Optimization Takes Command[1]: Miscalculations in Performative Design

DORIS SUNG
University of Southern California

As the *natural* in nature gradually disappears, research's obsession with simulating, replicating, deviating, and mutating nature as means to control the extinction of that same organic world around us, ironically increases the realm of artificiality and, ultimately, the dependency on math, sciences and technology. Design research is no exception, where the notions of optimization are derived from the self-perpetrating obsessions with math and science, reliance on algebraic or logarithmic equations for geometry generation, and the dependence on the logic of the physics of nature for identification of the lowest energy states. This same pursuit of optimization has profoundly influenced decision-making in the design process. In many cases, efficient use of materials, effective selection of design/construction strategies, lower energy use and minimal waste have affected the choices that are made from schematic design to construction, and add to the traditional pressures of cost effectiveness and densification of planametric space. Engineers have become integral players of schematic design teams, playing larger roles in the integration of structural and M/E/P systems in order to prevent unnecessary redundancy throughout. Additionally, newly available and powerful computer software makes the realization of optimization of complex shapes, fluid parameterization, unimaginable forms and material feasible. Never before have we been able to make, test and fabricate parts of architecture as we can today. As a result, projects have become more ambitious, resulting in forms and tectonics that are complex, multi-faceted and comprehensive with a definitive effect on the aesthetic outcome of a project and an indelible change on the new landscape of man. These projects have historically been limited to static systems.

Now, add dynamic input systems into this equation. Because realistically architecture must respond and mediate between multiple non-stationary variables, it is clear that the response of the architecture must also be dynamic and fluid from the large scale (programmatically) to the very small (nanomaterials). But, to understand the meaning of optimization vis-a-vis *performance criteria* in dynamic models, holistic understanding of the input, output and deviations must be considered. This paper will present projects completed by the author made of thermobimetals, where the consequences of sheer science resolution and idiosyncratic inconsistencies from logic, lead to an aesthetic of optimization, responsiveness and performance of dynamic systems, namely in the use or misuse of incomplete digital tools (scripting, programs, etc.), true understanding of fabrication tools and assembly limitations, irregular insertion of overlapping mobile components (material behavior), and wavering definition of criteria in structural systems. Although "form, structure, and material act upon each other, and this behavior of all three cannot be predicted by analysis of any one of them separately" (Weinstock, 2010), for purpose of discussion, each will be identified in its own section, but, by no means, should be considered in isolation from its intertwined context.

OPTIMIZATION OF THE COMPLICATED CRAFT

Digital tools, without dispute, have been primary promoters of optimization in recent years. Through the digital medium, ideal forms and shapes can be generated from a variety of imposed input parameters, reducing extraneous parts and producing forms and geometries that are unimaginable. Sometimes, the forms are so complex that traditional model-making methods are useless and digital models are preferred; Other times, the reliance on equation systems to generate forms produce unanticipated results. In most cases, designers rely on what they believe are the most exacting method of form-making, relative to its limited parameters and/or rule systems. One might called this method, optimization. But, the moment that outside variables are added, the continuous deviation from the ideal begins the process of compromise that challenges the concept of optimization, a relative term, and once again, confronts the appropriateness of applying an artificial model in effort to simulate reality.

In generative design processes like many other industries that form our contemporary culture, math has taken an influential role. Algorithms are the favorites of computer processing. "And it's specifically algorithms, which are basically the math that computers use to decide stuff. They acquire the sensibility of truth, because they repeat over and over again. And they ossify and calcify, and they become real." (Slavin, 2011). That new sense of truth has now invaded our built world. But, before the sense of direction is lost and what the goals of optimization should be, the value of math in design has to be rethought. How much should designers be dependent on contemporary math? Should architects really be designing for a machine dialect (i.e. scripting), where the major command is simply, "stop"?

