacaton & Vassal, 2015). Although less innovative material and construction materials are incorporated in these two faculties, students can be still aware of the differences of materiality when shifting from one room to another. This traditional type of workshop space is common in many other architectural schools; however, these spaces are shifting towards embracing more cutting-edge fabrication tools.

Rather than focusing on fabrication techniques and functional requirements, for the MIT Media Lab and TU Delft, steel was used as a metaphor for different stages of making. The Delft workshop exposes all the structural frames and joints, while MIT Media Lab conceals these elements with a minimalist approach (Maki, 2012; Octatube, 2009). By exposing and revealing construction materials and details, students are able to see how materials and components are put together. Similar interior design strategies can be seen in some other architectural education faculties across the world, like the Melbourne School of Design, where ceilings in the classrooms and workshops expose all the services, elements and ducting. This type of classroom and workshop design is beneficial to students for their study of construction-related subjects.

In summary, the seven workshop spaces reflect the emerging making pedagogy through different strategies, including the incorporation of cutting-edge fabrication technology, allocation of materials to different functional zones and exposure or concealment of structural elements and construction details (Table 4). These design strategies can be applied in architectural faculties to reinforce the design-build pedagogy.

Table 4
Materiality of selected workshop spaces

Name of Institute	IAAC	TU Delft	ETH	Princeton	KTH	MIT	Nantes
Materiality	Steel and glass	Steel and glass	Steel and glass	Timber	Steel and glass and timber	Steel and glass	Steel and concrete
Main strategies	Allocating materials to different functional zones	Exposing elements	Cutting-edge fabrication technology	Cutting-edge fabrication technology	Exposing elements	Concealing elements	Allocating materials to different functional zones

Discussion

Limitation

As an impetus study that analyses and compares current makerspaces in architectural schools, this research mainly relies on qualitative research methods. More quantitative methods can be involved in future studies. For example, a questionnaire survey can be organised to collect feedback from staff, students and community members to evaluate how spaces are perceived and appreciated by key stakeholders. Further research is recommended to collect quantitative data and conduct a post-occupancy evaluation on these makerspaces, in order to study how effective they are at facilitating design-build learning pedagogy.

The scope of this study focuses on seven institutes in Europe and the United States. Institutes from other regions are worth investigating for comparing the similarities and differences with these seven case studies. Another key limitation is that the making activity within architectural schools may take place outside of dedicated workshop spaces. Other spaces within faculties that are potentially used for making by students are also important, and are worthy of investigation. Likewise, some design-build work happens off-campus and in situ. Further research is recommended to evaluate the relationship between design-build pedagogy of off-campus and in-situ workshop spaces.

Conclusion

The literature review revealed the four critical components of design-build pedagogy to be understanding of materiality, engagement with the community, collaboration and digital fabrication tools.

To integrate the pedagogy within makerspaces, the corresponding strategies identified in the examined case-studies include porosity, incorporation of the atrium and built pedagogy (Table 5 and 6). To our knowledge, this is the first comparative study of design-build spaces with a focus on the alignment of the design with pedagogy, and builds on Storonov's (2017) work by developing a matrix summary of seven seminal case-study spaces. This study is timely, given the increasing uptake of design-build pedagogies within the context of increasingly affordable, digital fabrication technologies.

Results of the study show how makerspaces in the selected case studies interact with the surroundings to foster community engagement. Showcasing the internal activities on the exterior can invite the public to engage in the making process, and the seven workshop spaces may have different levels of building porosity with the surroundings. However, workshops with higher level of porosity may cause security and management concerns. Some levels of community engagement are beneficial for architectural learning, and reinforce design-build learning pedagogy by making learning visible.

Applying an atrium design can facilitate more social interaction among the participants and users. Different atrium typologies facilitate different learning experiences. Based on the seven case studies, four atrium typologies are summarised, which are centralised, attached, semi-enclosed and enclosed. Most of the atrium spaces act as a gathering space and/or part of an open-floor workshop. Some of the selected atria incorporate digitally fabricated elements as part of their design. We anticipate that future atrium spaces will increasingly embrace innovative construction methods and materials, as part of the built pedagogy approach.

Another critical point drawn from this study is that more emphasis will be put onto designing makerspaces as design-build pedagogy evolves. Apart from the seven selected cases, other architectural schools have started to experiment with the design-build pedagogy by incorporating more design-build elements into their curricula. As more institutes realise the effectiveness and importance of design-build, more ideas will be incorporated into the design of makerspaces.

More and more cutting-edge construction is observed in makerspaces of architectural schools. A few case studies, including ETH and Princeton, have workshops embracing the most innovative technologies and materials. These innovations are reflected in construction methods like robotic construction, digital fabrication and new sustainable materials. Some faculties have their workshops constantly evolving, to help students learn more about materials and how they are constructed. This study provides some examples of current high-tech workshop design, but as technology is constantly evolving, more research is required to investigate how innovative workshop design suits students' needs.

To conclude this research, a careful selection of materials and construction methods can raise students' awareness and understanding of materiality and fabrication tools involved in the building process. With more institutes interested in design-build pedagogy, more research can focus on the design of makerspace, with more quantitative data through surveys and other post-occupancy evaluation tools. The development of new advanced technologies will also influence how makerspaces are designed and constructed in the future.

