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Design intercalated: The AtFAB project

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This paper describes tools, concepts and workflow used to develop AtFAB, a digitally fabricated, customizable furniture system, and apprehensible model for employing simplicity, interconnectivity and adaptability in architecture. The investigation deploys parametric modelling, interaction design, and digital fabrication to develop a multi-agent system that recasts the roles of designers, users and fabricators and re-imagines the architect's role of balancing user needs alongside other generative agents. It proposes that innovative design thinking might replace our discipline's prevailing focus on the transactional and object-cantered capabilities of technology with an emphasis on its ability to facilitate the design of systemic and networked relationships.

Keywords. parametric design, emergence, participatory design, design thinking, multi-agent systems

1 Introduction

Innovative digital tools and techniques have enabled architects to realize unprecedented form, have introduced novel workflows in construction and delivery, and have redefined collaboration with the client and the project team. Architects' embrace of everything from building information modelling and computation, to digital fabrication and social networking among the delivery team, has given our profession the capacity to revolutionize our role on projects as well as those projects themselves. However, the true potentials of these fluid, networked tools are being limited by their almost exclusive deployment to define physicality[1 2] and/or to serve the transactional structure of architect-client-constructor relationships.[3 4] This paper proposes an epistemological shift of our focus from the reductive, object-oriented capabilities of these tools and put it on their ability to facilitate the design of (and for) systemic and networked relationships. Intercalation, as used in materials science, is the controlled insertion of a guest molecule between other molecules to produce a compound with transcendent properties like greater conductivity or structural strength. This investigation sought to redeploy digital tools to demonstrate how architecture could become an intercalate that inextricably links the interrelated systems occurring within it to the complex conditions that surround it.

This paper documents the design of a furniture system, as an apprehensible model for architecture and as a model to demonstrate a shift in design thinking. It documents an investigation of how emergence, networked organization and open source design might drive an intercalated design methodology. The test subject in this investigation is the design of an ecologically sound, customizable, and digitally fabricated line of furniture pieces called AtFAB. AtFAB involves a fab-

1 Parametricism Manifesto provides five agendas that roster how parametric tools can enable architects to register forces onto form. Parametricism advocates for a mono-disciplinary intelligence that's exclusive to a classical creative process, accessible to the architect, rather than an involutionary and evolutionary set of procedures composed of material, mechanical, maker and user intelligence.

2 Schumacher, P. (2008). Parametricism as Style - Parametricism Manifesto, 11th Architecture Biennale, Venice

3 The conference presented the leading legal, technical, theoretical and design perspectives on BIM and its implications to the architectural profession. It raised many ramifications within the rication workflow that employs ubiquitously available sheet material products, the proliferation of 3-axis CNC routers and contour cutters, and the growing social media and share platforms[5 6] that connect professional and DIY digital fabricators[7] to local consumers with projects. The workflow process begins online, where users would select and customize furniture pieces with an online interactive interface. They download the cut file, select a sheet material, and connect with a local CNC fabricator through one of several fabber networks. The user retrieves the milled flat pieces from the fabrication shop, intuitively assembles the furniture object without the aid of hardware or adhesives, and finishes their piece as desired.

The investigation purposefully sought the most ubiquitous digital technology rather than the most advanced, because the diverse conditions of everyday implementation present a robust opportunity to test adaptability and feasible field-testing. Similarly, it sought Cartesian geometries, uncomplicated programs, and a small delivery team that would maintain focus on a design-thinking model over design technique. This investigation enabled an examination of how the principles of emergence can be employed to design a system that yields adaptable outcomes. It also allowed a pursuit of how a networked delivery process could recast the roles of designer and user, and use distributed fabrication to produce diverse, abundant, and efficient interactions and results. It also facilitated an examination of how an intensively empathic up-front design effort can be tactically deployed to balance controlled outcomes with unanticipated eventualities, in order to deliver the most responsive design.

2 Primary Research Questions

2.1 Research Aims & Scope

The investigation was driven by several key questions:

Can a design process modelled on the principles of Emergence, deriving much from little, enable design that efficiently responds to wide sets of external criteria? If an emergent architecture is possible through the design of simple components enabled by parametric modelling, then the resultant objects might be abundant and fit over a broader range of criteria. The research team defined a basic set of essential elements of the furniture system that could be combined to produce a limited number of distinct furniture objects. When these objects were affected by specific parametric definitions, using combinations of Rhino Grasshopper and Revit, the resulting number furniture pieces become infinite but still reducible and understandable back to the essential unit. Through this study, the team sought to analyze if (and how) much could arise from a little, as emergence in nature works, and how this process might apply beyond a system of furniture to the larger, more complex and many numerous systems of architecture.

