Integrating Digital Design and Fabrication and Craft Production

by

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Abstract

This thesis examines if methods of manual craft production can be utilised to overcome the indeterminacies of physical materials and processes that hinder Digital Design and Fabrication (DDF). Indeterminacies in physical materials and processes are considered to be errors that prevent DDF from achieving its stated goal of a seamless transition from digital model to physical artefact. One of the definitions of craft, by contrast, is “(potentially) error through and through... [where error is]... an incomputable deviation from the norm” (Dutta, 2007, p. 211).

This concept of error as being ‘incomputable’ is analysed using theories from computation, systems theory and sociology to formulate a definition of *material* craft production for this thesis. Material craft production is then compared to the concept of digital craft and it is argued that digital craft is limited in its capacity to negotiate physical materials and processes.

Tools from systems theory are then used to propose a model describing material craft production. This model is called the Sensing-Evaluating-Shaping (SES) model. The validity of the SES model is tested through case studies of material craft production.

The SES model is analysed using systems analysis tools and a role for DDF is proposed within the SES model, giving rise to digital SES production. The ability of digital SES production to negotiate indeterminacies in physical materials and processes is tested through the fabrication of a series of increasingly complex physical artefacts.

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1.0 INTRODUCTION

1.1 Personal Background

Working as an architect I had the good fortune to be exposed to a range of construction techniques from sophisticated digital fabrication to skilled manual labor. Two projects that made me aware of the differences and similarities of these different ways of building were a full scale bamboo shelter project designed and built in the first year of my B.Arch program, and the Jindal Power Ltd. Gateway which I worked on as an architect.

In the first project my team built an approximately 18'x18' hyperbolic paraboloid structure with natural bamboo poles, steel bolts and jute rope. We did extensive digital modeling and physical prototyping at small scales using bamboo broom sticks as scaled representations of the bamboo poles, cotton sewing thread to represent jute rope and pins for the steel bolts. The physical prototypes were used to plan the construction sequence for the full scale structure.

Despite the careful planning, digital models and physical prototypes, we could not determine the exact dimensions and angles of the final structure because they were dependent on a variety of unforeseeable factors such as the exact diameters of the bamboo poles, the positions of the nodes on the bamboo poles (which were used as points of strength to locate joints) and the tightness and ‘give’ of the jute rope knots. The final dimensions of the structure were thus arrived at only as the structure was being built.

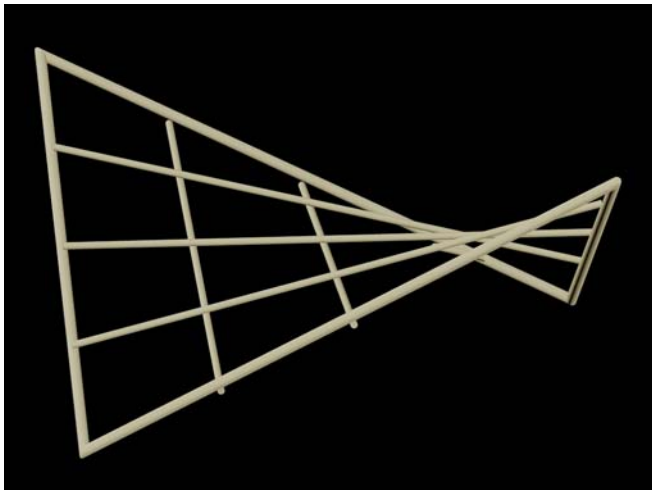


Figure 1: The Digital Model for the Bamboo Hyperbolic Paraboloid

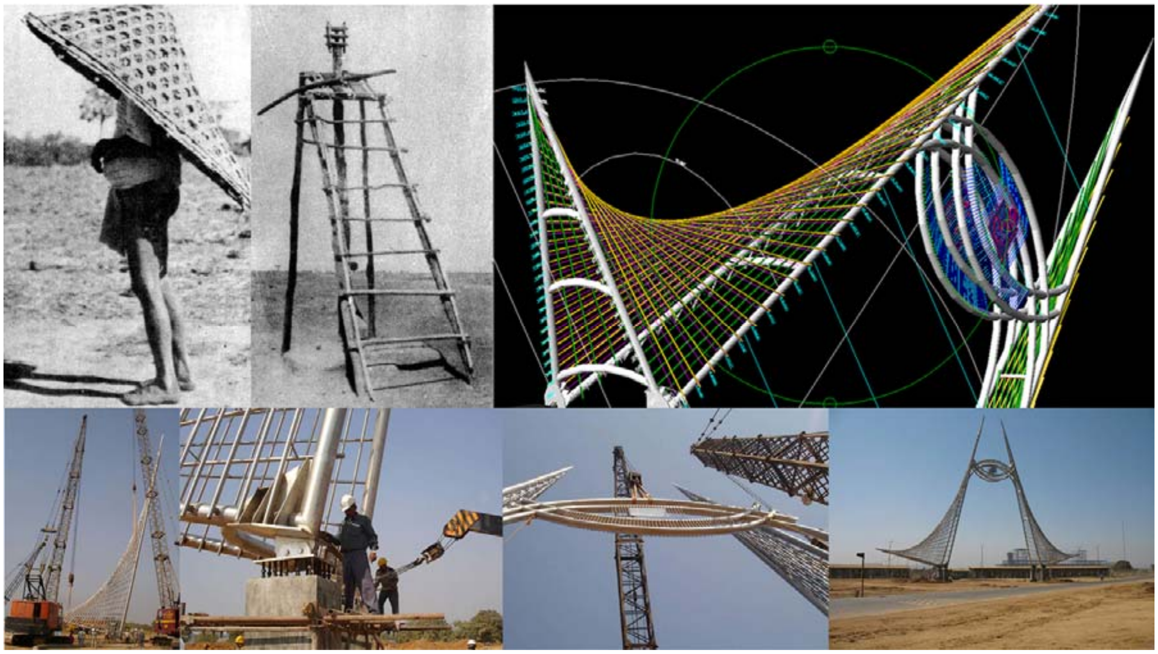


Figure 2: The Inspiration, Design and Fabrication of the JPL Gateway

The Jindal Power Ltd. Gateway was a structure made of stainless steel tubes and consisted of two hyperbolic paraboloids connected by an ‘eye’. One of the objectives of this design was to use stainless steel tubes like bamboo poles are used in the vernacular architecture of the region. The design work flow in this project consisted of first creating a digital wireframe model of the structure which was used for structural analysis. The results of the structural analysis gave the diameters of the members and the strength required at the joints. These were used to create a digital solid model. The dimensions from the solid model were used to derive construction data for the CNC prefabrication of all the components which were transported and assembled on site. The use of 3D computer modeling to create fabrication data for construction allowed greater planned complexity in the design compared to the bamboo structure where only the sequence of construction could be planned and complexity in the design was a result of unforeseeable factors. However, with the stainless steel structure, any deviation from the digital model would have resulted in errors that would have made the assembly of the structure impossible.

Working on these two projects made me ask the question of whether there is a middle ground between these two very different construction methods. Is it possible to combine digital design and fabrication with skilled manual craft processes, and if so, what its implications may be for digital design and fabrication and for manual craft? It is with this background that I began my studies on design computation, in particular in digital design and fabrication.

1.2 Digital Design and Fabrication

Sass and Oxman (2006) quote Kolarevic's (2003) definition of digital fabrication as “the application of RP [Rapid Prototyping] for design and CAD – CAM for construction” (p. 328) and themselves go on to define digital design as “a self-contained way of designing exclusively within a computational environment” (p. 333). The goal of digital design and fabrication is stated by Botha (2006) to be the creation of a “construction process [which] never negotiates back and fourth between dimension, aiming for an effortless transition from digital to physical artifact” (p. 15). The “effortless transition from digital to physical” is made possible by digital fabrication technology which can create a physical artifact from a 3D digital file.

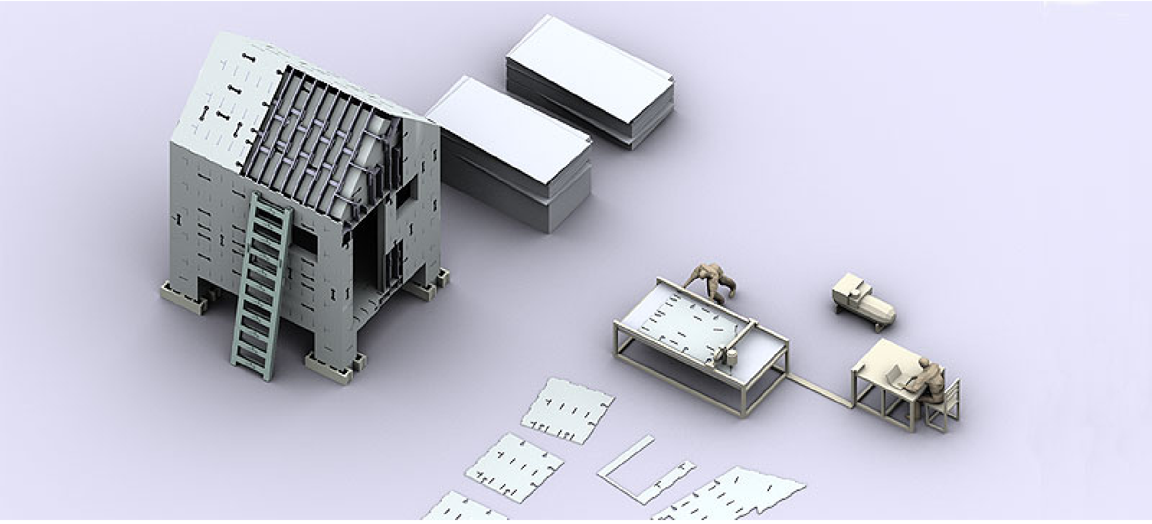


Figure 3: The DDF Workflow (Source: http://momahomedelivery.org/)

Cardoso (2007) lists one of the problems with this method as being the warping of material used for digital fabrication because “These distortions are caused by different factors such as humidity, temperature, and therefore are very (*sic*) impossible to fully predict in a digital model” (p. 43). Such phenomena, termed errors by Papanikolaou (2008), are responsible for creating indeterminacies in the outcomes of all physical processes. These errors may be small enough to be negligible or be large enough to warrant correction.

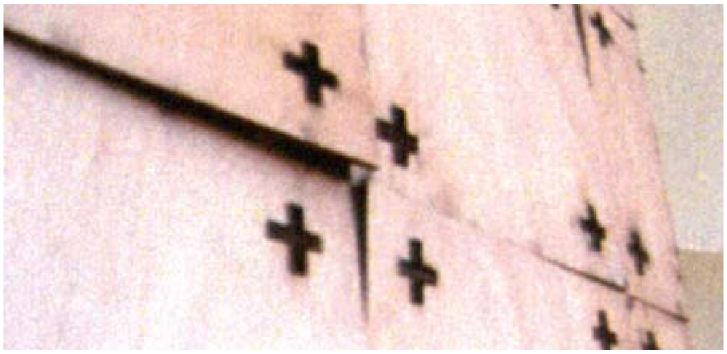


Figure 4: Warping in a Digitally Fabricated Object (Cardoso, 2007)

1.3 Craft

The architectural historian Dutta (2007) shows that “felicitous error” (p. 211) is essential to craft and he defines the term error as “variation from the programmed” (p. 211). Craft is then defined as “(potentially) error through and through, where every pick bears the possibility of an incomputable deviation from the norm” (p. 212). Dutta’s argument of error being “incomputable” connects to Cardoso's (2007) assertion that errors are “impossible to fully predict in a digital model” (p. 43).

