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DESIGNING WITH MAXWELL'S DEMON: INTEGRATING MATERIAL INFORMATION INTO DESIGN COMPUTATION

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Abstract

Conventionally, builders transform and assemble physical materials into buildings based on geometry provided by architects. Building construction creates geometric order in the physical world and results in a decrease of entropy (which, in simplistic terms, is a measure of disorder). The Second Law of thermodynamics states that the entropy of a system cannot decrease without expending energy. The amount of energy required in construction indicates the extent of transformations required to convert raw materials into the building.

If designs don't start on a blank sheet of paper, or with a blank screen, but are instead based on the observation and collection of information about raw materials, then designers can minimize the amount materials need to be transformed during construction. This minimizes the decrease in entropy, reducing energy required for building. The role of computation in such a work-flow becomes one of integrating material information with the designer's goals. This paper outlines and illustrates such a material-first design work-flow.

The historical role of drawing in architecture.

In *Translations from Drawing to Building,* Robin Evans (1997), explores the relationship between design, construction, and drawing. He explains that architects use geometry to abstract certain fundamental properties about the physical world as a basis for developing their designs. Euclidean geometry is the architect's *'way of accessing objects (of knowing and manipulating them) and making them move without transformation (that is, maintaining a certain number of characteristics)'* (Latour & Yaneva, 2013, p. 109). Thus, *'the most complex figures may be moved at will into perfectly congruent formations anywhere else'* (Evans, 1997, p. 181). The formalized use of drawing in architecture by Alberti in the Renaissance was preceded by increasing material complexities in construction – from the stone masonry of Greek times to the wide variety of trades seen in Medieval buildings – and the use of projective geometry enabled the Renaissance architect to differentiate himself from the builders and assume overall control of the design (Kolarevic, 2003).

Evans (1997) cautions that the use of drawing in architecture causes a disconnect between the design process and the materiality of construction. Kolarevic (2003) describes the history of *'disassociation'* (Kolarevic, 2003, p. 57) between design and construction. Latour and Yaneva (2013, p. 109) concur, saying that the abstract transformations of geometry are *'definitely not the way material entities (wood, steel, space, time, paint, marble, etc.) have to transform themselves to remain extant'*. This disconnect can be overlooked when there is enough correlation between the behavior of projective geometry and physical objects to not cause any significant contradictions during construction (Evans, 1997). Historically, projective drawing has proven to be very useful to architects and the profession has worked out how to minimize the discrepancies between geometric representations and construction so that projective drawing has become an indispensable and integral to how architects design (Evans, 1997). Conversely, this dependence on projective drawing has obscured the underlying disassociation between the design process and the materiality of construction (Evans, 1997). According to Evans (1997, p. 165),*'[D]rawing in architecture is not done after nature, but prior to construction; it is not so much produced by reflection on the reality outside the drawing, as productive of a reality that will end up outside the drawing.'*

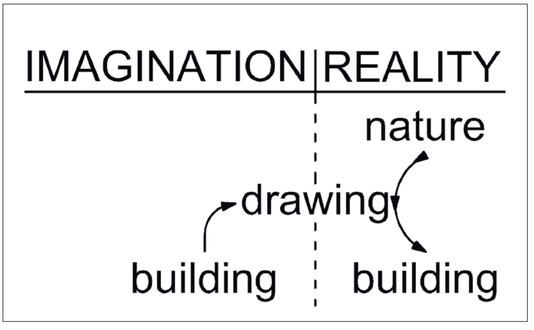

Figure: 1

Figure 1 is an expression of Evans' conclusion where the building first exists in the architect's imagination and is then is constructed into reality through the artifact of the drawing. Nature, in this scenario, is the backdrop from, and into which, the constructed building emerges.

In going from the imagined to the real building, Evans (1997, p. 183), recalling the essentialism of Alberti and Palladio, discusses how, *'Things were supposed to degrade as they moved from idea to object.'* This *'entropic account'* (Evans, 1997, p. 183) of the role of drawing as a representation of ideas, and the inevitable degradation in the transformation of the imagined to the real building, reflects the disassociation between the design process and the materiality of construction, and is couched in the implicit use of projective drawing in the profession of architecture.