Can a design process, informed by principles of network theory, prioritize the design of relationships alongside the design of objects in order to produce more responsive design outcomes? If networked thinking enables us to understand objects through their manifold relationships, then more responsive designs, strategies and scenarios might emerge. To test this hypothesis, we sought to design AtFAB's series of interrelationships simultaneously as we designed its physicality. We designed AtFAB as a network hub intercalated between a digital tool and common material, a social network linking digital fabricators, and an interface

profession, but did little to address how to leverage the tools to recontextualize or reposition professional scope.

4 **Bernstein, P.** & **Deamer, P**. (2010). In: Deamer, P. ed, Introduction in Building (in) the Future: Recasting Labour in Architecture, Princeton Architectural Press, Princeton, NJ, pp 17-20

5 The increasing number of companies embracing "share platforms" as a business strategy is enabling small entities (like consumers) the opportunity to borrow/rent/lease tools or resources that were once only available in an ownership context.

6 **Gansky, L.** (2010). The Mesh: Why the Future is Sharing, Portfolio Books, New York, p 21

7 The proliferation of networks like ShopBot's CNC fabber network 100Kgarages.com and Ponoko.com are connecting people to fabricators. The growing number of hackerspaces, storefront outlets like .MGX Flaghip in Brussels, MIT's Mobile Fab Lab and the TechShop chain in North America are increasing the general public's access to digital fabrication.

for users with desires for furniture. We designed relationships, like its distributed fabrication workflow that recast roles of designer, fabricator and user. We designed the internal network of relationships occurring at multiple scales between joints, assemblies, combinations of assemblies and parametric definitions.
By using both emergence and network theory as generative models, can a designer's role shift from maker of handed-down objects to the choreographer of systems? If we focus design efforts at the front end of the process to balance controlled outcomes and inconclusiveness, then we might be able to offer up rigorously considered design that has a breadth of relevance not achievable through singular design solution. The investigation examined user-centred product design discourse as well as the open source programming movement to understand how user and designer can collaboratively achieve adaptable outcomes. The investigation focused both on how AtFAB could be designed so as to productively leverage the user's agency, and how the framework that underpins a collaborative design space could be developed. The investigation defined, tested and analyzed this space through prototyping the interactive process, combining 3D modelling with animation simulations, and eliciting user and fabricator feedback.

2.2 Building upon Diverse Precedents

This research draws together several seemingly unrelated positions that share a common aspiration for a form that is evolved from the accommodation of intangible forces, whether technologies, natures, things or humans. The three cases below successfully incorporate invisible, intangible forces into form, but each has its limits. This investigation sought to develop a design approach that learns from all three in order to surpass the limits of each.
Peter Testa's Carbon Tower project[8] is based on a set of digitally enabled relationships between architect, material and method of construction, which combine to make transformative iterations derived from variables. Through modelling and scripting, Testa designed a system for a multi-story occupiable structure shaped by the specific structural capability of carbon fibre composites, the robotic weavers that would construct them, and the site or other conditions that impact it. This investigation pursues a similar object-relationship link for emergent design, but seeks to address relationships between ubiquitous materials and technologies that would make realization feasible in a present, everyday context. It also seeks a less generic design approach that can incorporate a range of human needs and specificity.
Alvaro Siza describes a circuitous path towards realizing architecture, and that by navigating this lengthier, curved trajectory, as opposed to a direct linear one; a project naturally picks up "more and more information, ultimately becoming part of everything, part of the universe."[9] Whether its employing a lineage of construction systems and details or the designer's interrelating of space, program, light, site and circulation, Siza prioritizes relationships over objects in his endeavors to incorporate as much as possible into architecture, where form becomes a by-product, or registration, of the gathering and accommodation of these information. Similarly, this investigation aspires to understand and articulate how design becomes a part of everything, but in contrast to Siza, seeks to do so with the help of digital tools, models of emergence and network theory.
Human Factors Research, User-Centered Design and Participatory and co-

8 Rohrbacher, G. (2005). Dreamweaver: Building the Carbon Tower, Praxis Journal of Writing and Building, 6, pp 54-61
9 Testa, P. (1996). Alvaro Siza, Birkhauser, Basel