1.4 Thesis Question

This connection between craft as ‘incomputable’ and error as indeterminate in a digital model leads to the thesis question: Can methods of manual craft production be utilized to overcome the indeterminacies of physical materials and processes that hinder Digital Design and Fabrication (DDF)?

2.0 CRAFT

There are many different ways of looking at craft and craft production. Below is a discussion of different aspects of craft with respect to industrial production and computation.

2.1 Craft, Industry and Computation

Until the industrial revolution craft production was the only form of production available to humans. In addition to the development of industry, the industrial revolution was also a critical time in the development of computation. The architectural historian Dutta's (2007) discussion brings together the concepts of craft, industrial production and computation. Beginning with the everyday idea of craft as highly detailed manual work, Dutta proposes that detail in craft is that which is incomputable. Being incomputable, the detail in craft can not be repetitively produced by a machine. In the context of mechanical production these incomputable details take on the form of errors – an idea attributed by Dutta to Charles Babbage. Dutta (2007) thus defines craft work as, "(potentially) error through and through… [that requires the intervention of a crafts-person] in the mode of a fecund miscomputation" (pp. 211-212).

The philosophical origins of Babbage's conception of the incomputable as error are traced by Dutta (2007) to the ideas of Descartes, Kant, Bourgoin and others. Descartes saw the bodily senses as distorting the objective world, and the mind as having to correct these distortions of the body to reconstruct the world as it actually is. Kant called this process of mental reconstruction "reason" – an "internally consistent set of principles… [that do not rely on] nature… [to stimulate] empirical chance insights" (Dutta, 2007, p. 83). With respect to a visual and spatial reconstruction of the world "reason" took the form of "geometry" according to Kant. Bourgion contrasted this Western conception of geometry with the oriental conception that is based on the physical production of patterns and is thus “entirely subordinate to the skill of the artisan and in no way supposes reasoned scientific knowledge of geometry” (Dutta, 2007, p. 85).

In addition to artisanal skill as a source of ‘error’ in craft production, Dutta (2007) identifies ‘nature’ as another source of ‘error’. Form giving natural processes (such as the growth of trees or the formation and erosion of rocks) that are “incapable of stasis… [cause the] inevitable resolution [of morphology] into a morphotropy … [that is] inevitably at odds with the principal modus operandi of industrial production: mechanical repetition … therefore, naturally occurring ‘accidents’ such as knots [in wood] were to be excluded from the surface [of a wooden artifact], not because of the structural problems that this might create, but because to reveal the knot is to once again stumble into the pitfall of naturalist verisimilitude that makes imitative painting defective for industrial replication” (Dutta, 2007, pp. 112-120).

Therefore, one can say that craft production is ‘non-cogitative’ and based on bodily senses and actions to create incomputable and unique objects from, and stimulated by, materials having ‘errors’ due to ‘accidents’ of nature, whereas industrial production is based on ‘internally consistent’ mental reconstructions, to produce reproducible, ‘error-free’ objects from ‘perfect’ materials.

2.2 The Computability and Predictability of Natural Phenomena

A key concept that emerges from the previous section is that of computability and incomputability. Wolfram (1984a), a pioneer of cellular automata, proposes that cellular automata are equivalent to digital computers and that the qualitative behavior of cellular automata can be categorized into four different classes (1984b). He defines cellular automata in the following way: “Cellular automata are mathematical models for complex natural systems containing large numbers of simple identical components with local interactions. They consist of a lattice of sites, each with a finite set of possible values. The value of the sites evolve synchronously in discrete time steps according to identical rules. The value of a particular site is determined by the previous values of a neighborhood of sites around it” (Wolfram, 1984b, p. 1).

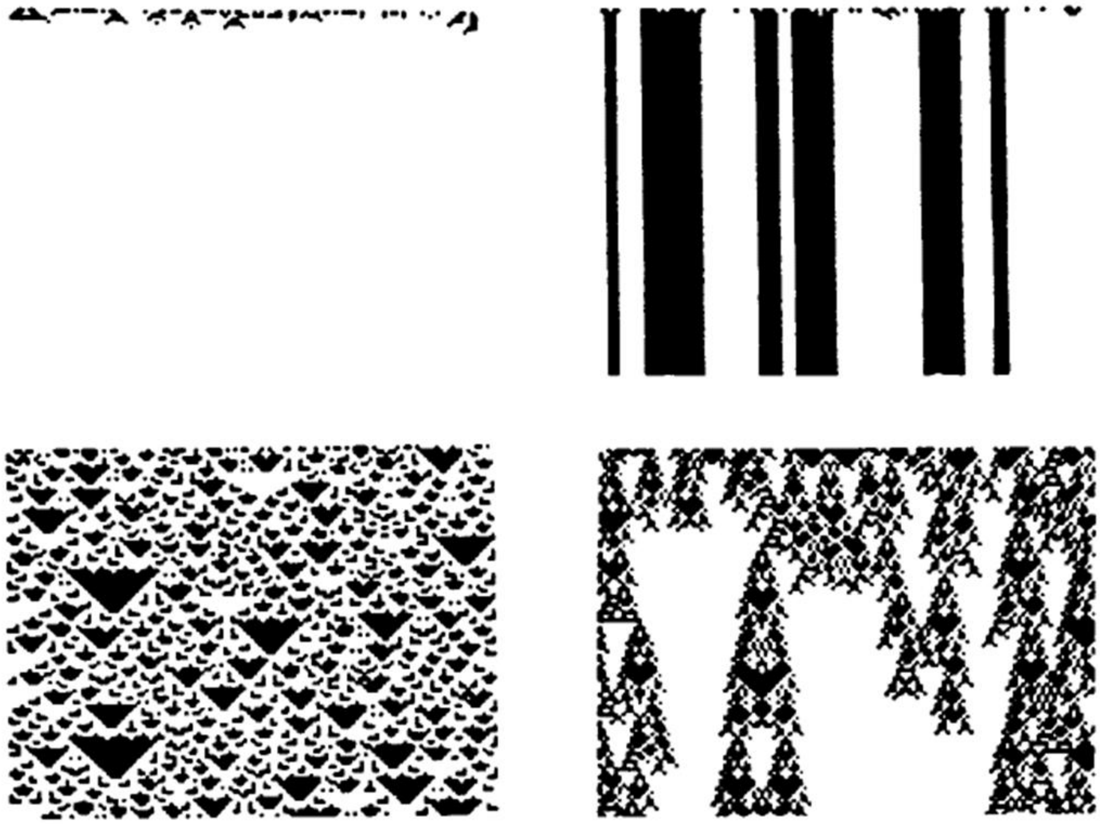


Figure 5: The Four Classes of Cellular Automata Behavior (Wolfram, 1984b)

Wolfram (1984b) shows that the different classes of behavior have consequences for the predictability of a future state of a cellular automaton, given the initial state and the rules governing its behavior. “For the first class, all initial states yield the same final state and complete prediction is trivial” (Wolfram, 1984b, p.34). With behavior of the second class, knowledge of the initial state and the rules allows the prediction of a future state of a given length of sites only. In the third class of behavior, “the effects of changes in the initial state almost always propagate forever at a finite speed. A particular region thus depends on a region of the initial state of ever-increasing size. Hence any prediction of the “final” state requires complete knowledge of the initial state” (Wolfram, 1984b, p.34). In addition to ‘complete knowledge of the initial state’, predicting behavior of the fourth class is further complicated by the fact that the dependence of a future state on the initial state “may be arbitrarily complex, and the behavior of the system can be found by no procedure significantly simpler than direct simulation. No meaningful prediction is therefore possible for such systems” (Wolfram, 1984b, pp.34-35).

Cellular automata can be thought of as being ‘discrete idealizations’ of continuous dynamical systems that describe a variety of natural phenomena such as crystal formation, fluid turbulence, and multi-cellular growth in biology. (Wolfram, 1984a and 1984b). In the context of dynamical systems theory “the attractors [in phase space] in class 1, 2 and 3 [of cellular automata behavior] are roughly analogous respectively to the limit points, limit cycles and chaotic (‘strange’) attractors found in continuous dynamical systems” (Wolfram, 1984b, pp. 1-2).

While Wolfram (1984b) states that ‘no meaningful prediction’ is possible for class four behavior of cellular automata, he explains that “given the necessary set of initial values, it is conjectured that the value of a site in a class 3 cellular automaton may be determined by a simple algorithm.” (p. 2). However, this predictability is valid only for mathematical models, and not for the physical phenomena that they model. Bertuglia and Vaio (2007) provide two reasons for mathematical predictability not to translate into the predictability of physical phenomena. One reason is the practical difficulty in obtaining a ‘complete knowledge of the initial state’ required for predicting class three behavior. The other (more fundamental), mathematical reason is loss of accuracy “linked to the numerical approximation that we inevitably have to make when a real number has to be replaced by a rational number ‘close’ to it, in order to be used in practice, namely in measurements. … [since] We will never be capable of formally establishing, on a purely mathematical level, whether the value obtained from measurements is an approximate value of a rational or an irrational number” (Bertuglia and Vaio, 2007, p. 155).

Therefore, even though class three and four behaviors of cellular automata are computable (i.e. an algorithm exists that can model a system displaying these classes of behavior), they can be considered to be unpredictable in a physical sense. However, not all physical phenomena are computable in the first place. Alternatively, they may be stochastic: “the result not of law, but of that which is commonly called ‘chance’ and follows a probability distribution” (Bertuglia and Vaio, 2007, p. 179).

While methods of statistical analysis can give probability distributions for stochastic and chaotic systems, such systems are indeterminate, that is, their outcome can not be determined with an absolute probability of one or zero. Since the outcome of indeterminate phenomena can not be determined with absolute probability, such phenomena can not be repetitively reproduced by mechanical means. It may, therefore, be more accurate to consider the unpredictability of natural phenomena as a source of ‘error’ in craft production rather that their outright incomputability as argued by Dutta (2007). Thus the definition of craft proposed in the previous section may be revised as follows: Craft production is ‘non-cogitative’ and based on bodily senses and actions to create indeterminate and unique objects from, and stimulated by, materials created by indeterminate form giving processes.

2.3 Skill and the Computability and Predictability of Human Actions

With reference to the component of human action in craft, McCullough (1998) defines the term skill to convey the inarticulable experiential knowledge embodied in the ‘hands.’ Skill, in this sense, can be thought of as a type of tacit knowledge due to its inarticulability. Collins (2001) discusses the different possibilities available to articulate and make explicit, and thus automate, the creation and application of tacit knowledge. He discusses three types of tacit knowledge – the motor-skills metaphor of tacit knowledge, the rules-regress model, and the forms of life approach. With respect to the motor-skills metaphor of tacit knowledge Collins (2001) takes the example of riding a bicycle and argues that it is tacit only because humans can not calculate and apply the results of the governing laws of physics fast enough, but for a machine this is no problem. According to the rules-regress model of tacit knowledge some forms of knowledge are tacit because “rules do not contain the rules for their own application” (Collins, 2001, p. 110). However, Collins (2001) shows how even this kind of tacit knowledge is tacit only due to the limitations of the human brain. The forms of life approach to tacit knowledge is based on the idea that tacit knowledge is founded on beliefs and “the true source of our beliefs are in large part the social contexts we inhabit” (Collins, 2001, p. 111). He calls such actions ‘polimorphic actions’ and argues that to compute the results of such actions computers “would need all the status, persuasive power, understanding of what might be credible to others, and so forth, which the sociology of scientific knowledge has shown to be involved in the process of new knowledge formation… [and]… Perhaps one day this will be possible, but no one has the slightest idea how to do it now, not even in principle” (Collins, 2001, p. 115).