Entropy across disciplines.

The concept of entropy emerges from the second law of thermodynamics. The second law of thermodynamics states that, in an isolated system, when energy is converted from one form to another, it is transformed from a state of lower disorder to a state of higher disorder (Pasquinelli, 2010). Entropy is a measure of the disorder of a system (Pasquinelli, 2010). The second law of thermodynamics implies that energy transformations move in the direction of greater entropy (Ayers, 1996).

Tracing the history of entropy from its origin in the second law of thermodynamics, to other disciplines, Pasquinelli (2010) cites examples of its application to psychology, information theory, and economics. He explains that the simplistic application of the second law of thermodynamics as a law decreeing inevitable disorder, without regard to changes in scale and context across disciplines, leads to conclusions of *'energy fatalism or energo-determinism'* (Pasquinelli, 2010, p. 1). Based on the ability of systems to accumulate order locally, he argues against the literal use of entropy in fields outside thermodynamics.

Pasquinelli (2010) cites Schrodinger's idea of *'negative entropy'* accumulation in living organisms whereby order is incrementally increased within the confines of a cell membrane. This is not contrary to the second law of thermodynamics as cells are not isolated systems and they consume energy from their environment to reduce entropy inside the cell while expelling waste to increase entropy in the environment. The difference between inorganic materials and living cells is that the cell membrane is able to isolate the order created through metabolism and propagate it, thereby shielding the contents of the cell from the direct effects of entropy increase. Through the lifetime of the cell, this positive entropy is incrementally accumulated and passed on to daughter cells during reproduction (Schrodinger, 1944).

Pasquinelli (2010) characterizes this difference between the behavior of entropy in the organic and inorganic as representative of two *'regimes of entropy'* (Pasquinelli, 2010, p. 1) – the *mineral* and the *biological*. He then defines *mechanical* and *informational* regimes, with entropy exhibiting different behaviors in each regime. In the mechanical regime, *'Industrial machinery is designed to execute work and release energy in a constant and controlled flow'* (Pasquinelli, 2010, p. 5). The command humans gain over energy dissipation through machines differentiates the mechanical regime from the mineral and biological regimes. The discovery of the Turing machine as an abstract information processor gave rise to the informational regime – *'[A] Turing machine, being an abstract machine counting binary digits, does not refer to any material substratum and consumes almost zero: it runs on an ideal and virtual space at zero entropy. From the angle of abstraction, digital networks are purely mathematical spaces with no gravity, no friction, no entropy whatsoever'* (Pasquinelli, 2010, pp. 5-6). Pasquinelli (2010, p. 6) thus creates a *geology of entropic regimes* from the mineral, to the biological, to the mechanical and the informational (Figure 2), such that, *'[E]ach stratum produces specific phenomena of friction, energy dissipation and energy accumulation. In this viscous space, phenomena of surplus accumulation and not just entropic tendencies can finally be explained'*.

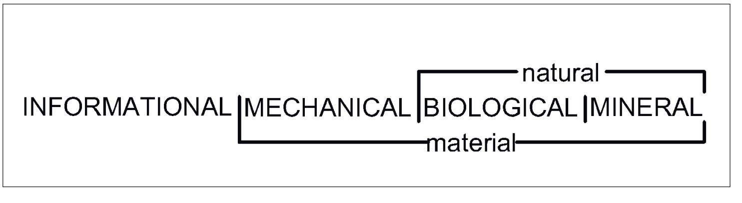

Figure: 2

Design and construction in the context of entropy and information.

Revisiting Evans' (1997) analysis of projective drawing in light of entropic regimes (Pasquinelli, 2010), entropic degradation from idea to object can be seen as a result of friction between the informational regime of the abstract imagining mind, with its zero entropy, and the three material entropic regimes. What enables a drawing on paper to represent the imagination is the use of abstract mathematics and geometry to construct it (Evans, 1997). A standard part of reading a hand drafted architectural drawing is the precedence of written dimensions over any dimensions measured physically off the drawing (Stephenson, 2011), thus reflecting the importance of abstraction over materiality.