Design methodologies elicit user input to elevate needs, uses and desires into the design process. Elizabeth Sanders has been a long advocate for co-creation in design, and breaks down a variety of methods of co-design used primarily in product and interaction design.[10] [11] [12] Increasingly, these methods are finding their way into the architectural design process and are provoking innovative spatial solutions. At its best, IDEO's CEO Tim Brown, describes Design Thinking, which relies heavily on this kind of research, as employing the designer's expertise and methods to match people's needs to what is feasible.[13 to 16] It is promising territory in the pursuit of an architecture that becomes a part of everything, and tempting to incorporate a more nuanced understanding of user, client and public needs into the design we make. However upon closer examination, user-centred design methods are still an exclusive approach and subject to similar finite outcomes of the design-centric processes that they seek to replace. Specific innovations are logical in product, graphic, and interaction design disciplines that yield ephemeral (market-driven) products that necessitate revisiting the entire design process whenever new interpretations, revelations, needs or contexts arise. For architecture, which is long in duration and intensive in resources, a user-holistic approach, that balances the demands of humans, nature, things and technology, might bring the powerful insights that lead to innovation while ensuring durability, resilience and relevance.

3 Design Research: System Design and Testing

The Design Research phase was spent designing the system, in conjunction with testing workflow and functionality with physical and process prototyping, so that it could ultimately be field-tested in a later Implementation Research phase. Our first phase of the research started with identifying analogous, operational models for emergence, network theory and open source, to test their potentials for use, and to evaluate their effectiveness in an applied context. With the presence and influence of subjective judgment inevitable, the research approach sought to productively use it. The research process was structured to simulate and evaluate these operational models for their fitness to be translated into architectural contexts beyond the immediate experiment.

3.1 Applying Emergence and Network Theory

Spinoza's concept of the object "that is not defined by its name but by its latitude, longitude and capacity to affect and be affected" explains the universe through these most essential components, position and relationships.[17] Spinoza's concept inspired the investigation to test a model of how architecture could be become a part of everything, and led to the adoption of John Holland's notion of emergence, "this sense of much coming from little".[18]

The project sought to define what could be "little," assuming that "much" was the ultimate proliferation of AtFAB's options and scenarios. The study established that the most elemental and intercalated component in furniture construction could be the joint, which worked between the tool and material, enabled simple and durable assembly without hardware, and aggregated to form multiple constructs. Through these conditions, the S/Z joint was developed for its strong 3-sided orthogonal relationship between two flat shapes cut from sheet material by a CNC router (Figure 1).

10 The furniture system interface that's integral to the system itself is a co-design platform that works in a similar way as the well-developed methods, tools and techniques that Sanders describes for enabling users to project future needs that are not typically explicitly articulated.

11 Stappers, P.J. & **Sanders, E.** (2008). Co-creation and the new landscapes of Design, CoDesign: International Journal of CoCreation in Design and the Arts, 7

12 Sanders, E. (2010). Stepping Stones Across the Gap, Rehearsing the Future

13 User-centred design was used to great effect in OMA & IDEO's collaboration on the interactive changing rooms at New York Prada Flagship Store.

14 Brown, T. (2008). Design Thinking, Harvard Business Review, June 2008, pp 259-260

15 Manufacturing Plant that radically co-located the engineering team alongside the airplane assembly line based on extensive staff interviews.