A potentially valuable use of these digital tools is at the other end of the digital process--in its increased capability for digital-to-digital fabrication or computer-aided manufacturing (CAM). A variety of powerful digital softwares are available for developing conceptual designs for complex geometries and surface articulation, but, there are fewer choices of tools when that same design is actually prototyped and fabricated using CNC milling, laser-cutting, waterjet cutting or rapid prototyping machines. The gap between CAD (computer-aided design) and CAM lacks a direct, clear or simple method. Upon reaching satisfactory resolution of the geometries of a project in preparation of digital files for fabrication, no single program can complete the many necessary steps--unfold, unroll, and nest the complex pieces. In some cases, the programs might deceptively have the commands available, but they are limited to projects that have simplest geometries. Those same commands are not effective for surfaces that have double curvature, for example. Given the infinite number of geometries, formulas and combinations that one might see on ambitious projects, it is impossible to limit digital actions to even a series of simple commands. Each project has completely different sets of problems, demanding completely different sets of solutions. In many cases, the most direct route to resolution is finding a project's unique combination of definitions, scripting sequence and/or commands, which can be obscure and require numerous hours for resolution. The potential for error or deviation has once again increased. But given the limitation of our own software, we call this condition "optimal", which is certainly not ideal.

In the case of the *Armoured Corset* project, completed in 2009 by the author, the process of developing a script for unrolling the parts of the surface did not exist in CATIA (Computer Aided Three-dimensional Interactive Application--the software used to instantiate the surface of the model with tiles). Each surface piece was tediously completed *by hand*, not literally, but by inputting individual commands on the computer in yet a separate program, Rhinoceros. The unrolling was completed on the computer by numerous, individual commands that would uncurl each line segment, re-attached all connections, and check for closed forms by eye and not by computer. Although not ideal, the choice to pursue this "by hand" process was more reliable and less time consuming, considering the alternative at that time. CATIA and Rhino could not accurately unroll the double-curved pieces and optimization had to be temporary pushed to the wayside.

In the *Bloom* project completed in 2011 by the author in collaboration with Ingalill Wahlroos-Ritter (glass consultant) and Matthew Melnyk (structural engineer), the preparation of the CAM files adhered to digital goals more closely, but not without consequences. Tremendous time was invested in designing a digital method to unroll the surface and in testing the method for accuracy. Inventive use of Grasshopper's commands and clever integration of CATIA capabilities resulted in a seemingly simple, but creative use of available digital tools without the need to generate the fabrication pieces by hand. As speculated, this solution was not one that could be applied universally to other projects, but rather identifiable only to this project by reducing the individual hypar shapes to single centerlines.

Hypar, or hyperbolic parabaloid, shapes are defined geometrically by a double-ruled surface. An infinite amount of straight lines in two directions make the saddle-shape continuous. However, reduced to four or five ruled centerlines, the overall geometry is compromised, slightly faceted (at least to the knowing eye) and less than optimal, compared to the ideal digital conceptual model.

The translation of the digital model into fabrication files is a faulty process. Ordering systems, preferred by the logic of the program, push common sense to the wayside. Humans overriding computer programs add another layer of compromise or error to the process. Software glitches confuse files, use an illogical method of layout, and accidentally delete pieces or parts. Quality control checking is a large part of the testing process, done "by hand", where each line in the fabrication file is compared dimensionally with correlating lines in the digital model. Numerous physical prototypes are mandatory (Fig. 1). In this project, because misalignments and miscalculations would be costly, accuracy was a must, making testing and re-testing mandatory. Perhaps these steps can be eliminated in future sequences as softwares improve and the demand for fabrication increases. When considering production time, its efficiency is questionable; when relying on the accuracy of these digital models to translate complex information, its effectiveness is sporadically faulty; and, when these components support the overall geometry, its optimization is compromised.

Figure 1. The tiling system was protyped in multiple mediums before being cut in the bimetal material.

THE MEANS OF OPTIMIZATION IN FABRICATION

When considering optimization as part of the fabrication process, it is important to understand all facets of the construction process as part of the defining factors of a design approach. Digital design and construction cannot be thought of as mutually exclusive. Fabrication machinery, connection detailing and assembly process can inform the design approach with serious repercussions if not thought through carefully. In various ways, "digital technologies are enabling a direct correlation between what can be designed and what can be built," (Kolarevic, 2005) which characterizes the architect's role to be what Branko Kolarevic terms the *information master builder*.