Evans (1997, p. 165) differentiates constructed buildings from *'nature'*. In entropic terms, this differentiation is the difference between the mechanical regime under human control and the mineral and biological regimes. This is illustrated in the Figure 3.

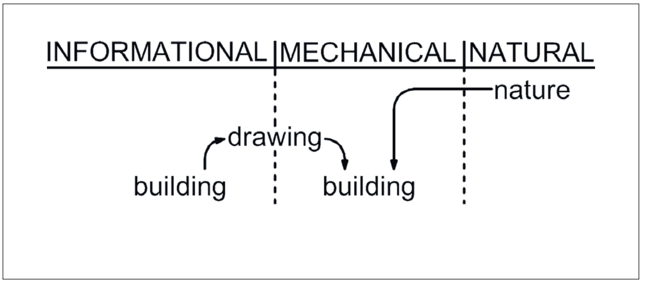

Figure: 3

Situating imagination in the informational regime explains the geometric and mathematical abstraction of architectural drawing as a tool for information manipulation. It is because drawing aids the mind in processing information that it enables design to go *'beyond the reach of unaided imagination'* (Evans, 1997, p. 180).

Frank (2002) shows that the entropy of a system is an inverse of the amount of information known about it. If an observer possesses all the information needed to describe a system, then the entropy of the system for that observer is zero. Conversely, if the observer has no information about a system, then that system is in a state of maximum entropy for the observer (Frank, 2002). Therefore gathering information about a system can reduce its entropy. This does not violate the second law of thermodynamics because as an observer gathers information about a system, it is no longer isolated (Frank, 2002).

In entropic terms drawing are a part of the informational regime. The lack of the influence of *nature* on drawing implies that there is minimal information about the nature of material in the design. This in turn implies that for the designer, the material world has high entropy. The entropic endeavor of construction is therefore to order the material world using information in drawings which represent designs produced in the informational regime. The creation of this order occurs in the material regimes – the raw materials of construction are biological or mineral in origin and humans use machines to transform these materials into buildings. The influence of the second law of thermodynamics in the material regimes implies that the creation of order, i.e. the reduction of entropy, in these regimes requires the addition of energy into the system of construction. The energy required to build buildings is significant – the construction industry in the United States consumes 30% of the country's energy requirement (Kibert, et al., 2002, p. 7). Steel, cement and aluminum are in the top five energy consuming materials produced in the world (Gutowski, et al., 2013).

Digital design and fabrication in architecture.

The most visible effect of the *'digital revolution'* (Corser, 2010, p. 12) on architecture has been the ability to draw on a computer. Two-dimensional CAD drawings and three-dimensional CAD models move the projective architectural drawing from its intermediate position between the abstract and the real, to being completely in the informational regime. The displacement of drawing from the material to the informational regime removes the effects of entropy. One way this manifests is the ability to accurately measure any dimensions off a computer drawing (unlike the inaccuracies of measuring dimensions off a physical drawing). Another is the ability to undo and redo steps in drawing without any loss in the quality of the drawing (unlike drawings on paper where repeated erasure and redrawing will ultimately deteriorate the medium). In manipulating geometry on the computer, *'the set of constructs is far more abstract'* (Menges, 2011, p. 25). Computers enable the designer to process far larger amounts of information as compared to hand-drafted drawings, thus producing more complex designs (Chaszar & Glymph, 2010). If hand drawings took architecture *'beyond the reach of unaided imagination'* (Evans, 1997, p. 180), digital drawings afford the architect the ability to manage previously *'unimaginable complexities'* (Kolarevic, 2003, p. 57).

However, the digital revolution has furthered the evolution of architecture rather than revolutionize the profession (Corser, 2010). Latour and Yaneva (2013, p. 107) argue that *'perspective space invented in the Rennaissance* [is not made] *radically different by computer assisted design'*. Gramazio and Kohler (2008, p. 10) trace the divide between nature and architecture to digital design and fabrication –

> '[C]omplex *arrangements that constitute the aesthetics and expression of digital materiality may be reminiscent of the organic structures of the animal or plant world. But this comparison, though appealing, falls short: it masks the fact that digital systems do not arise out of biological conditions, and are not rooted in them either. The digital is an independent cultural achievement resulting from centuries of human engagement with logic.'*