The systems theorists Bertuglia and Vaio (2007) discuss the mathematical modeling of social systems and argue that mathematical techniques developed for modeling phenomena in physical sciences may be applied to the social sciences. According to Bertuglia and Vaio most social science phenomena are more accurately described by non-linear mathematical models than linear models. Non-linear models, in turn, largely result in systems with chaotic attractors. As shown in the previous section, a chaotic system is inherently indeterminate. Diderot, in his Encyclopedie (1751-80), defines craft as the following: “This name is given to any profession that requires the use of the hands, and is limited to a certain number of mechanical operations to produce the same piece of work, made over and over again” (McCullough, 1998, p. 13). This view can be thought of as equivalent to the tacit knowledge, or skill, in craft being described by the motor-skills metaphor and thus being computable and predictable. It is this belief that is one of the bases for attempting to replace craft with mechanical production. However, certain aspects of skill in craft involve the forms of life approach to tacit knowledge which depends on a craftsperson being part of a social group.

If “groups of interrelated social actors” (Sterne, 2003, p. 375) are termed to be a “field” and “specific forms of agency and prestige within a given field” (Sterne, 2003, p. 375) are named “capital”, then, *habitus* is “a kind of ‘generative principle’ of spontaneous and creative social action based on one’s position in a field and one’s access to and possession of certain kinds of capital” (Sterne, 2003, p. 375). *Habitus* is thus “the socially organized base[ed] of physical movement... and the use of instruments or technologies.”(Sterne, 2003, p. 370). In this discussion technology has a very specific meaning. It “is a repeatable social, cultural and material process” (Sterne, 2003, p. 376). The formation of *habitus* in an individual connects their personal experience and understanding to their social setting. “*Habitus* is embodied belief, but it is also a generative principle; it allows for creativity and improvisation... It is spontaneous and generative because agents can act in creative ways, but it is ‘nonspontaneous’ because the basis of their action is rooted in education, cultural memory, upbringing, and social circumstance” (Sterne, 2003, pp. 375-376). Clearly, the craft skills resulting from *habitus* are ‘polimorphic actions’ (as described by Collins) and would need to be modeled using non-linear mathematical models that result in unpredictable systems. Thus the definition of craft proposed in Section 2 may be further revised as follows: Craft production is ‘non-cogitative’ and based on indeterminate bodily senses and actions to create indeterminate and unique objects from, and stimulated by, materials created by indeterminate form giving processes in nature and society.

3.0 DIGITAL CRAFT AND MATERIAL CRAFT

The discussion of craft production with respect to computation and industrial production requires an understanding of contemporary ideas linking digital design and fabrication technologies and techniques to traditional forms of craft production. The term digital craft, discussed by Malcolm McCullough (1998) is therefore analyzed with respect to the definition of craft formulated in previous sections.

3.1 Digital Craft

McCullough argues that the computer is a “tool for the mind – not the hands. Its essential action is to process and transmit not power but symbols” (McCullough, 1998, p. 151). It is in this context that McCullough (1998) discusses the possibility of a digital craft. Essential to this idea is the ability to create a digital medium within which information can be manipulated – “a medium conveys a sense of possibilities through the continuous probing and action of a tool” (McCullough, 1998, p. 151). In relation to the definition of craft formulated in previous sections, McCullough is proposing a craft that is based on virtual materials created using algorithms with unpredictable results in the digital realm as a source for indeterminacy in a digital craft. DDF too proposes similar objectives by “link[ing] cognitive design skills to modeling geometries” (Oxman and Sass, 2005, p. 336).

The creation of such a link, using digital design, rapid prototyping and CAD-CAM fabrication is illustrated by Oxman and Sass (2005) using the following example: “plywood is embedded with geometric rules based on the limits of a flat sheet of stock material. Geometries are constructed in CAD as planar geometries and then translated into a model for laser cutting or CNC cutting with a flat bed wood router. If generative methods are used, rules for plywood are based on rules for the manipulation of flat sheet stock. Laser cutting cardboard flat stock material acts the same as the cutting of plywood; in essence the rules of the material are the same.” (Oxman and Sass, 2005, p. 336). Taking the idea of a digital medium further McCullough (1998) suggests encoding the properties of a physical medium in a digital medium so that “This too becomes a mental model – a design world – and part of the challenge of effective software design is to impart a convincing representation of such worlds in action” (McCullough, 1998, p. 151). In order to create physical objects with a digital craft McCullough proposes the use of digital fabrication – “thus, conversely to the widespread condition noted by the cultural critics, wherein things become images, here there an inversion: thanks to CAD/CAM, and more controllably than ever before, images can become things” (McCullough, 1998, p. 51). An assumption made by Oxman, Sass and McCullough in this discussion is the seamless transition from digital model to physical artifact. However, computational and systems theory show this to be an unachievable ideal.

3.2 Constructionism and the Importance of the Physical

The pedagogical theory of constructionism formulated by Seymour Papert and others at the Epistemology and Learning Research Group in the MIT Media Lab is a contemporary explanation of Bourgoin's description of the Oriental artisan's mode of understanding geometry. In fact, Seymour Papert (1991) argues that the construstionist framework includes both the instructionist Western, and the constructionist Oriental modes, and “allows the full range of intellectual styles and preferences to each find a point of equilibrium” (Papert and Harel, 1991, para. 5). The underlying idea of constructionism is that of ‘learning-by-making’. This refers to the process of learning by manipulating concrete entities. The constructionist definition of a concrete object or phenomenon differs from the standard definition. While the standard definition of a concrete object is some thing tangible, and a concrete description of an object or phenomenon is one that “allows us to visualize (or, if you will, sensorize) an object.” (Wilensky, 1991, p.

194). The constructionist argument against this definition is that it makes the assumption that all individuals have identical and static ontologies. Instead, constructionism proposes that “concreteness is not a property of an object but rather a property of a person's relationship to an object... The more connections we make between an object and other objects, the more concrete it becomes for us. The richer the set of representations of the object, the more ways we have of interacting with it, the more concrete it is for us” (Wilensky, 1991, p. 198). The process of “concretion” then, is the process by which an individual converts sensory stimuli into ontology.

“Link[ing] cognitive design skills to modeling geometries” (Oxman and Sass, 2005, p. 336) in DDF can be thought of as a form of concretion. However, the use of a wholly digital craft will alter an individual's relationship to the objects they produce and interact with and will alter the craftsperson's ontological sense of the object that they are crafting. In the case of disciplines such as computer graphics both the manipulated entities and the crafted product are digital. If this were the case in architecture then the final product would be a digital model – not a physical building.

McCullough describes digital craft using the following words: “Think of a digital artifact, shaped by software operations, made up of data assemblies. Although lacking in physical substance, it is a thing with an appearance, spatiality, structure, workable properties, and a history” (McCullough, 1998, p. 155). However, it is not possible to unify physical and digital ontology by digitally modeling physical systems perfectly and providing a completely digital “medium” for physical craft, as demonstrated by computational and systems theory. It is the inconsistencies between the digital and physical mediums that cause those phenomena that can not be digitally modeled to be considered errors. A digital medium is not a rich enough representation of the physical medium and thus prevents interactions with certain physical phenomena that can not be modeled digitally and these are termed errors. Therefore if an architect designing physical buildings is to be able to develop a more concrete representation of materials and processes being utilized and the physical systems being designed, then it is necessary to take into account digital representations as well as their physical counterparts in the design process. Craft production, on the other hand, is able to take into account physical phenomena that are computationally unpredictable.

4.0 SENSING-EVALUATING-SHAPING

Having shown that craft production is in a position to negotiate computationally unpredictable phenomena, a system that enables this is proposed and modelled below.

4.1 The Sensing-Evaluating-Shaping (SES) System

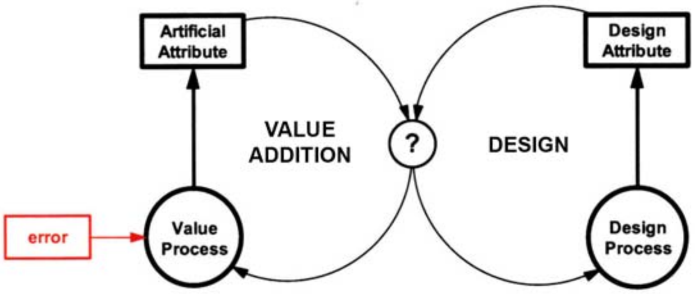


Figure 6: A Production System (Papanikolaou, 2008)

In his thesis on the feasibility of digital fabrication processes, Papanikolaou (2008) defines a production system as, “a feedback system whose goal is to match a set of artificial attributes to a set of design attributes. Artificial attributes are modified by a set of value adding processes. Design attributes are modified by a set of design processes” (Papanikolaou, 2008, p. 39).

The two components of a production system are the design process and the value adding process. Design processes can result in either implicit instructions or explicit instructions. “If design is explicit, its purpose is to direct; if design is implicit, its purpose is to indicate” (Papanikolaou, 2008, p. 21). In the case of “an artifact whose parts are fabricated by a number of different fabricators located at remote places from the construction site” (Papanikolaou, 2008, p. 21) the design process needs to be explicit, whereas for “an artifact whose parts are fabricated by only one fabricator located inside the construction site... the designer can implicitly define or even modify design instructions during production”

(Papanikolaou, 2008, p. 21-22). Value adding processes are those “which embed design information into [the] matter… A value adding process has an error factor that introduces noise in the outcome of the process. Chains of value adding processes propagate errors. There are two correction options: redo the process or redo the design” (Papanikolaou, 2008, p. 20). This is represented by the decision function connecting design to value addition.

The concept of ‘noise’ as ‘error’ is shown by Dutta (2007) to be a result of industrialization and the emergence of design as a profession distinct from production. In the context of design being separate from production, a design becomes a prescription of the precise dimensional (and material) qualities required of the artifact produced (McGee, 1999) – these qualities are denoted by the term Design Attribute. The role of the value adding process is then to match artificial attributes to design attributes and any deviation is termed an error. Design Attributes are therefore represented in drawings that are “stereometric or steriotomic” (Dutta, p. 87, 2007) since “the bodily eye as a potentially misrepresentational device in its reception of objective phenomena” (Dutta, p. 84, 2007). Interaction between the value adding process and the design process is then limited to the task of error correction and since the two processes are separate, ‘correction’ requires redoing one of the two.

The design process may include various methods of predicting possible errors in the value adding process through computer simulations and physical prototypes. However, it has been shown in previous sections that error is that which is indeterminate and will always exist in complex physical processes. Craft, on the other hand is defined by Dutta (2007) as “(potentially) error through and through” (p. 211). Since error is indeterminate, in craft “geometry is arrived at from a route other than reason… [and] is entirely subordinate to the skill of the artisan” (Dutta, p. 85, 2007) so that “drawing is indexical rather than stereometric or steriotomic in character” (Dutta, p. 87, 2007). Drawing in craft is therefore an implicit description of the object to be made, not an explicit description of it.

