ABSTRACT
Construction simplicity is crucial to cost control, but design complexity is often necessary in order to meet particular spatial performance criteria. This paper presents a case study of a semi-enclosed meeting pod with a brief that must contend with the seemingly contradictory conditions of the necessary geometric complexities imperative to improved acoustic performance and cost control in construction. A series of deep oculi are introduced as architectural elements to link the pod interior to the outside environment. Their reveals also introduce sound reflection and scattering, which contribute to the main acoustic goal of improved speech privacy. Represented as a three-dimensional funnel-like shape, the reveal to each opening is unique in size, depth, and angle.

Traditionally, the manufacturing of such bespoke architectural elements in many cases resulted in lengthy and costly manufacturing processes. This paper investigates how the complex oculi shape variations can be manufactured using one universal mold. A workflow using mathematical and computational operations, a standardized fabrication approach, and customization through tooling results in a high-precision digital process to create particular calculated geometries, recalibrated at each stage to account for the paradoxical inexactitudes and inevitable tolerances.
INTRODUCTION
Advancement in computational modeling techniques, coupled with simulation tools, promotes agency in design through the inherent integration of design criteria, conditions, and fabrication information to arrive at complex mass-customized geometric solutions that can be manufactured. However, these bespoke architectural elements sometimes result in lengthy and costly production processes.

Evidenced in the spatial design of acoustic environments, design and geometric complexity can be used to satisfy and respond to multiple goals and systems of requirements. To fully engage with the phenomenon of sound, materiality must be integrated in the design and interrogated at multiple scales from building volume to minute surface details (Peters 2010). Mitigating cost, particularly in these scenarios where unique elements are unavoidable, is important to their practical insertion on a broader industry scale.

Interestingly, the relationship between the digital model and the end product is, in most cases, defined by the outcome. For example, an acoustic surface manufactured using a CNC subtractive manufacturing process may synthesize all the information required to produce the geometric articulations that respond to the acoustic imperative within that one model. However, this paper questions whether there is an alternative to the commonly used design-to-production workflow, instead focusing on mass customized production of standardized elements, and through recalibration, transforming the product into its final form by manipulating the shape through exploiting the properties of the material.

PROJECT BACKGROUND
The case study presented in this paper furthers prior research on improving speech privacy of open plan offices by introducing a unique modular architectural design of a semi-enclosed meeting pod (Burry et al. 2013).

We propose a modular construction system in which the main structure is constructed from lightweight steel sheets, which are laser cut, folded, and bolted into three-dimensional cells in order gain structural strength and provide cavities for acoustic reasons. The acoustic performance criteria is satisfied by overcladding some of the steel cells with acoustic panels and by inserting architectural elements called “oculi” to provide controlled visual connections between internal and external environments, as well as to assist with sound scattering by varying the depth, curvature, and angle of each oculus (Alambeigi, Chen, and Burry 2017).

Previous iterations have used thermal forming and metal spinning techniques as an effective production method for the creation of three-dimensional doubly curved deep building components, exploiting the low tooling cost relative to other forming techniques such as stamping, and providing suitable outcomes for acoustic requirements, surface finish, aesthetics, and quality (Burry et al. 2013). However, with a newly introduced requirement of curvature differentiation coming out of acoustic research, such manufacturing processes cause a potential problem in terms of cost, as this would require multiple unique tools. This poses the question of how molded elements can accommodate flexibility in shape and size whilst remaining cost-effective in production.

1 a) Overall design showing the shape- and size-varied openings in the context of the acoustic meeting pod; b) modular elements of the oculus.
Economic efficiency in the fabrication of complex and varied architectural forms has predominantly been explored with flat materials using 2–3 axis machinery. Although a flexible mold system could offer a viable alternative, the system itself is intricate and would require a significant investment (Lee and Kim 2012; Schipper and Janssen 2011), as a substantial number of unique components need to be produced to negate the cost for the flexible mold. In the scale of this research, such a method was not applicable. Therefore, the present research aims to interrogate how the production of standard elements through mold-based manufacturing can achieve the required geometric variation by postproduction calibration utilizing material plasticity.

MATERIAL COMPUTERIZATION

Geometric Principles
The use of a developable surface is essential to this approach because its deformation is calculable due to the fact that it can be “unrolled onto a plane (‘developed’) without any deformation or distortion” (Glaeser and Gruber 2007). The use of developable surfaces has a long history in architecture, and with the advancement of computational techniques, they have shown great importance in the delivery of complex architecture (Shelden 2002). However, in many cases the use of flat sheet material has been the predominant focus.