Historically, the profession of architecture has been able to overlook the disconnect between design and nature brought about by drawing; intricate conventions minimize the discrepancies between imagined drawings and the realities of construction (Evans, 1997). *'Decades, even centuries, of effort have gone into creating the present set of regulations and contractual forms governing the design and construction of buildings'* (Chaszar & Glymph, 2010, p. 87). *'The relationship between an architect (as a designer of a building) and a general contractor (as an executor of the design) became… a rigidly codified process'* (Kolarevic, 2003, p. 58). Thus, *'both meaning and likeness are transported from idea through drawing to building with minimum loss'* (Evans, 1997, p. 181).

The processes of digital design and fabrication have pushed the boundaries of the status quo bridging the abstraction of design and drawing and the materiality of construction. The complex geometries of digital design have challenged *'"analog" norms of practice and prevalent orthogonal geometries'* (Kolarevic, 2003, p. 57). Thus, the poineers of digital design in architecture had to turn to digital fabrication processes in order to construct their complex designs. Digital fabrication technology uses the information contained in digital drawings and models to directly drive CNC fabrication devices (Kolarevic, 2003, p. 57) creating a new and direct path between the informational and mechanical regimes. The processes of digital fabrication become the bridge between the informational and mechanical regimes of entropy

– a position formerly held by hand drafted projective drawings. Figure 4 describes the changes that digital design and fabrication have brought to architecture.

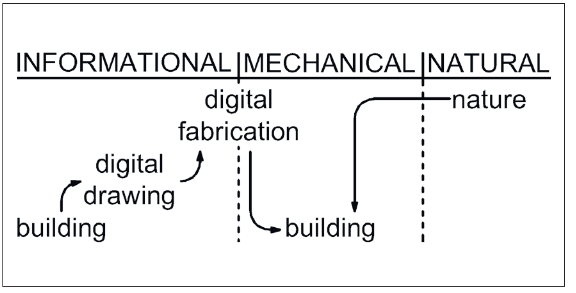

Figure: 4

The increased information processing power of computers has increased the complexity of digital designs and increased the information needed to describe them. The inverse relationship between known information and the entropy of a system (Frank, 2002) implies that the highly ordered, information-rich designs produced through digital design have lower entropy than the simple geometries possible with hand drafted designs. A comparison of figures 3 and 4 reveals that new technologies of design and fabrication have not fundamentally altered the way in which information and entropy flows in the design process.

Maxwell's demon and the four regimes of entropy.

With respect to the inverse relationship between entropy of a system for a given observer and the information known about it, Maxwell proposed a thought experiment that considered the observer to be a part of the system. He asked if the information gathered by this observer could be used to reduce the entropy of a system and contradict the second law of thermodynamics (Knott, 1911).Thomson described such an observer as a '*demon*' (Knott, 1911, p. 214). Maxwell (Knott, 1911, p. 215) clarified that this observer would be an *'intelligent'* molecular scale *'valve'* that could measure the speed and direction of molecules and control the movement of the molecule based on this information. Theoretically, such a device could be used to make energy flow from a state of high to low entropy (Knott, 1911). Such a demon/valve observer is defined by Maxwell as an abstract entity that can operate *'without friction or inertia'* (Knott, 1911, p. 214) and in terms of Pasquinelli's (2010) entropic geology, would therefore exist in the informational regime. The question Maxwell's demon thus asks is whether the zero entropy behavior of the informational regime can be carried over to the material regimes using the relationship between information and entropy.

Bub (2001) shows that the reason Maxwell's demon cannot contradict the second law of thermodynamics is because, for the demon to be able to store information about an observed system, it has to store this information in a physical medium (Bub, 2001). Examples of physical media for recording information can be anything from beads on an abacus to the quantum states of elementary particles. Whatever the physical storage medium might be, the recording of new information implies the erasure and loss of previous information stored on it, and therefore an increase in entropy (Bub, 2001).

Designing with Maxwell's demon.