Starting with the premise that every physical process results in some predicted attributes and some unpredicted attributes we can begin to model a craft production system using the Attribute Process Methodology (APM). APM was developed by Papanikolaou (2008) and is a modification of the systems modeling language called Object Process Methodology (OPM) developed by Dori (2002). In APM, a system is modeled based on a set of attributes that can describe the system and a set of processes that modify the attributes. Attribute Process Diagrams (APDs) are graphic representations where attributes are symbolized by rectangular boxes and processes by circles. Arrows connect attributes to processes, and vice versa, to represent relationships between them.

The definitions below can be used to create an APD as shown:

Craft Process: A value adding process using craft production (as defined in section 2.3) intentionally initiated by a human agent.

Natural Process: A value altering process not intentionally initiated by a human agent.

Design Process: A non-material process that results in a Design Attribute.

Design Attribute: A non-material, representational attribute that forms the input for a craft process.

Predicted Attribute: An attribute resulting from a Craft Process that matches a Design Attribute due to the intentionality of a human agent.

Unpredicted Attribute: An attribute resulting from a Craft Process that is not due to the intentionality of a human agent.

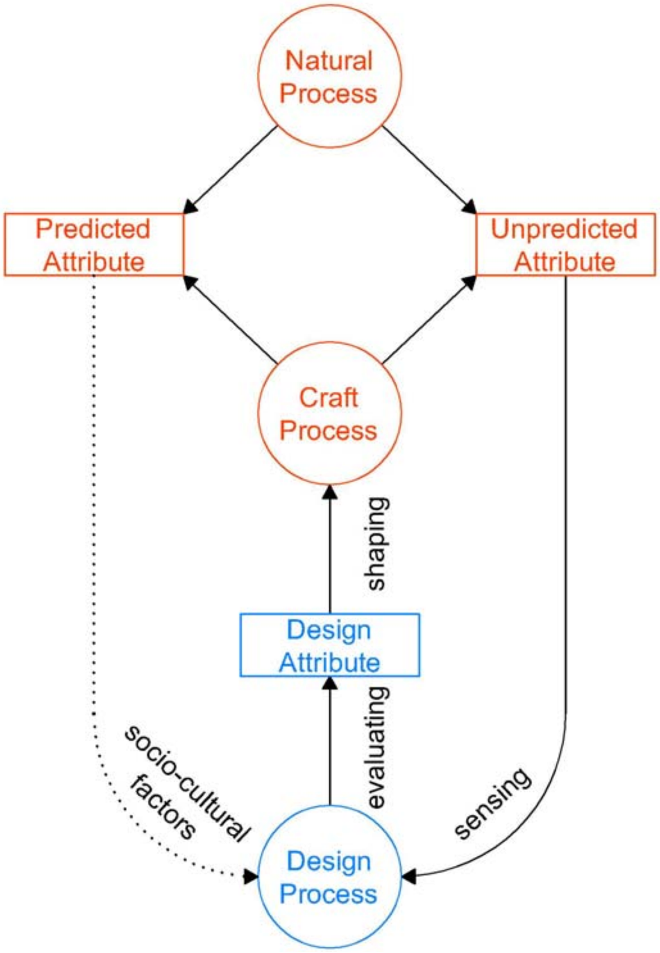


Figure 7: An APD of an SES System

The relationship connecting an Unpredicted Attribute to the Design Process is Sensing. Sensing is the gathering of information about the results of a process resulting in Unpredicted and Predicted Attributes so as to incorporate it into them into the Design Process. Evaluating is the relationship between the Design Process and a Design Attribute. It is the result of the incorporation of information (obtained from Sensing) into the Design Process to obtain a Design Attribute. Shaping is the transformation from informational to physical and forms the relationship between a Design Attribute and a Craft Process used to physically create it. Sensing, Evaluating and Shaping form fundamental relationships in craft production because it is through them that a craftsperson is able to react to Unpredicted Attributes. This is what differentiates craft production from other forms of production and forms the basic Sensing-Evaluating-Shaping (SES) model for Craft Production. The SES model is applicable every time an Unpredicted Attribute is encountered during the production of a design.

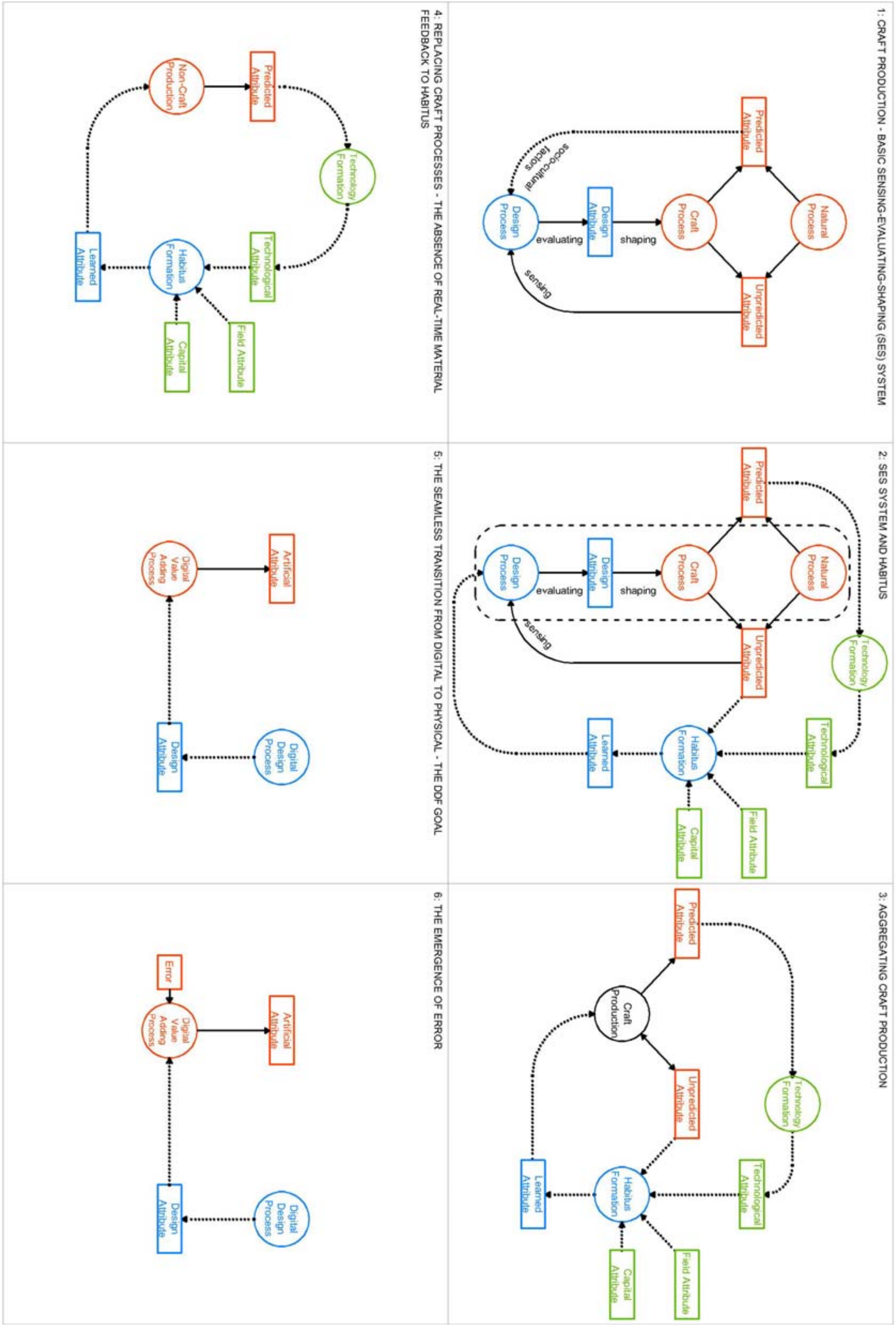
Error in a craft process then, is not an indeterminate “deviation from the norm” (Dutta, p. 211, 2007), or all noise in a value adding process (Papanikolaou, 2008), but only those results of a craft process that are incompatible with the results of previous iterations of the SES model. There is a subtle but significant difference between these opposing definitions of error – defining error in a process as any deviation prevents the process from acknowledging and negotiating the deviation, responding to it through “a fecund miscomputation” (Dutta, 2007 p. 212).

4.2 Incorporating the SES System into Craft Production

The relationship between the Design Process and Predicted Attributes is different from that with Unpredicted Attributes since Predicted Attributes are less likely to change during the production of a design. The effects of Predicted Attributes are more apparent in the long term. As craftspersons are exposed to a larger number of Unpredicted Attributes over the time of producing multiple designs, some of these attributes will become predictable. Once an attribute is predictable it can be repeatedly created in multiple designs and it becomes a Predicted Attribute. Predicted Attributes can, and inevitably will, spread in a society and give rise to new technologies where Technology is defined by Sterne (2003) as “a repeatable social, cultural and material process” (Sterne, 2003, p. 376). Sterne discusses the sociological concept of *habitus* formulated by Bordieu in relation to technology. A Technological Attribute is thus an attribute that can be repeatedly created by a social, cultural and material process (i.e. by a technology). Therefore, after a period of the practice of a craft in a society certain Unpredicted Attributes will eventually become predictable and enter the realm of technology. These technologies can then be learned by individuals who are a part of that society. This results in the formation of *habitus* in an individual. *Habitus* is “the socially organized base(ed) of physical movement... and the use of instruments or technologies.” (Sterne, 2003, p. 370) “*Habitus* is embodied belief, but it is also a generative principle; it allows for creativity and improvisation... It is spontaneous and generative because agents can act in creative ways, but it is ‘nonspontaneous’ because the basis of their action is rooted in education, cultural memory, upbringing, and social circumstance” (Sterne, 2003, pp. 375-376).

In addition to Technological Attributes, other socio-cultural attributes that affect the process of *Habitus* Formation are Field Attributes and Capital Attributes. A field consists of “groups of interrelated social actors” (Sterne, 2003, p. 375) and capital comprises “specific forms of agency and prestige within a given field” (Sterne, 2003, p. 375). Capital Attributes are therefore those attributes that contribute to *Habitus* Formation that result from a craftsperson's position in a field and the consequent capital gained. *Habitus* thus mediates what is learned by an individual from society and the individuals learning from personal experience.

If one aggregates the SES Model as the process of Craft Production in the context of *Habitus* Formation then it is possible to evaluate the effects of replacing Craft Production with other forms of production that do not enable a reaction to an Unpredicted Attribute. One effect of this is the absence of feedback from Unpredicted Attributes to the *Habitus* Formation process and the Design Process. This severely restricts the ‘spontaneous and generative’ component of *habitus* and enables the separation of design from material production. An absolute separation of design and production is seen in the DDF ideal of a seamless transition from digital to physical. However, once design is no longer based on *habitus* and does not receive feedback from Unpredicted Attributes any Unpredicted Attribute becomes exogenous to the system and is termed an Error. An important point in this discussion that may be overlooked in spite of being apparent is that, within Craft Production, the designer and the maker are the same human agent or group of agents – the craftsperson(s). It is the separation of design from material production in non-craft processes that allows the designer and the maker to be separate.