16 Moody, F. (2005). "Boeing's Building Boom" Metropolis Magazine, 07.2005

17 de Spinoza, B. (2007). Ethics. Cambridge University Press, Cambridge, p 43

18 Holland, J. (1997). Emergence from Chaos to Order, Basic Books, New York, p 21

19 op cit p 24

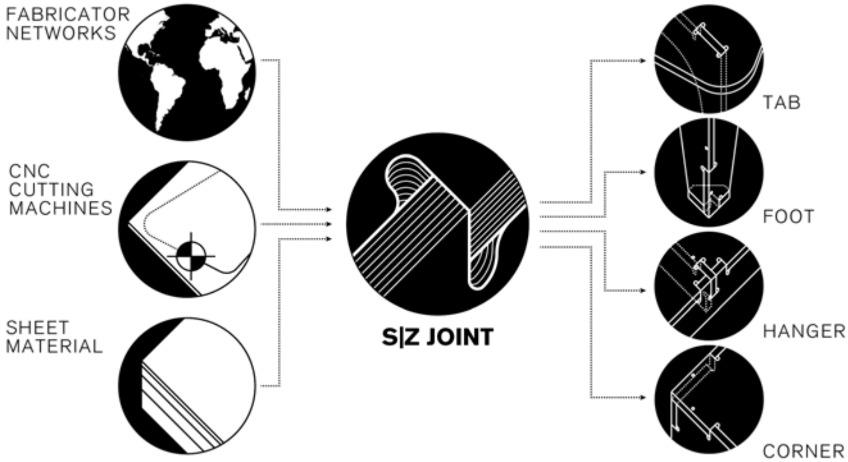

Figure 1 The S/Z Joint is an intercalate between tool, material system & social network that aggregates into four distinct assemblies

The investigation went on to define basic and specific sets of criteria that could combine with the S/Z and maximize the quantity and variety of outcomes, toward achieving "much." These sets include assemblies that aggregate S/Z joints to form hubs, interlocks and hangers, which connect pieces together in a multitude of ways. The assemblies aggregate to form a set of basic structures, the team identified as vierendeel, torsion, rotational and shear that efficiently resolve forces in distinct ways. Working together, the assemblies and structures respond to basic, reductive programmatic functions of sitting, working, storing and screening and adopt behaviours in contexts and flock, aggregate, stand-alone and sidle (Figure 2).

By combining and re-combining these sets of criteria, we were able to develop 12 distinct furniture objects that addressed the broadest array of furniture needs. The iterative design process provided ongoing feedback to revisit and refine the generative criteria (Figure 3).

To further yield "much" from these minimal sets of criteria, the investigation incorporated parametric definitions to find wider variation in the system. Under the assumption that if furniture objects are adaptable to a multitude of specific needs, the system would operate similarly to how emergence works in nature.[19] The investigation first enlisted a combination of 3D modelling and animation tools to design the degree and nature of transformation for each particular furniture object that would produce the greatest range across the entire AtFAB system. The study identified modular and dimensional growth for some furniture objects and revealed specific changes to shape for other kinds of objects; it also discovered how change to material thickness could create significant, tangible variety in all objects. Once basic kinds of transformation were defined, the process shifted to parametric software, using Grasshopper and Revit to further analyze the animated simulations and to precisely choreograph the transformations that could maximize the variety of outcomes for each furniture object (Figure 4).

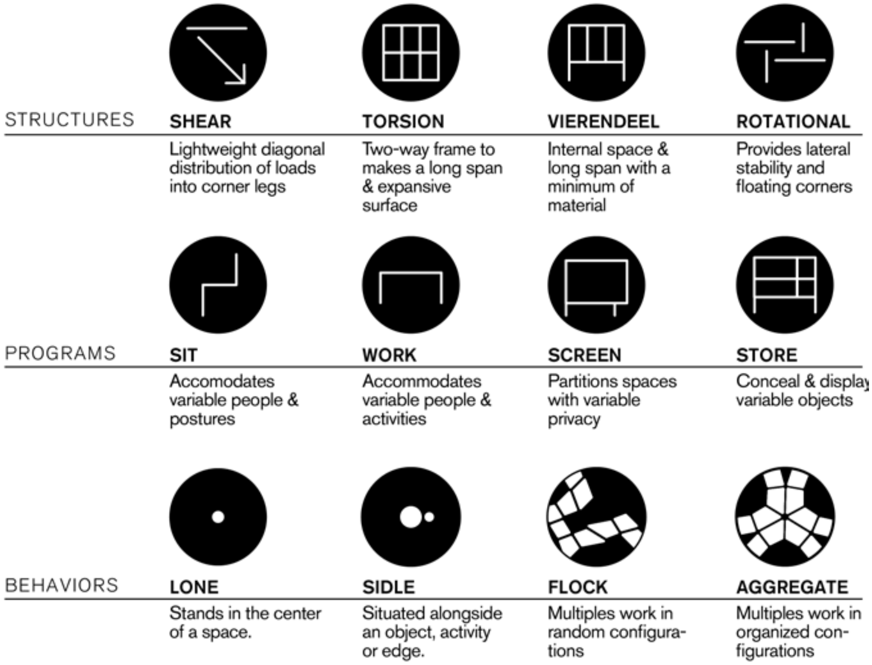

Figure 2 The generative criteria that determine how S/Z Joint assemblies aggregate to serve diverse array of furniture functions