While the zero entropy behavior of the informational regime cannot be translated into the material regimes by Maxwell's demon for the reasons explained by Bub (2001), the *'information revolution'* (Pasquinelli, 2010, p. 5) created digital computers that operate at *'(almost) zero entropy'* (Pasquinelli, 2010, p. 6) *'in comparison to mechanical engines'* (Pasquinelli, 2010, p. 5). The following diagram expresses the working of Maxwell's demon in terms of the regimes of entropy (Figure 5).

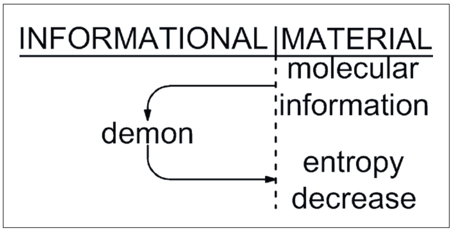

Figure: 5

Maxwell's demon may not be able to contradict the second law of thermodynamics, but the use of the informational regime to reduce entropy has the potential to use a lot less energy as compared to the mechanical regime (Pasquinelli, 2010). The strategy used by Maxwell's demon is to gather information about the system in which entropy needs to be reduced. The information about the system allows the demon to take decisions about when to open and when to close its molecular valve and thereby control the movement of molecules. The demon's strategy makes use of the inverse relationship between information and entropy, and links the informational and material entropic regimes.

Evans (1997), Gramazio and Kohler (2008) and Kolarevic (2003) have all identified a disassociation between the geometric abstraction of architectural design and the materiality of construction in architecture. In entropic terms, this disassociation is illustrated by the unidirectional flow of information out of the informational regime without any inflows (Figure 3 and Figure 4). The lack of inflows into the informational regime in design is explained by Evans' statement that, *'Drawing in architecture is not done after nature, but prior to construction; it is not so much produced by reflection on the reality outside the drawing, as productive of a reality that will end up outside the drawing'* (Evans, 1997, p. 165). All the entropy reduction in construction therefore takes place in the mechanical regime (Figure 3 and Figure 4), which requires large quantities of energy (Kibert, et al., 2002; Gutowski et. al., 2013) as compared to the informational regime (Pasquinelli, 2010).

The limited information processing capabilities of hand drawn geometry produce limited complexity in design (Kolarevic, 2003). Digital design processes on the other hand enable *'complex arrangements that… may be reminiscent of the organic structures of the animal or plant world'* (Gramazio & Kohler, 2008, p. 10). However, digital design has evolved by replacing hand drafting with computer modelling, so the similarities in the complex algorithmic geometries of the digtial and the complex forms in nature are fallicious (Gramazio & Kohler, 2008) since digital drawings, like their analog precursors, are *'not done after nature'* (Evans, 1997, p. 165) and are '*an independent cultural achievement resulting from centuries of human engagement with logic'* (Gramazio & Kohler, 2008, p. 10). However, the similarities in complex digital and natural geometries show that the information processing capacity of the digital can come much closer to natural forms compared to hand drafted geometry.

Rather than positioning the design process outside the system of construction, if, like Maxwell's demon, architects consider themselves a part of the system in which they have to reduce entropy, and use information about the system to reduce entropy in the informational regime, then architectural drawings do need to be *'done after nature'* (Evans, 1997, p. 165). Architectural drawings will therefore contain information from the material regimes as well as information about the building created by the designer. The design process of such a demon architect can be described in the following diagram (Figure 6).

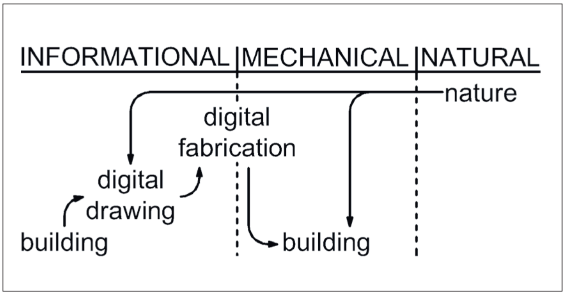

Figure: 6

The following projects illustrate what designing with Maxwell's demon might look like –