1: CRAFT PRODUCTION - BASIC SENSING-EVALUATING-SHAPING (SES) SYSTEM

2: SES SYSTEM AND HABITUS

3: AGGREGATING CRAFT PRODUCTION

4: REPLACING CRAFT PROCESSES - THE ABSENCE OF REAL-TIME MATERIAL FEEDBACK TO HABITUS

5: THE SEAMLESS TRANSITION FROM DIGITAL TO PHYSICAL - THE DDF GOAL

6: THE EMERGENCE OF ERROR

Figure 8: The Relationship between SES System, *Habitus*, Craft Production and DDF

4.3 Case Studies of Craft

The following case studies apply the SES Model to two examples of the material craft of glass blowing by Peter Houk, Director of the MIT Glass Lab.

4.3.1 Petrotopia

Figure 9: 'Petrotopia' by Peter Houk

Figure 10: The Preparatory Sketch for 'Petrotopia'

‘Petrotopia’ is an artifact consisting of a set of hand crafted bottles. Comparing the hand crafted physical artifact of 'Petrotopia' to the preparatory sketch one is struck by two differences – the shape of each bottle in the sketch is different while the bottles in the artifact are similar to each other and that while the sketch shows five bottles the artifact has six. These observations show that the sketch does not prescribe dimensions of the physical artifact, but is indexical. The differences in shape of the sketched bottles show that there are likely to be indeterminate factors in the value adding processes that will give the bottles their final shape. Had the preparatory sketch been stereometric or steriotomic the design process would consider the results of the indeterminate processes to be errors.

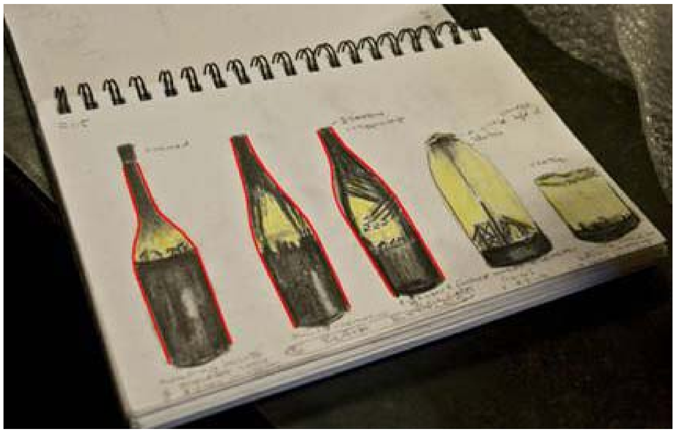


Figure 11: The Differing Bottle Profiles in the Preparatory Sketch

Figure 12: The Relationships between Consecutive Bottles in the Preparatory Sketch

The bottles were blown by Peter Houk in sequence from the largest to the smallest. It was only after the first (largest) bottle was blown and given a precise form and dimensions did the forms and dimensions of the subsequent bottles get determined. The diminishing sizes and the irregular tops of the bottles were created by 'breaking' the bottles during blowing and then annealing them to strengthen the sharp edges. The 'breaking' process is an indeterminate one and if one recognizes that the preparatory sketch denotes the relationship of one bottle to the next bottle in sequence and that of the first bottle to the last, then, it follows that the actual number of bottles in the artifact can not be determined till the results of the 'breaking' is known. Thus, during production the breaking of the fifth bottle resulted in a bottle that was taller than that shown in the sketch so an additional bottle was required to be made to preserve the relationship between adjacent bottles and the first and the last bottles. Thus what would have been considered an error as an indeterminate “deviation from the norm” (Dutta, p. 211, 2007) was incorporated as deviation as “a fecund miscomputation” (Dutta, 2007 p. 212) through the SES system.

4.3.2 Christmas Glasses

The Christmas Glasses are a set of hand crafted drinking glasses produced by Peter Houk as Christmas presents for his family and friends. The production of the second glass in the set of Christmas Glasses illustrates the process of sensing-evaluating-shaping in detail. Based only on an idea of the “kind of proportions” he wanted to achieve, Houk set out to make a set of glasses as a Christmas present. Drinking glasses are a category of object that is well established in glass blowing technology and that is a part of Houk's *habitus*. Thus preparatory sketches were only of possible patterns on the glasses, not of the entire object or set of objects as in the case of the ‘Petrotopia’. These preparatory sketches were accompanied by procedure notes detailing the key steps in achieving certain kinds of pattern effects in glass as shown below.

Based on an idea of the “kind of proportions” and the procedure notes, Houk produced the first glass of the set. The precise dimensions of this first glass constrained the dimensions of the subsequent glasses to be made. Thus the height and diameter of the first glass were noted and the circumference was found using a pi-caliper. The circumference and height of the first glass were used to measure the amount of raw glass required for the second glass.

Figure 13: Measuring Material Based on the Size of the First Glass

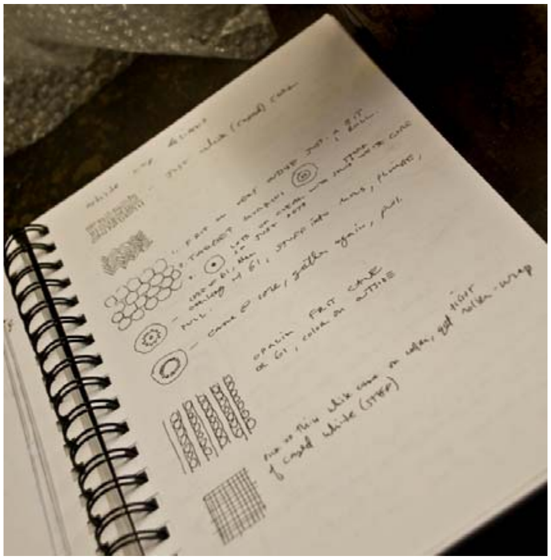


Figure 14: The Preparatory Sketch

As can be seen from the pictures above, the raw materials used consisted of irregularly broken pieces of irregularly patterned glass rods. The raw materials used may therefore be considered to be irregular in dimension and material properties. The raw materials were then put through a series of value adding processes with indeterminate outcomes.

At the end of these processes, once the glass began to acquire some of its final properties, the process of sensing-evaluating-shaping began. The calipers that were initially fixed to the dimensions of the first glass were compared to the dimensions of the second glass after every indeterminate step. The information gained from these comparisons was used to determine the subsequent steps.

Figure 15: Sensing-Evaluating-Shaping

It can be seen from these observations that deciding which dimensions are to be measured in the sensing-evaluating-shaping process was a trivial task, but the glass blower required a very detailed mental model of the process to decide on when to record these measurements so that they are meaningful with respect to the value adding processes. This task requires the glass blower to have a detailed and complex ontology of the production process. Similarly, evaluating the information obtained from the measurements to influence the indeterminate value adding processes is a dynamic task requiring Houk to remember and contextually apply the procedure notes made at the start of the process. Lastly, performing the actual actions required to influence the value adding processes as needed requires complex manual skills.

If one looks at the production of the whole set of glasses, the dimensional attributes of the first glass fixed those of the subsequent glasses produced and any deviations from these attributes would have resulted in errors. However, the exact visual character of the patterns formed on each glass informed the patterns of the subsequent glasses. That is, Houk started with only a set of possible patterns for the glasses, not the exact patterns on each glass. As the individual glasses were produced, the indeterminate character of the patterns on each glass informed the patterns of the glasses produced subsequently based on Houk’s evaluation of his unarticulated vision for the set of glasses as a whole thus incorporating indeterminacy through “fecund miscomputation” (Dutta, 2007 p. 212). While the overall vision was left unarticulated in this case, the relational preparatory sketch made for the ‘Petrotopia’ shows how such a vision may be articulated.

The reason for the lack of an overall preparatory sketch in the case of the Christmas glasses can be attributed to the drinking glass being a type of object that Houk was familiar with, and thus required only an idea of the “kind of proportions” he wanted to achieve and sketches of the patterns he wanted to create on the glasses. ‘Petrotopia’, however, was a unique artifact where Houk was attempting something he had not attempted before (that is, the production of a series of etched bottles of diminishing height using the process of ‘breaking’ the bottles during production).

An important point to note from this case study is the way the sensing-evaluating-shaping process is dictated by the pace of the material processes. Thus the sensing and evaluating have to take place in real time so as to be able to gather information about the artifact that is otherwise impossible to predict, and then influence the value adding process in time to achieve the desired properties in the artifact produced. Looking at this process from a constructionist perspective (where “The richer the set of representations of the object, the more ways we have of interacting with it, the more concrete it is for us” (Wilensky, 1991, p. 198)), this real time design decision making and execution allow the craftsperson to have a more concrete representation of processes and properties that are otherwise indeterminate in a non-craft design process.

5.0 PRECEDENTS INTEGRATING DDF AND CRAFT

The following precedent studies look at attempts to integrate digital design and fabrication with craft in different ways.

5.1 The SensAble Phantom

The SensAble Phantom is the first “commercial desktop haptic feedback system... [that] allows the user to feel and press on the surfaces of virtual component geometry by applying force feedback when the cursor comes into contact with the digital object” (Evan, Wallace, Cheshire, Sener, 2004, p.490). The makers of the SensAble Phantom claim “that precise and intuitive design changes can be easily made” (Evans et al., 2004, p.490) by incorporating it into the design process. “Haptic devises have been defined as ‘technology that provides sensing and control via touch and gesture’ and a haptic feedback device translates these sensations to the operator (Hodges, 1998)” (Evans et al., 2004, p. 489).

Figure 16: The SensAble Phantom Haptic Device (Source: http://www.sensable.com/)

The effects of this system on design was evaluated by Evans and others (2004) in the process of designing and prototyping a toaster. In this study, the SensAble Phantom system was used at two stages in the design process. First, in the virtual 3D modeling of the overall form of the toaster from hand sketches and then for creating a textured surface finish for one part of the toaster. The study concludes that the system was unsuccessful in modeling the overall form because “the outcome of the FreeForm/Phantom tactile interaction was a degree of undulation on curved surfaces that was considered unacceptable for both rendering and downstream tooling operations” (Evans et al., 2004, p. 499). The unresolved dichotomy between the “undulating” form produced by haptic feedback and the requirements of “downstream tooling” operations clearly illustrates Dutta’s (2007) concept of 'the human as error' with respect to industrial production processes.

The use of the system for the production of a textured surface with a “hammered” effect required the designers to experiment with the haptic property of “hardness” of the virtual material being “hammered”. The haptic system created “an extremely close association to working with a physical material. Each individual blow delivered to the virtual surface was felt by the designer who could precisely control the positioning and depth of deformation. Nonetheless, some of the blows onto the component surface were unsatisfactory (i.e. too deep, shallow or in the wrong place)... these errors could be easily deleted and another attempt made to achieve the required effect” (Evans et al., 2004, p. 500-501).

The fundamental difference between this haptic feedback system and Craft Production is that design and physical production are still separate in the haptic feedback system. Since the material being worked on is virtual, uniform and produced by predictable computational processes, the only source of Unpredicted Attributes in this system is the human agent. These Unpredicted Attributes of human action are therefore not stimulated by Unpredicted Attributes of the material. Additionally, since design and production are separate processes, the design can not take into account any unpredictability in the actual, non-virtual, physical production processes.