Even though digital fabrication technology has eliminated some of the craft trades of the construction industry in the recent past, the skill of craftspeople, working in real time with real materials, cannot be ignored. Working directly with materials and tools, allow them to completely understand the building process so that when changes need to be made in the field, acceptable compromises can be made. Some, like Dan Willis and Todd Woodward, point out the changes to the industry as we move towards a digital construction process as one that "renders the skilled building trades largely obsolete and reduces opportunities for taking advantage of serendipitous occurrences during construction, eliminating the sorts of chance happenings that artists, and many architects, often find enliven their works" (Willis and Woodward, 2010). But, rather than consider these occurrences obsolete, these chance happenings will inevitably appear during the construction process.

Even if humans are eliminated from construction processes, somehow tools and machines still need be factored into the equation. The capabilities of the laser-cutting machines will limit the size of the material (thickness and piece size); the tolerances of the laser will limit the margin on the sides of the material; and, the temperature and number of passes will vary the burn on the residual material, to name a few potential factors, which are similar with other type of CAM processes. And even in the assembly process, the unit or part size has to correlate to the abilities of the robotic arm or the human hand in a reasonable manner. In the case of the *Ar-*

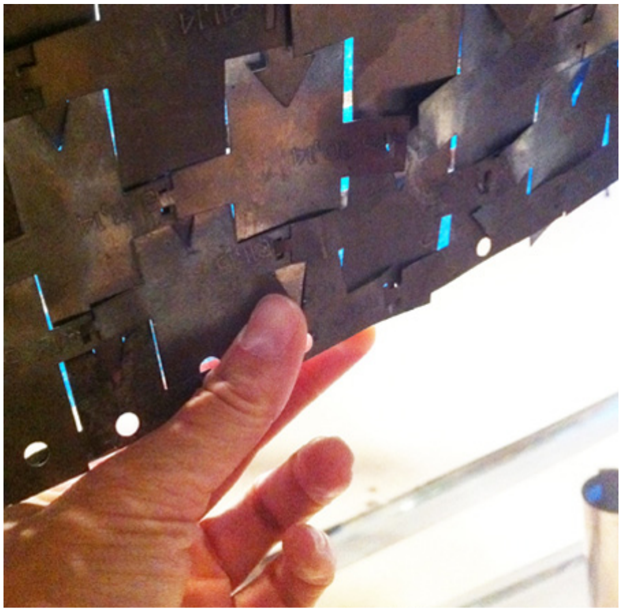
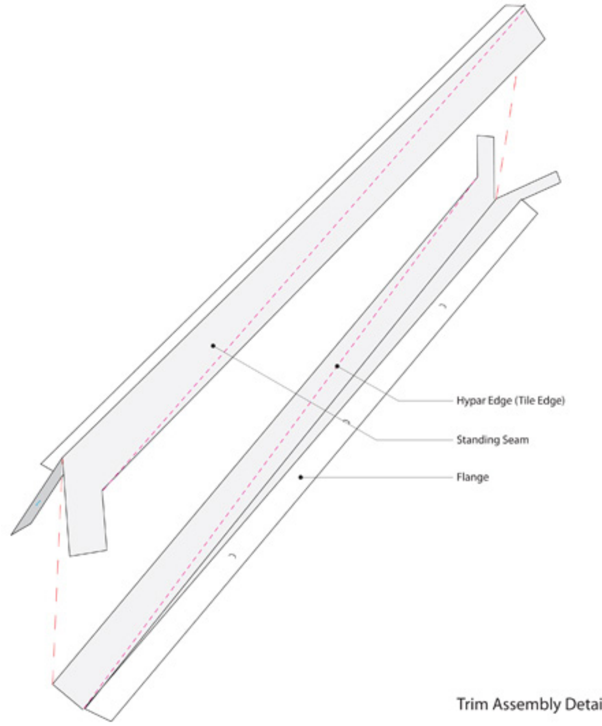


Figure 2. Proportions of details should be designed to accommodate the fabrication tool AND the assembly system.