Bamboo notch joint

A variety of techniques exist for building joints in bamboo construction. Some techniques use only bamboo and a natural lashing material such as rope or rattan, while others involve the use of mechanically processed materials such as steel hardware, cement, or plywood (Janssen, 2000). The mechanical processing of these materials gives them consistency of size and shape which allows for accuracy in construction. This is unlike natural bamboo which is *'tapered, has nodes at varying distances and it is not perfectly circular'* (Janssen, 2000, p. 90). Thus a plate of metal or plywood maybe cut to a predetermined shape and holes may be made such that two pieces of bamboo can be bolted to the plate at a specific angle. The plate maybe fitted to the bamboo by cutting simple slots in the bamboo pieces corresponding to the thickness of the plate (Figure 7). The uniformly flat shape and

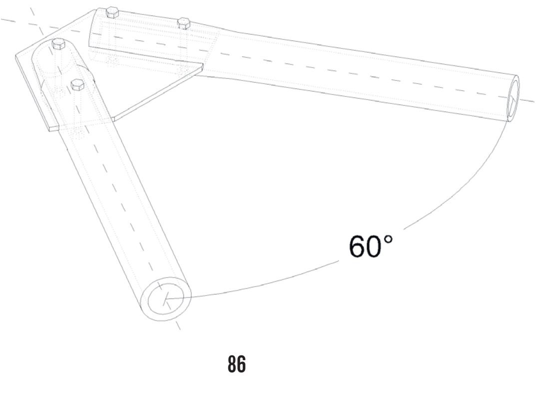

Figure: 7

the consistent thickness of the plate, and the ability to cut it to a predetermined shape enable the inconsistent bamboo pieces to interface with the plate by simple bolting. The inconsistencies in the properties of the natural material mean that with conventional design methodologies described, energy needs to be expended in the manufacture of mechanically processed materials to gain accuracy in the construction of the joints since there is no information available to the designer about the irregularly shaped natural material.

While it would be difficult to fully describe the irregular form of the bamboo pieces using hand drafted two-dimensional drawings, the complexity of the bamboo pieces can be modelled to a sufficient level of accuracy using three-dimensional computer modelling. While 3D scanning technology exists to easily digitize the bamboo forms, this was not available to the author. Instead, two pieces of bamboo were scanned on a flatbed scanner as shown (Figure 8).

Figure: 8

The profiles of the scanned bamboo were traced on the computer to create a three-dimensional computer model (Figure 9) for each of the two pieces of bamboo. A simple Boolean subtraction was done between the three-dimensional models of the two pieces of bamboo to find the shape of the notch required in one piece to fit the second piece at a specific angle. The three-dimensional geometry of the notch obtained was then used to CNC-cut the notch accurately in the piece of bamboo and the two pieces were lashed using jute rope (Figure 10). This joint has the advantage of accuracy, like the bolted plate joint, but without the need for mechanically processed materials.

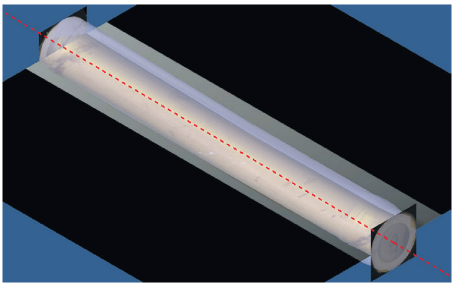

Figure: 9

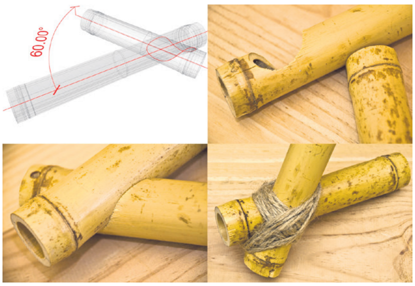

Figure: 10

Bamboo space-frame structure.

As a part of the second year design studio of the B.Arch program of the University School of Architecture and Planning (USAP) in Delhi, the class built a space-frame structure using bamboo. This structure used the strength of the nodes in bamboo by positioning joints between the space-frame members at the nodes. However, the designer cannot know the distance between the nodes (Janssen, 2000) if they are designing without information about the material.