This research extends the principal of the developable surface, taking a formed cone rather than a flat sheet as the base form. Using a highly custom approach beginning with a mold-based manufacturing process, both the axial freedom offered by robotic machining and elastic deformation of the base material acrylonitrile butadiene styrene (ABS) is exploited to incorporate cone depth variation and varying surface shape.

Geometric Standardization and Variation
The general theory of developable surfaces is well established and can generally be categorized into three main types: (i) tangential developable, (ii) generalized cone, and (iii) generalized cylinder (Glaeser and Gruber 2007). In this research, a conical base surface is chosen for its

(Re) calibrating Construction Simplicity and Design Complexity Chen, Burny
geometric proximity to the desired final form. An unrolled surface domain of a cone is predictable by determining the angle between the cone slant and its central axis. While this angle equals 30º, the unrolled cone is a half circle, and any surface that falls onto this flat surface domain matches the surface of the cone in three-dimensional space (Figure 2). As such, any given conical developable surface with the angle summation of each neighboring pairs of ruling lines equal to 180º will fall into the surface domain of a 30º cone. This specific cone angle was selected for the stock material, primarily for its manufacturability and ease in setting up trigonometry for further calculation for geometric translation.

Noting the above features, any freeform initial curve outline can be assigned with a hypothetical apex. More importantly, when an axis is in the position where the angle summation of the ruling lines equals 180º, we can predict that it will fall into the unrolled surface domain of a 30º conoid. Therefore, an algorithm can be established to assign a hypothetical apex and axis to any freeform curve, from which one can calculate how it would fit a desired surface domain by iteratively moving the hypothetical apex along the axis until the angle summation of the ruling lines equals the desired degree—the possibilities are virtually infinite (Fig.3).

Mathematical Calibration and Tolerances

With the peak points of each conical surface identified, its surface ruling lines can be mapped onto a cone using a polar array around the central axis of a cone so that it can be extracted from a standard mold. Furthermore, in order to array the ruling lines around the standard cone’s central axis, the angle β, which sits on the plane perpendicular to the cone’s central axis, is needed. Given that the ruling lines are based on the equal subdivision of a freeform curve, the angle α between each pair of the ruling lines is unique. Therefore, each angle between the projected ruling lines, β (Figure 4), needs to be calculated according to the corresponding degree of α. As a result, a series of mathematical equations are used to translate the angles between each pair of ruling lines on the freeform conical surface to the rulings on the projected plane surface. These mathematical functions, based on trigonometry, can be described as below:

\[ E = \sqrt{(2C^2 - 2D^2 \times \cos(\beta))} = \sqrt{(2A^2 - 2B^2 \times \cos(\alpha))} \]

\[ E = \sqrt{(2C^2 - 2C^2 \times \cos(\beta))} = \sqrt{(2 \times (2C)^2 - 2 \times (2C)^2 \times \cos(\alpha))} \]

\[ \beta = \arccos\left(4\cos(\alpha) - 3\right) \]

Precision tolerance was an important consideration in deriving the mapped curve from the designed form. The resolution, defined by the number of ruling lines used to approximate the form, determines the accuracy of the outcome, the higher being more accurate. As illustrated in Figure 5, reducing the number of ruling lines results in differing curve lengths and therefore overall geometry. However, the exactitude of a large number of ruling lines, although resulting in high precision, slowed computing speed and was not required for accurate fabrication. Therefore, a balanced calibration between digital exactness and material manufacturing tolerances was optimized, allowing for approximately a 1 mm calculation difference.

Toolpath Calibration

As a production method, the mapped oculi are extracted using a CNC router attached to a robot arm. A series of axes are used to generate machine code to determine the trimming toolpath. In the toolpath generation, the material thickness is considered. A flush finish is desired between the oculus and the glass/window for aesthetics and functionality. Therefore, the robotic trimming axes do not follow the cones surface normal, but rather, are calibrated to achieve a flush detail by predicting shape translation. The toolpath for both edges of the oculus sit on flat planes,
which is the deployed state (Figure 6, left). The oculus pictured third in Figure 6 illustrates the designed oculus mapped onto a conical form. This detail and complexity in the toolpathing is supported with the axial freedom of robotic operations together with a synchronized table.

PHYSICAL PROTOTYPING AND FABRICATION CALIBRATION

Realizing the workflow through prototyping revealed the environmental and human influences on the design, which may not have otherwise been obtained or preempted through digital simulation (Burry and Burry 2016). The prototype provided data regarding the nuances of materials and tolerances that then could be integrated into the digital model to assist in the refinement of the outcome.