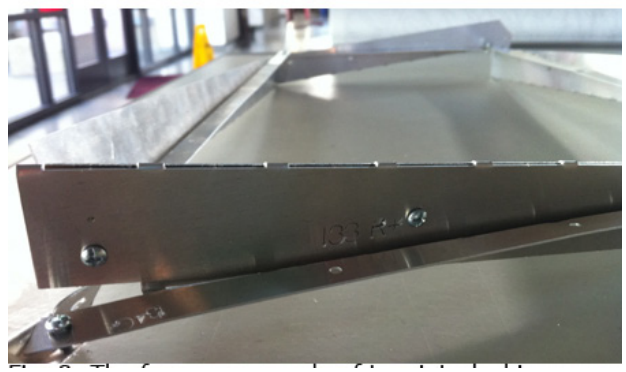


Figure 3. The frame was made of two interlocking, folded aluminum pieces.

moured Corset, some of the parts, designed to test the dimensional limits of the fabricating machine, did not take into account the difficulty of the assembly process. Some pieces were so small, tweezers had to be used to finish the tab-slot connections (Fig. 2). Additionally, force was required to pull the two pieces to together for assembly, requiring additional tools to aid in the process. In retrospect, the parameters of the surface needed to be controlled in the design phase, so that select dimensions were not smaller than the width of a person's fingers. If more advanced assembly processes were used, it would be the size of the robotic tweezers that might limit the size of the individual pieces.

As for the *Bloom* project, understanding the process of assembling the large hypar panels was a major factor in the digital design, even though the visible changes to the digital model changed were minimal. The individual members of the monocoque[2] frame system were originally designed to be lasercut and folded from a single piece of sheet aluminum. Two adjacent members of the frame would be pre-attached to the infill material so that when multiple panels were assembled, the frame and the infill would be completed simultaneously, providing instant structure. This strategy proved to be unwise in the prototype, because the entire system relied on the individual panels to conform to a specific hypar[3] shape. The framing member had to be split into two parts to allow the panels to take a rigid form before assembly on-site. The result was an improved two-part frame system that facilitated on-site assembly, while inadvertently increased structural integrity of the overall form (Fig. 3). Understanding the sequence of assembly operations informed major detail alterations, but to qualify this change as optimal is misguided. The pursuit to optimization in fabrication and assembly is heroic, but not easily measurable.

OPTIMIZATION ENCOUNTERS CHEMISTRY

The degree of optimization is relative when considering smart materials. In static systems of the past, the inherent performative nature of specific materials predetermines how to use it in an optimal manner. In some cases, when determining the ideal selection, the material palette is limited to ones with certain thermal insulating values such as stone, brick or concrete. This selection is often combined with interest in the use of indigenous or locally produced materials fueled by global interest in reducing carbon footprints. But, ultimately, in the United States, that decision for optimization has been driven by costs or economy of mean. More recently, the use of smart materials or responsive systems in design begins to challenge the common view of cost effectiveness when looking at the life cycle of a building. The argument is based on the ability to modulate a system to accommodate the varying needs at different times of day, different times of year and different climate zones. In contrast to the one-size-fits-all pattern of modular construction or mass production, the position to support greater adaptability of materials and/or systems argues for greater cost savings over time. Further, if smart materials are used in lieu of standard materials, the need for artificial energy would also be reduced, if not eliminated. "Energy and matter flows can be optimized through the use of smart materials, as the majority of these materials and products take up energy and matter indirectly and directly from the environment" (Kronenburg, 2007).

Smartness is a term used for materials that can change significantly in response to external stimuli without external energy. The stimulus can range from temperature, moisture, stress, light, movement, electric fields, etc. and can respond by changing shape, color, and various other properties. All static and inert materials also change by swelling, warping, decaying, shrinking, expanding, etc. But, unless these changes are harnessed in an effective way, the materials are not categorized as a "smart" material. Once the smallest behavioral change is recognized and celebrated, the material qualifies as one that can be optimized. Even if changes are applied to the molecular value of the material matter, the off-the-shelf description of the material is one that is common or standard. At best, the new form of the material would be categorized as "ultra" or "mega" or, perhaps, another newly coined term. But the ones whose behavior changes are harnessed for purpose are the ones that are tagged as "smart".