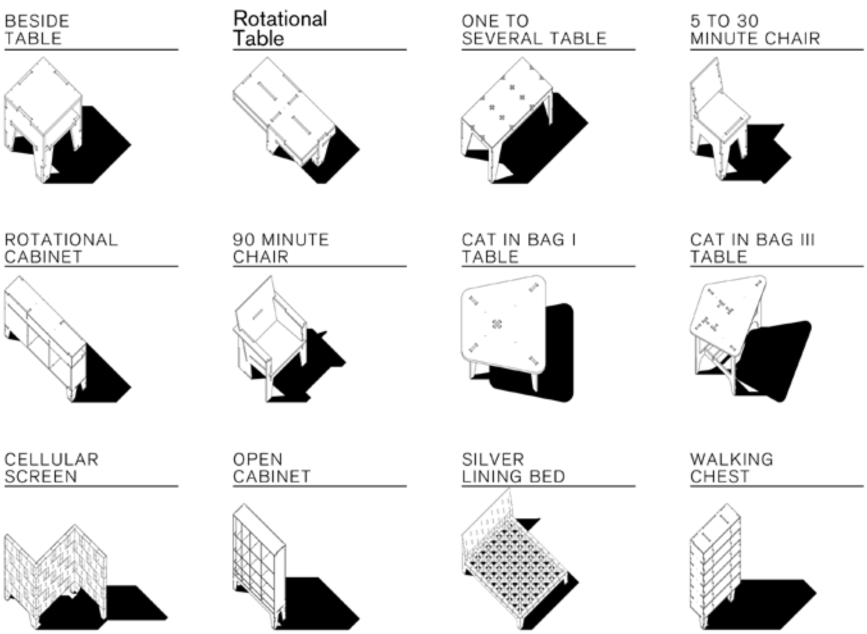

Figure 3 The 12 resulting furniture objects

The process of developing AtFAB's system of parametric definitions yielded unexpected findings and potentials for user collaboration. The investigation discovered that defining limits, paradoxically, could maximize options for users and have the potential to adapt to their unanticipated needs. With this realization, the

20 Deleuze, G. & **Guattari, F.** (1987). Capitalism and Schizo-phrenia, University of Minnesota Press, Minnea-polis

study focused on limiting transformations in number for each object, situating growth between the S/Z assemblies and preserving structural performance, and also working within human, machine and material proportions. It became apparent that designing generative limits was as essential as the design of the transformations and the objects themselves – when we removed limits, we did not find more qualitative outcomes. A second finding at this stage of the investigation was that these choreographed parametric definitions could become the platform for our multi-agent design process by forming the foundation of AtFAB's User Interface.