The desired shape of the structure was modeled as a three-dimensional surface on the computer (Figure 11). A custom script took the distance between nodes as input, three pieces at a time. These three distances were triangulated and modeled using the script (Figure 12) so that the designer could make sure that the addition of the members approximates the shape desired (Figure 13). The final configuration of the space-frame members was thus determined only after making observations about the materials (measuring the distance between nodes), not prior to it. The computer integrated the information from the numerous observations (the lengths of each space-frame member) with the designer's initial intent. By measuring the inter-nodal distances, the designers gained information about the material and reduced its entropy. Had the inter-nodal distances not been known then the design could not have made use of the strength of the nodes and would have required more material (in the form of thicker bamboo).

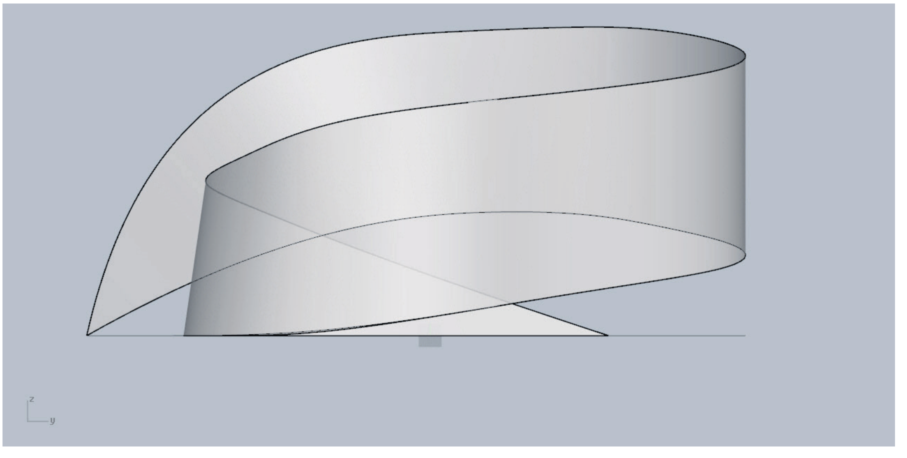

Figure: 11

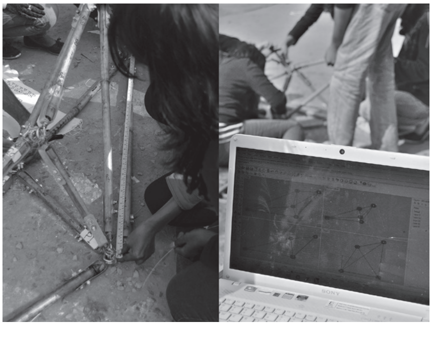

Figure: 12

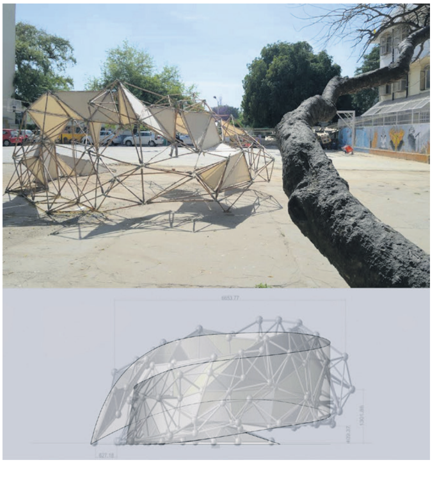

Figure: 13

Conclusions and further research

The two case studies illustrated the idea that the use of digital technology to record and manipulate information about materials to reduce entropy can be applied at a variety of scales. While the notch joint involved recording detailed information about a small part of an irregular natural material, the space-frame project involved collecting a single piece of information (inter-nodal distance) about a large number of parts. The notch joint made use of only natural materials but used digital fabrication for accurate construction. The space-frame required steel hardware for the joints but was constructed manually and approximately. However, the space-frame project involved the construction of a building scale artifact while the notch joint was a table-top object. Further studies integrating material information at different scales might combine the advantages seen in both case studies.

This paper considers materials from the biological and mineral regimes to be natural materials that differ from materials of the mechanical regime that are manufactured by the human control of energy flows. However, the difference in the entropic behavior in the mineral and biological regimes is significant (Pasquinelli, 2010), and these differences have the potential to affect the approaches to designing with them. The author is currently working on design strategies tailored specifically to materials from each regime.

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