Smart materials optimize efficiency through the effectiveness of material systems. The need for stabilization has now been replace by a greater interest in responsiveness and variability. Rather than design for a singular condition with areas of compensation, the new mode of design is consider multiple, temporary states of stability. "Throughout architectural history, materialisation has predominantly to do with reducing change and neutralising its effect through some way of stabilisation or compensation. Think, for instance, of the dimensional changes of materials due to changes in environmental conditions, such as thermal expansion. This was seen as undesirable, problematic and to be avoided at all costs" (Menges, 2008). This attitude is implemented in the multi-faceted investigations of sheet thermobimetal, a common industrial material that has only recently been categorized as "smart".

Thermobimetals have been used since the beginning of the industrial revolution. A lamination of two metals together with different thermal expansion coefficients, it simply deforms when heated or cooled. As the temperature rises, one side of the

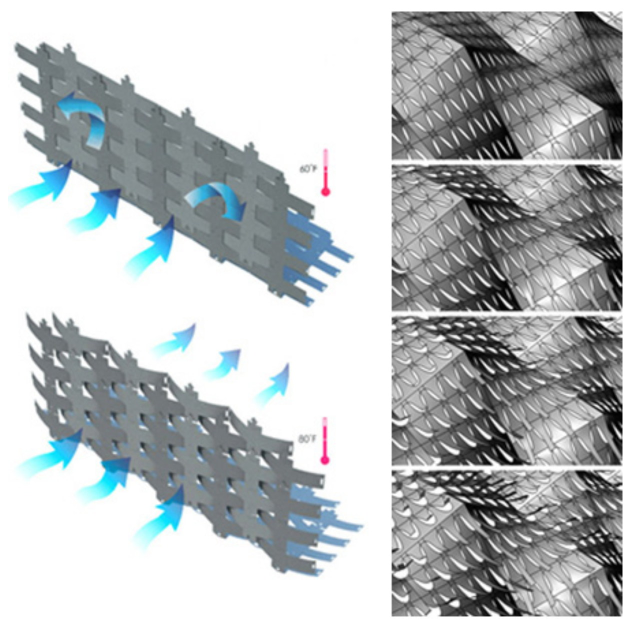


Figure 4. The diagram on the left demonstrates the self-ventilating capability of the Armoured Corset and the right shows the changing bimetal form on Bloom.

laminated sheet will expand more than the other. The result will be a curved or curled piece of sheet metal. Reacting with outside temperatures, this smart material has the potential to develop self-actuating intake or exhaust for facades (Fig. 4). Available in the form of strips, disks or spirals, thermobimetals are commonly used today in thermostats as a measurement and control system and in electrical controls as components in mechatronic systems. So far, however, few applications in architecture have been documented. Automatically opening and closing ventilation flaps have been developed and installed in greenhouses and for use as self-closing fire protection flaps, but nothing has been published on the development of this material for building skins.

Thermobimetals can be a combination of any two compatible sheet metals. The combinations of metals with different expansion coefficients and at various thicknesses can produce a wide range of deflection. P675R, the ideal thermobimetal for this investigation, had the highest amount of deflection in the temperature range of 0-120 degrees Fahrenheit. The low expansion material is called Invar, which is an alloy of 64% iron and 36% nickel with some carbon and chromium. The high expansion material is a nickel manganese alloy composed of 72% manganese, 18% copper and 10% nickel. This bi-metal is also called 36-10 and the ASTM name is TM2. Made corrosion-resistant by plating with chrome and copper, this material is available in sheets or strips in several thicknesses. The amount of deflection varies dependent on the size of the sheet, the air temperature, the position of clamping and the thickness of the material. The range of thickness selected for this study is 0.008" to 0.010" (Engineered Materials Solutions, 2011).

Shapes are much easier to represent digitally than material properties, environmental characteristics, and aspects of physics and gravity. "Parametrics can effectively model only *quantitative* characteristics. Parametric models leave aside the qualitative and immeasurable things considered by architects during the design process that make for a complete work of architecture" (Willis and Woodward, 2010). Digital modeling could not solve all the potential problems of architecture. Friction, gravitational forces, and material flaws could not be applied to the computer model. The only option for further testing was building prototypes, the old fashioned way, physically. It was "impossible to achieve a *direct* correlation between digital data and a constructed building. Interpolation, based on an understanding of construction tolerances, material behavior, and the ergonomics of building assembly, will always be required" (Willis and Woodward, 2010). As it turned out, the weight of the material in the *Armoured Corset*, combined with friction forces, added a remarkable amount of tensile force, preventing the tiles from curling at the manufactured temperature. Instead of operating at 70°F, the tiles began to curl at 80°F (Fig. 5). Without the building of the prototype, the true performance of the surface would be unknown and the digital model unreliable. "But, as nothing in 'real' reality is truly exact, and as the software is fully exact, we also had to define small gaps to account for 'errors' in the production and assembly, such as adding the paint or varnish after machining, which can make the parts sufficiently thicker to introduce inaccuracies into the process" (Willis and Woodward, 2010).