5.2 Reverse Engineering a Work of Craft

Soo, Yeun and Yu (2005) study the issue of reverse engineering a hand crafted object. The object selected for their study is the framework of a ceremonial lion head made of split bamboo tied with strips of paper. The authors define reverse engineering as “the process of capturing the three-dimensional object form and transferring it to a computer compatible representation (i.e. a CAD model).” (Soo, et al., 2005, p. 3). The digitizing technology selected for the object in the study is a “human triggered contact type 3D digitizing portable measuring device” (Soo et al., 2005, p. 3) commonly called a digitizing arm. “The physical bamboo split is digitized into virtual three-dimensional points along its shape.” (Soo et al., 2005, p. 3) The points thus obtained are connected to form curves. The authors state that since “Every bamboo split has its own dimension” (Soo et al., 2005, p. 2), these were represented by rectangular cross-sections of three standardized sizes which were swept along the curves. The digitized points along the irregular cross-sections of bamboo “require additional positioning [by the authors] in order to become a smooth curve” (Soo et al., 2005, p. 2). This smoothing of curves along with the replacement of irregular cross-sections with standardized rectangular sections cause the strips of bamboo in the virtual model to overlap and intersect each other. Also, the authors are not able to propose a technique to reverse engineer the paper knots holding the strips of bamboo together “because of its arbitrary and irregular shape” (Soo et al., 2005, p. 6).

The CAD model of the craft object thus obtained attempts to eliminate the Unpredicted Attributes inherent to the natural bamboo used as well as the Unpredicted Attributes resulting from human actions in response to the material in the form of the “ arbitrary and irregular” (Soo et al., 2005, p. 6) paper knots. The approach of the authors in smoothing the curves of the bamboo and using standard cross-sections considers the craft object from the point of view of industrial production and therefore results in “errors” in the form of intersecting bamboo members and is unable to negotiate the paper knots and thus results in an inadequate CAD model. The solution proposed in the study is to create a connected node graph that records the positions of bamboo strips at the knots and can be used to correct the errors of intersecting members. This proposal is reminiscent of the dichotomy between the Kantian concept of geometry as ‘reason’ – an “internally consistent set of principles… [that do not rely on] nature… [to stimulate] empirical chance insights” (Dutta, 2007, p. 83) as opposed to the oriental conception of geometry that is based on the physical production of patterns and is thus “entirely subordinate to the skill of the artisan” (Dutta, 2007, p. 85).

5.3 Chesa Futura: DDF and Craft

The Chesa Futura (House of the Future) at St Moritz, Switzerland, by Foster and Partners “fuses state-of-the-art computer design tools and traditional, indigenous building techniques” (Whitehead, 2003, p. 94). The building was designed using a parametric model to coordinate the complex form of the external envelope with construction details using 3D models and rapid prototypes at different stages of design. The building consists of a structural shell consisting of “full-size ribs [that] were CNC fabricated from glue-laminated beams – thin layers of wood glued together under pressure” (Whitehead, 2003, p. 98) and a cladding of “timber shingles, cut with an axe by an 80-year-old local expert, and nailed on by hand by the rest of his family” (Whitehead, 2003, p. 98).

While there is no doubt that the cladding would have required the 80-year-old local expert and his family to respond in indeterminate ways to indeterminate properties of timber, this has no bearing on the CNC fabricated structural shell that was made of glue-laminated members. The only integration between the two construction methods took place in the last of a series of rapid prototypes where

“The shingles were modeled in strips of etched brass which were applied on the course lines and then painted over. Due to the level of detail achieved, this model allowed us to rehearse all the key aspects of the full-scale assembly process and to discuss points of detail with the craftsmen involved.” (Whitehead, 2003, p. 98).

5.4 The Case Western Reserve University: Scaled Material Representations and Reverse Engineering

The Case Western Reserve University building by architect Frank Gehry was designed after his design techniques had matured during the construction of the Bilbao Museum and the Disney Concert Hall. The exterior of this building consists almost entirely of developable surfaces made of metal shingles supported on a steel frame structure. The exterior form of this building was generated by making a physical model out of a rigid paper that would form only developable surfaces. This paper exterior model was digitized and a structural steel frame was designed on the computer to support the building.

This design technique used for this building is interesting in that it starts with a physical model unlike the Chesa Futura which started with a digital parametric model. The design exercise with the paper model can be thought of as a craft process where the designer could respond to the developable surfaces formed by the rigid paper with design responses that would otherwise be indeterminate. While it is possible to achieve the same forms through computer modeling, a physical design medium was chosen due to its speed and intuitive (physical) interface (Glymph, 2003, p. 115). While it is possible to computationally generate developable surfaces in a CAD environment, developability is an Unpredicted Attribute in the physical design medium. Thus the forms achieved with rigid paper are indeterminate to the designer in the physical design medium until they are achieved physically. Once the physical model was digitized the rest of the design and fabrication process was computer controlled using parametric design software and digital fabrication

Looking at the design process as a whole, the form finding paper model could be thought of as a craft process, but one which did not deal with material properties which are computationally unpredictable in an absolute sense. It was only a matter of convenience that physical models were used instead of digital ones and that the properties of paper in the model were representative of the properties of metal at full scale.

6.0 DDF AND THE SES SYSTEM

What makes Craft Production using the SES Model unique is that it allows otherwise indeterminate processes to occur and then responds to them after sensing their result. Based on the precedent studies in the previous section the process of reverse engineering – “the process of capturing the three-dimensional object form and transferring it to a computer compatible representation (i.e. a CAD model)” (Soo et al., 2005, p. 3) – is one analogue of Sensing in Craft Production using digital technology. However, the three-dimensional form of an object is only one of many attributes of an object that can be Sensed during Craft Production. Traditionally craftspersons have used all five senses. Blacksmiths and potters, for example, regularly use sound to test material integrity, chefs (arguably craftspersons) use smell and taste. Contemporary technology, in the form of x-ray, sonar, magnetic resonance imaging (MRI) etc. provides digitizable counterparts to human sensory perception. These digital sensing technologies are potential processes for integrating DDF with Sensing in Craft Production.

Once information resulting from indeterminate processes has thus been digitized it can be manipulated in a digital environment. If the goal of the information manipulation is to produce a physical object then the manipulation of this information can be correlated to Evaluating (defined as the relationship between the Design Process and a Design Attribute) in Craft Production. Directly transforming a digital Design Attribute into a physical attribute of an object requires the process of digital fabrication (i.e. the use of CAD-CAM for fabrication) which can be compared to Shaping (the relationship between a Design Attribute and a Craft Process used to physically create it).

The identification of these areas of similarity between Craft Production and DDF creates a framework for digital design (defined as “a self-contained way of designing exclusively within a computational environment” (Oxman and Sass, 2006, p. 333)) to negotiate phenomena which can not be modeled “exclusively within a computational environment”.

6.1 Digital SES and Natural Processes

Figure 17: the Branch Bookend

The Branch Bookend is an object testing the possibility of integrating SES with DDF. The objective in this study was to try and integrate the very complex natural form of a tree branch that can not be exactly replicated algorithmically, in a timber bookend. With this objective in mind a piece of scrap timber and a tree branch were obtained. The piece of timber had been discarded due to the presence of a large knot in it. This knot was a part of an interesting pattern in the grain of the timber that marked the origin of a branch in the tree from which the timber was obtained. It was decided to attach the tree branch so that it appeared to be a part of the original branching tree that had left a pattern in the timber. This required that a negative of the form of the branch be created in the timber such that the branch could fit in it.

In order to do this the branch was 3D laser scanned using a Minolta VIVID 910 Non-Contact 3D Digitizer to obtain a point cloud of the side of the branch to be fixed to the timber. The point cloud obtained from the 3D scanner was imported into Rhinoceros 4.0 to obtain a series of contour lines of the surface. The contour lines were then used to create a surface that was the inverse of the branch surface. This inverse surface was CNC milled into two locations on the timber to allow the tree branch to attach in a manner integrating it with the grain pattern on the timber.

Obtaining the digitized representation of the surface of the branch surface constituted the digital version of Sensing. Evaluating – to obtain a Design Attribute – involved the digital process of creating the inverted branch surface and the non-digital process of locating where to mill the surface on the timber. The transformation of the Design Attribute into a physical object – Shaping – was done using a CNC router to mill out the surface and the human hand and eye to position the timber for milling in the right place. Thus DDF techniques of designing in a digital environment and the use of CAD-CAM for fabrication are shown to be able to negotiate the indeterminate phenomena of the branch form and timber grain through an SES Model.

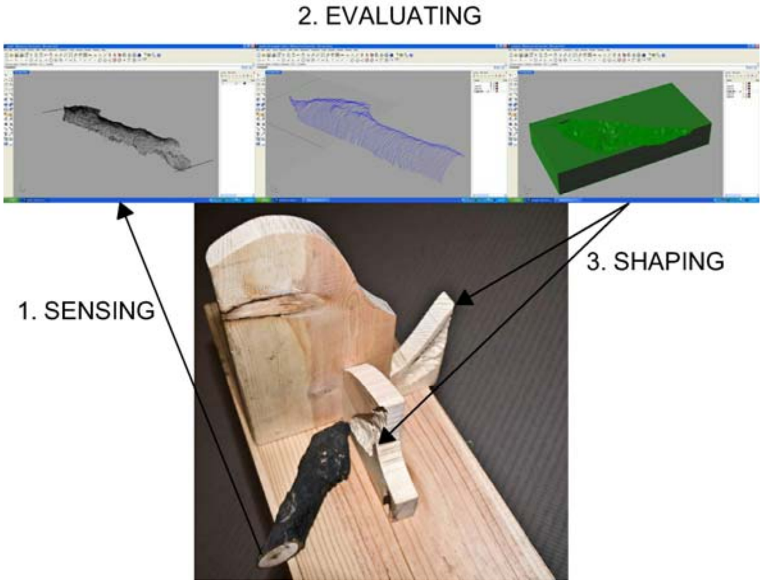


Figure 18: Digital SES

6.2 Comparing Digital SES and DDF

Design Structure Matrices (DSMs) are a systems analysis and project management tool. “It enables the user to model, visualize, and analyze the dependencies among the entities of any system and derive suggestions for the improvement or synthesis of a system” (Lindemann, 2009). In a DSM representation each component of a system is placed once in a row and once in a column to form a matrix. Therefore the matrix is always square with equal rows and columns. The DSM is read one row at a time moving from top to bottom and left to right. If a cell in the matrix at the intersection of the second row and the first column contains a mark, this implies that a change in the component in the first column causes change in the component in the second row. The order of components along rows and down columns is the same and generally corresponds to their sequencing in time. Marks in cells below the diagonal of the matrix indicate that the information flow/dependency is a “forward information link” (marked in green) while marks in cells below the diagonal indicate a “feedback link” (marked in red) where “an upstream task is dependent on a downstream task” (Lindemann, 2009).

The following is a comparison of the digital SES joint in the Branch Bookend with a typical digitally fabricated friction fit joint, using DSMs.