The cone manufacture (Figure 7) uses ABS as the base material to thermoform a set of standardized conical blanks. The dimension and depth of the cone blank is set at an optimal size, which provides a surface area that is large enough to allow for design variations, but at the same time constrained to avoid extreme uneven material thickness distribution in the thermoforming process caused by geometry depth. As a result, a set of cones—1100 mm in radius and 700 mm in height—is manufactured. A material thickness difference of approximately 2 mm from top to bottom results, which is mitigated through the architectural detailing and allowing a tolerance between the cone and the steel frame opening.

Although the simulated and calibrated digital toolpathing for robotic trimming was successfully realized, production setup and machining requirements, including jig design, drill bit selection, spindle speed, and feed rates, required several tests and recalibrations to arrive at a high level of finish for the final product (Figure 8).

The deformation accuracy of the manufactured and trimmed conical shape is tested by pressing the form into the cavity of the steel frame. The steel framed oculus is designed with strapped fixing points, which allows the oculi to adhere to the housing frame. The aforementioned specific toolpathing in trimming (Figure 8) is evident in the two images pictured right in Figure 9, which show the final deformed shape with an edge finish that is coplanar with the steel frame cell.

DIGITAL MODEL CALIBRATION AND PRODUCTION WORK FLOW VALIDATION

As this is an integrated computational modeling approach, information gained through the prototyping process is fed back into the parametric design framework (Figure 10). Dimensions and offsets are built in the frame model to accommodate the controlled tolerances. Digitally having an integrated algorithm that combines the fabrication information, tolerance, and its constraints allows designers to explore and calibrate between design opportunities and fabrication limitations efficiently and intuitively through constant visual feedback. The algorithm allows the modification of the locations and directions of the hypothetical apex and axis as described earlier in Figure 5. Such modifications allow designers to adjust the design geometries for manufacturability when the designed surface falls out of the manufacturable domain without changing the input oculus outline (Figure 11).

As a result, Figure 12 displays all the oculi laid out, clearly demonstrating that not only are variation and complexity.
7 Fabrication of conical blank using acrylonitrile butadiene styrene (ABS) and thermo-forming technique.

8 The calibrations of material mounting, tool bit selection, spindle speed, and feed rate are crucial to the quality of the fabrication outcome.

9 Early prototype: a) conical surface; b) fitted in plan; c) details of fixing; d) finished edge.

10 Various material tolerance and calibration information in digital model.
achieved in the design, but also that all oculi fit onto the prefabricated universal mold. The digital information of the highlighted oculi in Figure 12 is validated in the physical design production. The accuracy of this translation is evident through the use of a singular jig that enables multiple base cones to be uniquely trimmed (Figure 13, pictured top left).

11 Through the manipulation of axis and apex, the unfit oculi (highlighted in red) can be remapped in the manufacturable domain of the conical blanks without altering the desired outline.

12 Unique oculi (left) mapped onto one standard cone size (right). The oculi lighted in red were prototyped.

13 Production test of oculi. The cutting paths of the eight oculi can be seen on the cutting jig. (Top left)
CONCLUSION
Through a case study, this research paper presents a way to meet a requirement for custom geometric surfaces in order to satisfy specific acoustic performance criteria. Using a high-precision process of mathematical and computational operations, particular calculated oculi geometries are created with the underlying limitation of fabricating unique elements with only a singular mold. The paradoxical inexactitudes and inevitable tolerances resulting from this workflow, which doesn’t directly translate design to production, relies on prototyping and data feedback into the digital model to successfully translate a standard mass-produced cone into many elemental unique forms by utilizing properties inherent to the base material.

Beyond the scope of the meeting pod, future research could explore the design potential of combining the three-dimensionally formed developable surfaces and their predictable deformation with highly flexible and custom robotic trimming. Through sophisticated algorithms, the behavior of more complex compound developable surfaces may be predicted, and a possibly complex three-dimensional geometric composition could be achieved with this relatively cost-efficient fabrication method.

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REFERENCES


IMAGE CREDITS
All drawings and images by the authors.

Canhui Chen is a Lecturer in Architectural Design at Swinburne University of Technology. Canhui’s interests are centred around exploring the synergic relationship between computational modeling with manufacturing techniques and fabrication process, embracing possibilities and opportunities.

Jane Burry is a Professor and the Dean of the School of Design in the Faculty of Health Arts and Design at Swinburne University of Technology, formerly Professor and Director of the Spatial Information Architecture Laboratory (SIAL) at RMIT University.

Jane is engaged in research into the relationship between architecture and advanced manufacturing, and the integration of analysis feedback, including sound, in early design and its intersection with interactive physical and digital architecture (Designing the Dynamic, Melbourne Books, 2013). She is lead author of The New Mathematics of Architecture (Thames and Hudson, 2012), co-author of Prototyping for Architects, (Thames and Hudson, 2016) and author of over 100 publications.