Figure 5. The bimetal tiles in the Armoured Corset started to curl at 80° F.

As more research in material development is being produced and more prototypes built, architects will be able to anticipate potential problems and hazards to incorporating new materials in architecture. Perhaps, the precision of the digital medium will someday be able to accommodate the inaccuracies of real construction, in both material behavior as well as human error. In that case, the irony will be in the smartness of the material.

OPTIMIZATION ENCOUNTERS STRUCTURE

The most obvious use of the term optimization appears when referring to the development of the structure, where efficiency and economy are operating terms for engineers. The economy of means is equivalent to the use of the minimum amount of materials and is obtained by the efficiency of a structure in resisting forces imposed on it. The soap bubble tests of tensile structures by Otto Frei are some of the most well-known examples of this form-finding technique, where the forces determined the most efficient shape, but disregard other important elements of construction. In digital modeling and analysis, it clearly shows that some design parameters, like structure, are easier to incorporate than others. “Shapes are much easier to represent mathematically than (for example) material properties, environmental characteristics, and aspects of a building’s context” (Cache, 2010). But, clearly, in the case of a large tree, the final form is a combination of many elements, not necessarily geometrically derived, but perhaps behaviorally, where the mathematics can be applied in the development of an algorithmic equation. This notion is not commonly practiced, but is gaining more and more interest as computer technology and capabilities improve.

Admittedly, the same dichotomy between the ideal geometry and the ideal behavior contributed to the final shape for the *Bloom* project. Originally designed as a tensile surface, the overall shape emerged from the development of a basic structural form--the hyperboloic paraboloid, or hypar form--and a complex surface made from a grid of mini-hypar shapes. The intersecting zig-zags formed a strategic space frame-like structure and, ultimately, allowed the overall form to be liberated from its tensile structure limitations and transform into a structural shell system. The canopy no longer had to be hung but could be freestanding. As a result of this change, the range of formal options widened, challenging the purist notion of optimization as being an approximation rather than an absolute. Optimization, in this case, was more guideline than criteria.

For architects, unlike engineers, pursuing structural optimization can oftentimes be incompatible with design intent. Detailing, which is often eliminated for purposes of economy and not necessarily designed for purposes of efficiency, differentiates design from its simple structural diagram. It is what adds articulation and meaning to a building and can aid in assembly and constructability. Despite the aid of advanced digital programs and the particular science of form-finding, the fabrication of complex surfaces, if not made from stretchable fabric, in real world terms must be made by the aggregation of smaller pieces. In order to make surfaces continuous and connect various pieces together, special attention must be made to the designs of these details, especially in the areas where two different materials are being seamed together.

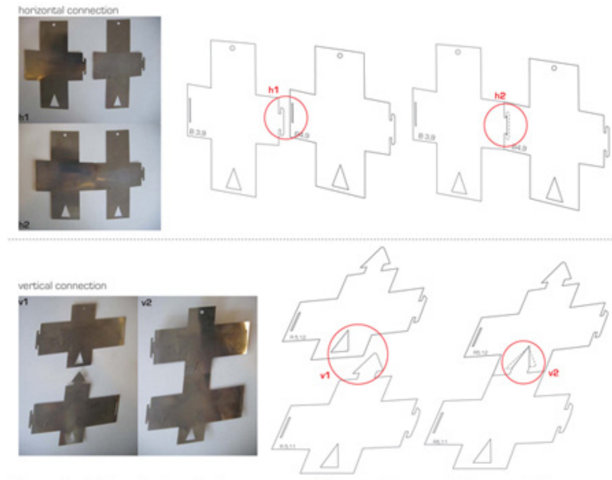


Figure 6. The tab-slot connection allowed for quick assembly and stabilization of the geometry.