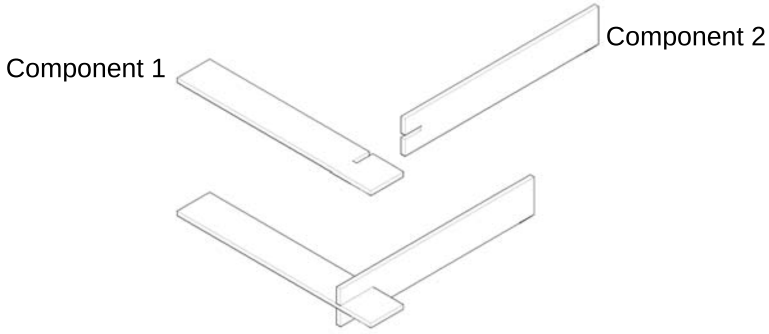
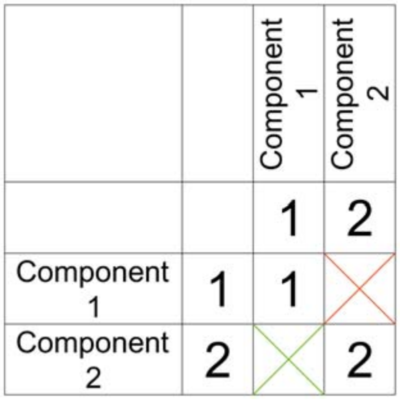
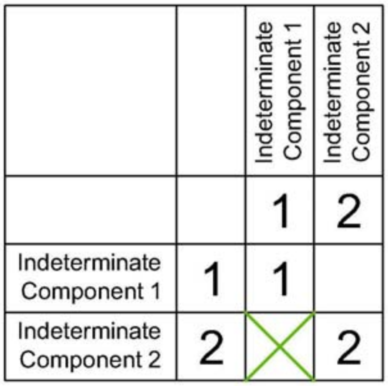


Figure 19: A Typical DDF Joint Between Two Components



		Component 1	Component 2
		1	2
Component 1	1	1	✗
Component 2	2	✗	2

Figure 20: A DSM for a Two-Component DDF Joint



		Indeterminate Component 1	Indeterminate Component 2
		1	2
Indeterminate Component 1	1	1	
Indeterminate Component 2	2	✗	2

Figure 21: A DSM for an SES Joint

6.3 Digital SES and Craft Processes: The Digital SES Dovetail Joint

The example of the Branch Bookend takes into account only those unpredicted attributes that are a result of natural processes. Craft production, however, is the result of unpredicted attributes from natural processes and those arising from craft processes intentionally initiated by a human agent. The Digital SES Dovetail is an example involving unpredicted attributes from natural and craft processes.

Figure 22: A Traditional Dovetail Joint

A traditional dovetail joint comprises pins carved from one member and dovetails carved from the second member of the joint. The dovetails fit into the pins forming the joint. In order to make the dovetail, the pins are hand carved in the first member based on the direction of the grain, the thickness of the second member, the size of the chisel, the strength of the wood and other such indeterminate factors. The carved pins form a template for the profile of the dovetails which ensures that the pins and dovetails fit together. The profile is transferred to the member to be dovetailed by tracing it with a pencil and then carving along the traced lines. This is a clear example of SES in craft production – using the pins as a template is a form of sensing the indeterminate result of the craftspersons actions in response to the indeterminate properties of the timber. The indeterminacy of the craftsperson’s actions are a response to indeterminate material and physical phenomena as well as the craftsperson’s training in a social context resulting in the formation of *habitus*.

Figure 23: SES in the Production of a Traditional Dovetail Joint

The DSM for a dovetail is the same as that of the Branch Bookend with the dovetailed member being dependent on the member with pins. The dovetailed member may be produced by digital SES where instead of tracing the profile of the pins and using the profile to carve by hand, the profile of the pins is scanned on a flatbed scanner and the resulting image traced in a CAD environment. The CAD traced profile is then used to laser cut the dovetailed member[1]. Since the profile of the dovetails is dependent on the pins and a deviation from this profile would hinder the joining of the pins and dovetails, such a deviation would be an error. The introduction of digital SES to produce the dovetails reduces this error since there is more control and thus fewer resulting unpredicted attributes as

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[1] The use of 1/8” thick fiber board for the dovetailed member was due to the inability of the available CNC router to cut a sharp interior corner required in a dovetail joint. While the laser cutter available was able to cut a sharp interior corner it was unable to cut the 3/4” timber used for hand carving the member with pins. This shortcoming was a result of the immediate circumstances and does not reflect any inherent inability of CNC fabrication machines.

compared to hand carving while still allowing a craftsperson to respond to indeterminate properties based on *habitus*.

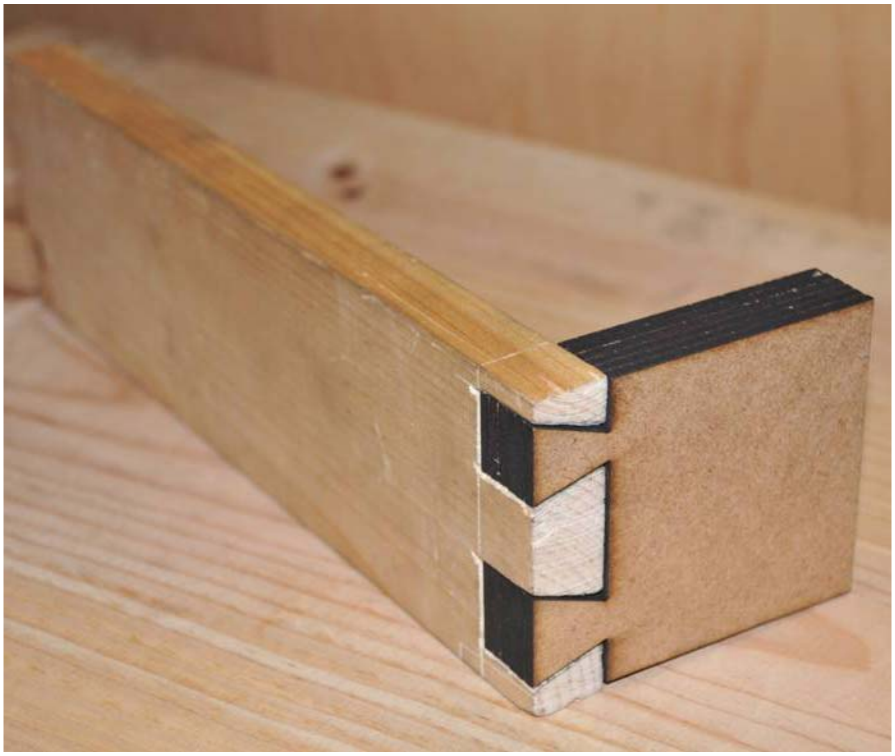


Figure 24: A Digital SES Dovetail Joint

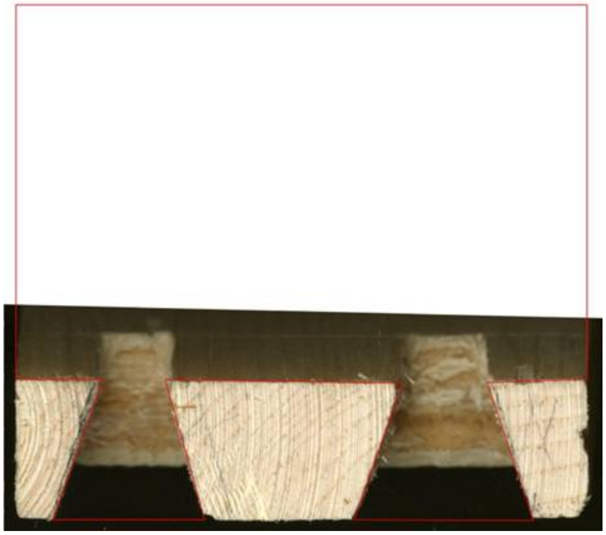


Figure 25: Scanning and Tracing the Pins Using CAD

6.4 The Digital SES Bamboo Notch Joint: The SES Approach to Reverse Engineering

While the Digital SES Dovetail shows how DDF and craft processes can be combined through digital SES the 3/4" timber used in the joint requires extensive preparation resulting in its regular orthogonal shape. The Digital SES Bamboo Notch Joint once again follows the same DSM of one member of the joint being dependent the other. Compared to 3/4" timber, bamboo poles require less preparation and thus have more irregular forms and profiles that are the results of indeterminate processes. Selecting appropriate pieces of bamboo for a structure and the points along the bamboo to position joints for maximum strength are some of the indeterminate, *habitus* based design decisions a craftsperson must take while building with bamboo. Once these decisions have been taken various techniques of joinery exist for actually constructing a joint between two pieces of bamboo. One such method involves cutting out a notch in one member to allow the second member to sit in and then lashing the joint together with rope. Traditionally the notch is carved approximately resulting in less control of the angle of the joint.

Figure 26: Digital SES in the Bamboo Notch Joint

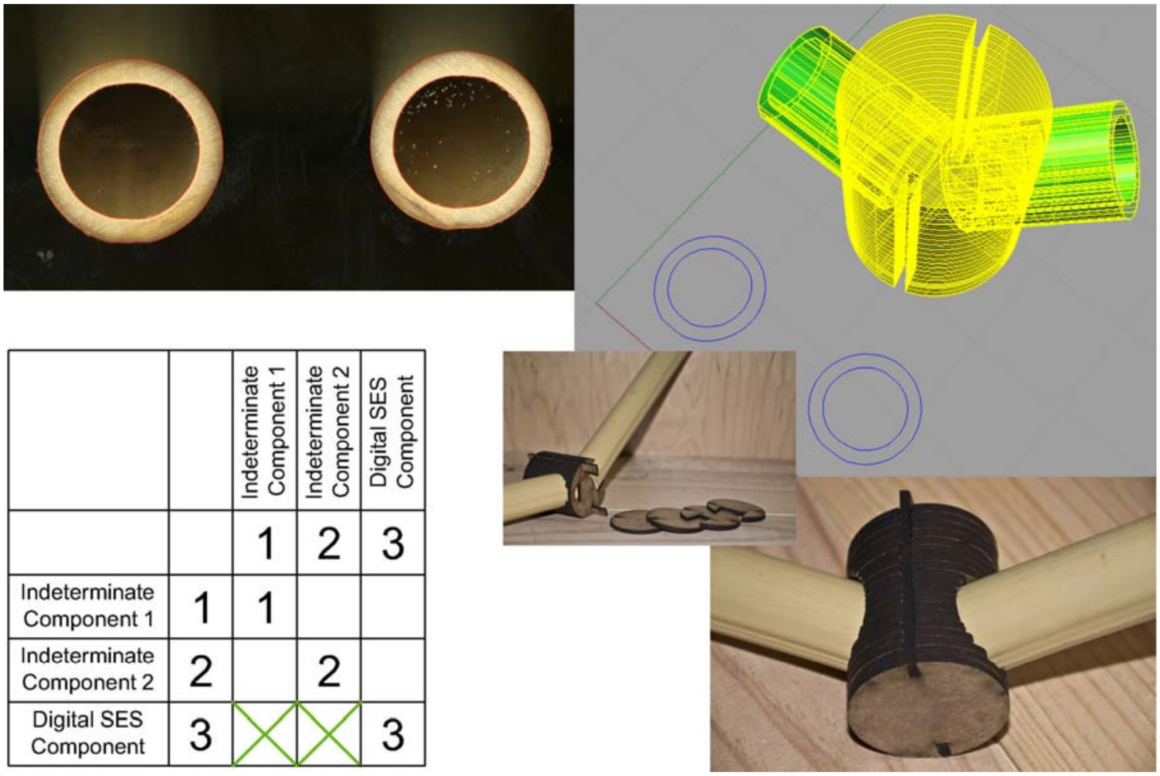
The Digital SES Bamboo Notch Joint requires that one member of the joint be reverse engineered using three scans from a flatbed scanner that are used to create a 3D CAD model. This enables its precise profile to be cut into the second member to the required depth and angle using a CNC router. The two members thus form a precise angle and can be lashed together with rope traditionally.