Table 5
Matrix of comparative study.
SOURCE: DIAGRAMS ARE DRAWN BY AUTHORS. IMAGES FROM BOTTOM LEFT TO RIGHT: IAAC, OCTATUBE, MIT MEDIA LAB MEDIUM, DETAIL MAGAZINE

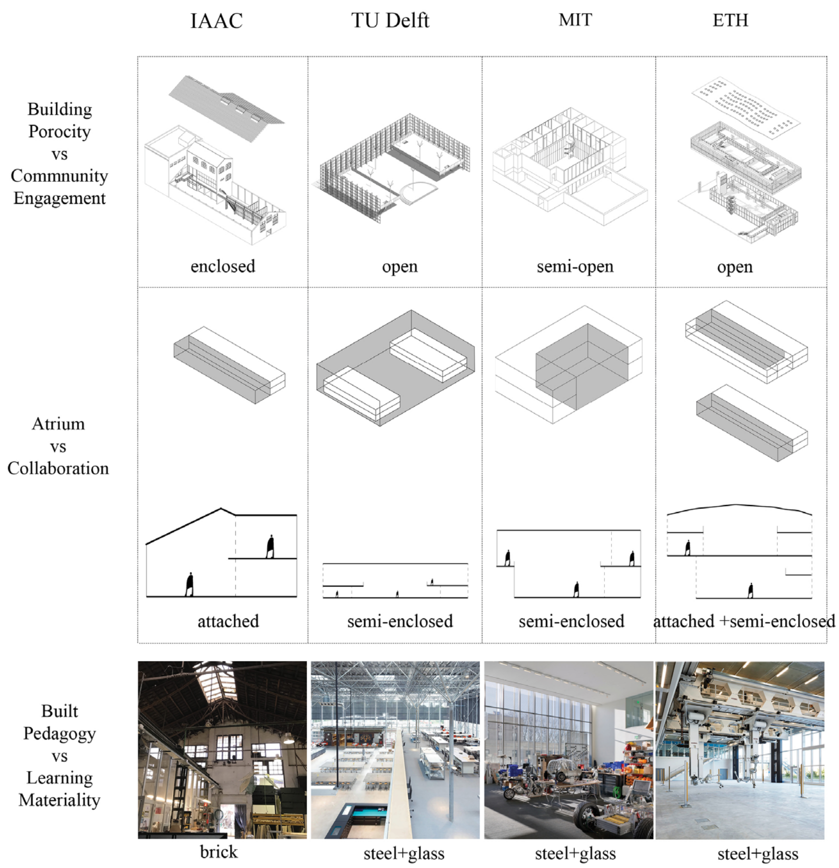
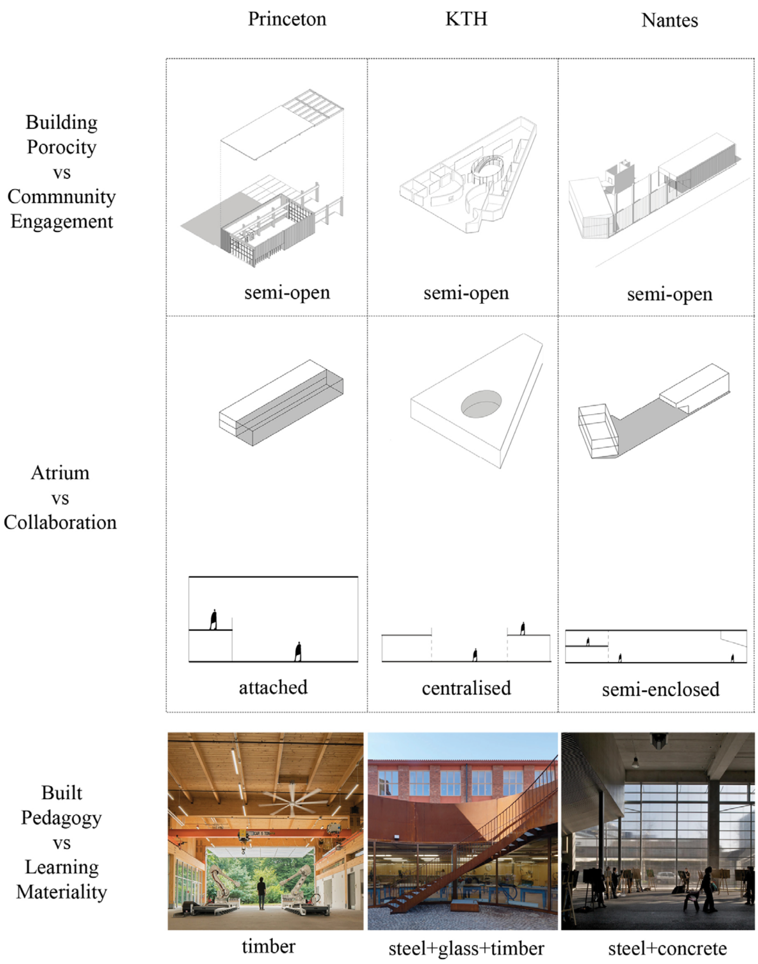


Table 6
Matrix of comparative study.
SOURCE: DIAGRAMS ARE DRAWN BY AUTHORS.
Images from bottom left to right: Architect Magazine, ArchDaily, Octatube, ArchDaily



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