The matrices, used in the *Armoured Corset* and the *Bloom* projects, have similar weave patterns, but use different connection strategies determined by structural need. In the former, the joints were made by male/female connections, cut from the bimetal material itself. To allow movement of the bimetal, all joints had to be hinged and not fixed. A tab/slot system simplified assembly and eliminated the need to add extraneous materials. The pattern articulation was enhanced by the connection detailing and differentiated by its orientation relative to the vertical and horizontal joints (Fig. 6). Because the connections of the woven matrix in *Bloom* was simplified to a rivet joint, these joints could not be flexible in tension. In areas that required more rigidity, all flaps were riveted along the gridline intersections, improving the structural capability.

In truly efficient systems, the structure is combined with the surface material to define the surface itself. “The defining characteristic of surface structures is the coincidence of the inner space and external form being almost identical; the form can be read from both inside and out” (Pedreschi, 2008). *Waist Tightening*, *Armoured Corset* and *Bloom* follow this mantra, where the envelopes’ structures are integrated in the skin system and visible on both the inside and outside, optimizing the material by collapsing the systems together. In the first two projects, the derived shapes are determined by form-finding exercises and follow a basic catenary curve, while the latter is enhanced by a codependent monocoque system of surface and frame. This lightweight frame system is integrated into the skin to hold rigid the hypar panels, which, together, dramatically increases the overall rigidity of the complete structure. Neither the frame nor the undulating surface can hold its form without the other, but together make a surprisingly stable structure. Designed to flex, but not fail, this structure is optimized to use the least amount of material as an overall strategy by increasing depth in areas that necessitate more strength and reducing dimension in areas with little need.

CONCLUSION

Performance criteria cannot be limited to the measurements of optimization. Although optimization may seem like a popular route for design engineering, its ability to hold up to critical evaluation is doomed to be faulty and weak. Because the number of variables that inform architecture are diverse, it is virtually impossible to establish reliable or measurable methods of optimization. The complicated craft involving digital tools has numerous gaps. Because programs have become so complex the need for repetitive operations increase, but the forms and geometries combined with real materials and tools seem to resist this interest. Instead, digital operations become more and more specialized, individualized and isolated. For every new project, there are new digital operations, new methods of fabrication, and new variables to factor in.

Other variables lie in the understanding of practical construction methodologies and real material applications. In the former, much can be lost in translation. Limited to the tools and machines of current fabrication processes, general construction tolerances must be factored into the sequence of construction to accommodate any deviations or discrepancies due to translations problems. Similar tolerances must be made to reconcile the realities of material inconsistencies. In the case of thermobimetal, it is impossible to even guarantee that the material, although specified as flat, is completely flat. This simple, but common, problem will have repercussions with the laser-cutting process (lack of precision), with the assemble sequence, and, ultimately, with the performance of the surface relative to the original design intent. In the case of *Bloom*, this small deviation in material changes the sun-shading performance of the canopy. With every addition of a dimensional tolerance, the level of performance capability is diminished.

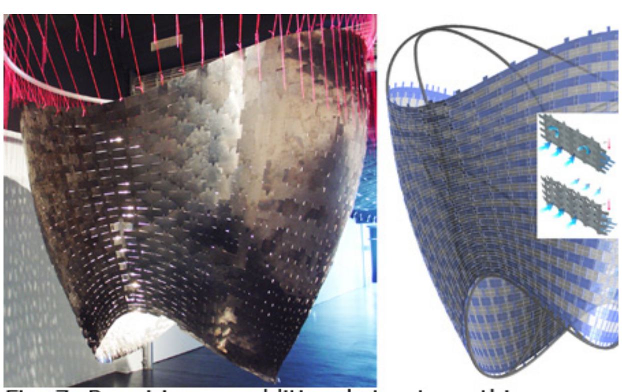


Figure 7. Requiring no additional structure, this project's 1,000 + pieces hung in a natural catenary curve.