The difference between the reverse engineering process described here and that used in the case study of the ceremonial lion head (see Section 5.2) is that in the study of the ceremonial lion head the reverse engineering process attempts to impose an idealized geometry ignoring the indeterminate “arbitrary and irregular shape[s]” (Soo *et al.*, 2005, p. 6). In the Digital SES Bamboo Notch Joint, on the other hand, the purpose of reverse engineering is to record and digitize those attributes that are otherwise indeterminate so that these unpredicted attributes can inform the design. The indeterminate nature of the attributes to be digitized implies that the craftsperson must determine what information from the physical artifact needs to be digitized. This will therefore require the craftsperson to act in an indeterminate way based on *habitus*.

6.5 The Layered Bamboo Node

The DSM analysis of the Branch Bookend illustrates one way to overcome the feedback loop in a typical DDF joint. Another method for resolving the feedback is to introduce a third node component in addition to the two members of the joint. The design of the node connects the two members and is dependent on both members such that there is no longer feedback between them. The form of the node is based on the shape of the members and the angle required between them. Thus the members are reverse engineered to allow the complex form of the node to be designed in a CAD environment. The 3D model of the node is divided into layers that can be individually laser cut from flat material and stacked to form the Layered Bamboo Node. The connection between the node and the member gains strength by making use of the kink in the shaft of the bamboo at the nodes. The exact form and location of the nodes are indeterminate and require SES in order to be incorporated in the design.

For the sake of simplicity, the node is considered to be a single component in the DSM analysis rather than considering each layer of the node as a different component which will increase the size of the DSM matrix without aiding the analysis.



		Indeterminate Component 1	Indeterminate Component 2	Digital SES Component
		1	2	3
Indeterminate Component 1	1	1		
Indeterminate Component 2	2		2	
Digital SES Component	3	☒	☒	3

Figure 27: A Layered Bamboo Node and its DSM

The Layered Bamboo Node was used in two projects – the Bamboo Triangle and the Bamboo-Glass Joint. In the Bamboo Triangle project the objective was to create a triangle with three pieces of bamboo using the Layered Bamboo Node. The lengths of the bamboo extended from node to node and were thus indeterminate. The bamboo members were reverse engineered and the joint angles required for triangulating them were found using parametric modeling. The shapes of the nodes were obtained from the shapes of the bamboo members and the angles required between them, and then divided into layers which were cut out of 1/16” Plexiglas on a laser cutter. These components were assembled to form the Bamboo Triangle.

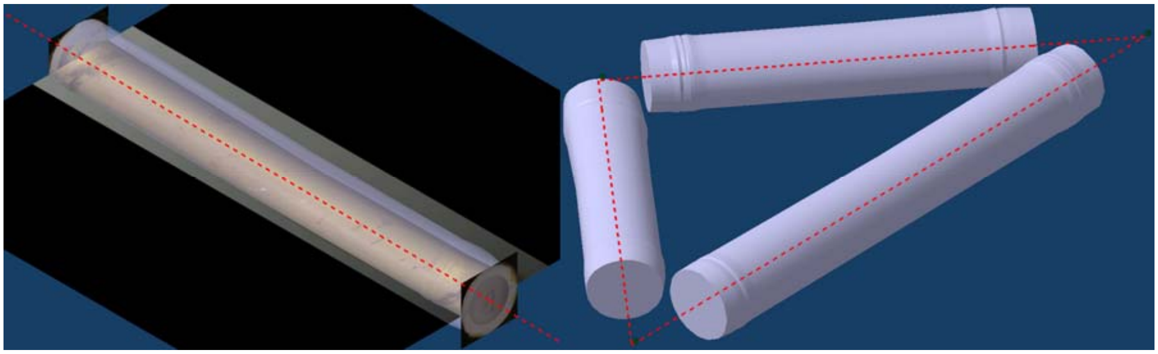
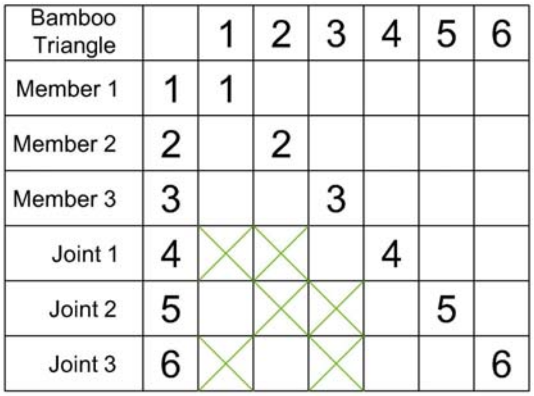


Figure 28: Reverse Engineering and Triangulation for the Bamboo Triangle

Figure 29: The Bamboo Triangle



Bamboo Triangle		1	2	3	4	5	6
Member 1	1	1					
Member 2	2		2				
Member 3	3			3			
Joint 1	4	☒	☒		4		
Joint 2	5		☒	☒		5	
Joint 3	6	☒		☒			6

Figure 30: A DSM of the Bamboo Triangle

In the Bamboo-Glass Joint project the Layered Bamboo Node was used to resolve the dependencies between four components – three bamboo members and a hand crafted glass object. The aim of this project was to create a node with the glass object at the centre and have the bamboo members radiating out from it at an angle of 120 degrees. The three bamboo members and the glass object were reverse engineered and the form of the node was obtained through 3D CAD modeling. The node was divided into layers which were laser cut and to assemble the joint.

Figure 31: The Bamboo-Glass Joint

Increasing the number of components that the node depends on increases its complexity. It is the use of digital design environments that allows the resolution of these dependencies and digital fabrication enables the manufacture of the complex form of the node. The importance of SES in this process is highlighted by the irregularities in the thickness of the Plexiglas material used for the nodes. Assuming a standard thickness for the material resulted in a node that was not of the correct dimensions for the joint. In order to resolve this error multiple layers of the flat material had to be measured to obtain an average material thickness for the layers.

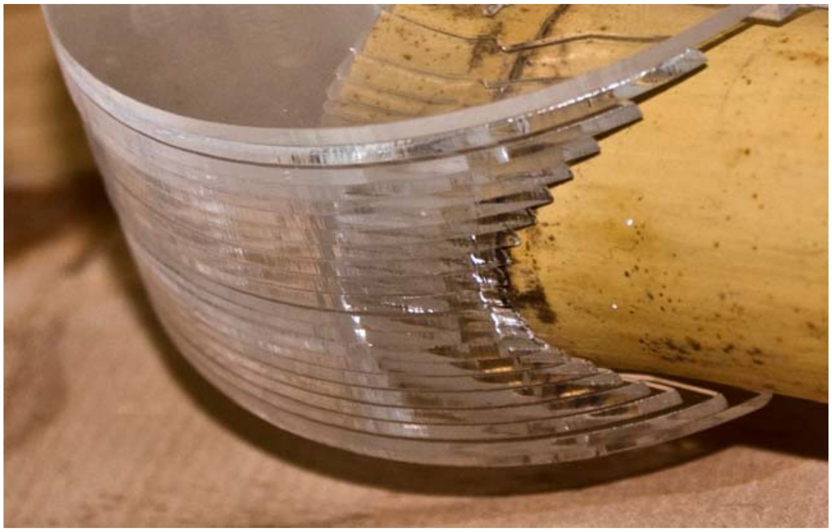


Figure 32: Errors in the Layered Joint due to an Assumption of Layer Thickness

Figure 33: Smaller Error in the Layered Joint after Measuring (Sensing) Layer Thickness

7.0 CONCLUSIONS AND FUTURE DIRECTIONS

The conclusion of this thesis is that the indeterminacy of natural materials and manual processes that are characteristic of craft are not incompatible with the tools of DDF. Craft production negotiates indeterminacy through the use of the Sensing-Evaluating-Shaping (SES) System. The SES System integrates design and production in an iterative process where physical and informational processes can inform each other continuously. Sensing involves the gathering of information from physical processes; Evaluating transforms the information to an attribute that is desired from physical processes; and Shaping involves the transition from informational to physical only to return to the point where the physical is transformed to information through Sensing.

Digital SES provides a framework that enables DDF tools to be used in an SES System. Sensing thus involves digitizing the information resulting from physical processes; Evaluation can thus be performed in a digital environment and digital fabrication can be used in the transition from informational to physical. This is in contrast to the DDF workflow which aims for an “effortless transition from digital to physical artifact” (Botha, 2006, p. 15). Thus digital design environments and computer numerically controlled fabrication devices to interact with computationally indeterminate physical and social phenomena in design. The results of such interactions can range from solutions for overcoming processes such as warping in DDF to the use of complex algorithmic procedures in craft production.

Having found a middle ground between DDF and craft, the broader design implications of this synthesis may now be further explored. Possible applications for digital SES could be combining performance based generative design methods from design computation (such as scripting and parametric design) with non-industrial materials with indeterminate properties using indeterminate processes of construction to create low energy performance buildings with low embodied energy.

The Fab Lab program of the Centre for Bits and Atoms at MIT aims to allow ordinary people to satisfy their “desire to measure and modify the world as well as access information about it” (Time Inc. and Time Warner Publishing B.V., 2007, para. 5) by providing access to digital fabrication tools through a “cross between microfinance and venture capitalism” (Time Inc. and Time Warner Publishing B.V., 2007, para. 6) in under served areas of the world. The process of measuring and accessing information about the world – sensing – and modifying the world – shaping – are the essential ingredients of craft production. Digital SES offers a design framework to allow digital fabrication technology to be integrated into indigenous craft processes that form a part of local social and environmental contexts.

Papanikolaou (2008) differentiates two kinds of value chains describing how buildings can be fabricated and assembled – the traditional value chain and the digital value chain. A value chain explains how materials are fabricated into building components and these components are assembled to build a building. In a traditional value chain fabrication and assembly take place on the construction site allowing the builder to take spontaneous decisions in response to unforeseen circumstances. A digital value chain involves off-site digital fabrication of building components which are then assembled on site. Here “all decisions have to be taken before production starts... [and] the assembler can not use his experience to assemble a number of pre-manufactured parts because the assembly sequence is already determined by the designer. As a consequence, any mistake during design process is irreversible if manufacturing of parts has taken place.” (Papanikolaou, 2008, pp. 22, 23). The difference between a traditional value chain and a digital value chain is what I had experienced while working on the bamboo structure and the stainless steel structure described in section 1.1. The digitizing of indeterminate material properties and the digitizing of the results of indeterminate processes in digital SES allow an individual to analyze the construction system and spontaneously react to indeterminacies within a digital design environment while making use of digital fabrication. The digitizing of design information additionally enables the remote exchange of data between collaborators like in a digital value chain while allowing them to respond to unforeseen circumstances. Another field that is taking steps in this direction is teleoperated surgery. “Teleoperators are machines designed to allow a user to manipulate objects in a location remote from his own.” (Madhani, 1999, p. 22). Teleoperation technology thus allows the sensing and digitizing of relevant data from indeterminate materials and processes (human tissue and complex biological processes in case of surgery), the transfer of this data to a remote human user (surgeon), the recording and digitizing of the indeterminate responses of the human, and the digitally controlled remote execution of these responses.

However, in order to use digital SES as a feasible design framework it will require the development of digital design environments which are based on a geometry that, in the words of Dutta (2007) rely on “nature” to stimulate “empirical chance insights” (p. 83) and are thus “entirely subordinate to the skill of the artisan and in no way supposes reasoned scientific knowledge of geometry” (p. 85). Shape grammars stand out as one possibility for basing such a geometric tool due to their ability to perform shape based computations without the imposition of predetermined geometrical relationships (Stiny, 2006).

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