Finally, the structural modeling analyses tools seem like the most like place for optimization, given the history of optimization in engineering. However, this same strategy does not seem to always be the ideal when the range of optimal options seems to widen. All kinds of geometries, that are not derivative of a form-finding process and appear less like structural diagrams, have merit as long as they stay within a range of *reasonable* structural capability. The difficulty is defining what is reasonable, which inadvertently challenges the current definition of optimization.

Evaluating one isolated variable in architectural design is futile. Because there are so many factors, it might be more fruitful to consider optimization as a guideline to design. Instead of seeking a universal answer found more readily in the sciences and adopting the engineering method of decision-making, architects and designers may have to readjust the value system (and evaluation system) to something more holistic, robust and adaptable. Optimization is, to be fair, relative.

BIMETAL PROJECTS BY AUTHOR

Armoured Corset (2009)

Challenging the traditional presumption that building skins should be static and inanimate, this research project examines the replacement of this convention with one that sees the prosthetic layer between man and his environment as a responsive and active skin, in this case, thermally. Using a thermobimetal (TBM), a heat-sensitive smart material, building surfaces can self-ventilate and dramatically reduce the dependency on mechanical air conditioning or, ultimately, the carbon footprint. The completion of an eight foot tall prototype by the author demonstrated the profound potential of this material, a lamination two metal alloys with different coefficients of expansion together. The result was a surface made of multiple tiles that curled/crimped when heated and flattened when cooled. As temperature increases, the deformation allowed the building skin to breathe naturally much like the pores in human skin. (Fig. 7).

Waist Tightening (2010)

Using laser-cutting as a fabrication tool results in tremendous waste when building complex surface geometries. More than fifty percent of the virgin material is often discarded, depending on the size of the individual pieces. In order to build a demonstrative project with the highest optimization in use of material and lowest amount of waste, this project resorted to making a symmetrical geometry using slats of material and reducing waste to an absolute minimum. Inadvertently, this strategy aided in an improved, uniform operation of the bimetal surface. The evenly weighted pattern of triple horizontal pieces ensured higher performance in responsiveness than in the *Armoured Corset*. The change in deflection was more efficient, easier to control and visibly better, when artificial heat sources were installed on the interior, than in the previous prototype. (Fig. 8).

Figure 8. Simple rectangular shapes reduced material waste to a minimum in Waist Tightening.

BLOOM (2011) in Collaboration with Ingalill Wahlroos-Ritter and Matthew Melnyk

Figure 9. *Bloom* was made of 414 structural or performative panels.

Figure 10. The project was made of over 14,000 bimetal pieces.

When considering thermally-responsive smart materials, passive design strategies must be dismissed and replace by ones that incorporate multiple states of performance relative to the input source. The surface in this project is designed to respond to the movement of the sun at various times of year, shading areas under the project like a sundial. As the sun moves, select areas of the surface close, providing more shade below. Although the simplest version of a performative sun-shading canopy would be a horizontal surface, a complex double-curving structural form filled with mini-hypar panels challenged another level of structural potentials in architectural shell systems. The degree of opacity in the panels' surface mesh was determined by a balance between structural necessity, sun-shading capacity, and visual transparency, using various advanced digital tools. In some areas, the resulting mesh was contrary to logic. True decision-making was more willful than one might prefer. And, it was that same willfulness that aided in holistic optimization of this project, making the process difficult to control and impossible evaluate solely by software analysis, mathematics and science. (Fig. 9, 10).

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ENDNOTES

1 The title of this essay references Siegfried Gidieon's influential book, *Mechanization Takes Command*, when the handicraft was eliminated and the assembly-line process was glorified. The recent influence of digital technology and interest in optimization marks a paradigm shift to yet a new model of design, fabrication and building, replacing the one described in Gidieon's book.

2 Monocoque: a type of construction (as of a fuselage) in which the outer skin carries all or a major part of the stresses. *www.merriam-webster.com/dictionary/monocoque.*

3 Hypar or Hyperbolic Paraboloid: a saddle-shaped quadric surface whose sections by planes parallel to one coordinate plane are hyperbolas while those sections by planes parallel to the other two are parabolas if proper orientation of the coordinate axes is assumed. *www.merriam-webster.com/dictionary/hyperbolic%20paraboloid.*