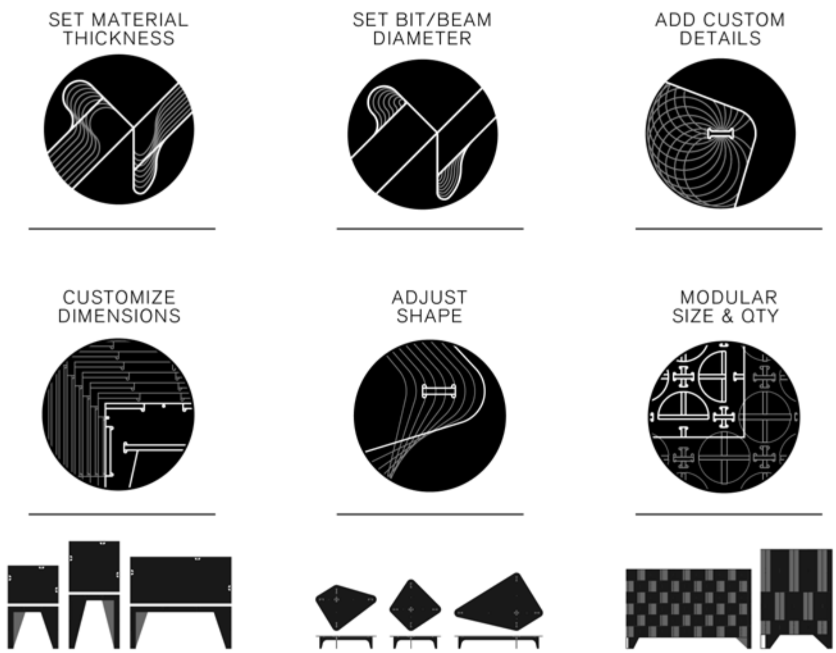

Figure 4 Six parametric definitions

3.2 Developing a Collaborative Workflow

The investigation translated its focus on decentralized and collaborative design to decentralized digital manufacturing. AtFAB was developed to implicate the increasing number of independent CNC fabricator shops, and emergent social networking tools that link them. We cast AtFAB's manufacturing process as a networked set of relations, like Deleuze and Guattari's "Body without Organs" which is not defined by its corporeal limits but by the relationships that sustain its being.[20] By analyzing AtFAB in this capacity, we developed it further as a connecting agent between fabricators and users that eroded the conventionally assigned roles of designer, fabricator and consumer in the process of manufacture. In this scenario, the consumer, recast into a new kind of user/maker, selects a furniture piece and transforms it through the online interface. Once downloaded from the website, the user/maker emails the furniture cut file and specifications to a local fabricator, who is linked to one of many emerging fabricator networks that connects independent digital fabrication shops. During our first phase of prototyping, our team found opportunities where relationships around digital manufacturing did allow roles to become more fluid, hybridized and collaborative. We found that users could often be their own fabricators, fabricators preferred to refine the design for specific machinery, and that users would interpret designs in ways we hadn’t anticipated. Fluidity in roles revealed that AtFAB’s manufacturing process could suit a wide array of delivery conditions and desired outcomes. This adaptability in the networked model would ensure greater possibility that the furniture system would find relevance, or as in nature, could ensure survival (Figure 5).

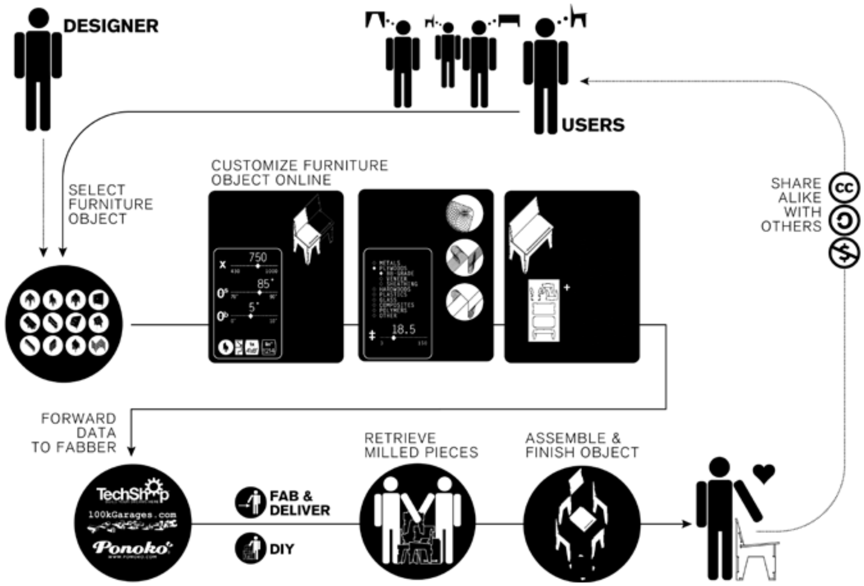

Figure 5 The AtFAB Workflow

The movement of information and material through AtFAB’s workflow revealed transcendence of the “corporeal limits” of geographical separation of materials, tools and acquisition of finished goods. Distributed digital fabrication, facilitated by the availability (and mobility) of CNC routers and networked information enables the furniture system production to rely upon the relay of information rather than the conveyance of material.[21] [22] The investigation learned first hand, in its prototyping phase, that fabrication could happen at the place of transaction and material procurement when our finished goods were milled without redundant and excessive materials and goods transport. This workflow enables a manufacturing process that reconstitutes the fabricator from a whole multinational single manufacturer, with a supply and distribution chain, to a robust network of individual small, local fabricators.[23] AtFAB’s design and system was refined and further simplified to enable these smaller but abundant interactions, which are more efficient, adaptable and responsive than a large centralized source.

3.3 Analyzing the System

The investigation concluded with a final quantitative analysis of the furniture system. The basic sets of criteria and essential elements that combined to produce furniture objects were re-evaluated alongside the parametric definitions, the

21 AtFAB is not a flow of matter-energy, but a flow of information “as patterns capable of self-replication and catalysis” with an “ability to switch from one stable state to another.”

22 De Landa, M. (1997). A Thousand Years of Nonlinear History, Zone Books/Swerve Editions, New York

23 Barabasi, A-L. (2003). Linked: How Everything is Connected to Everything, Plume, New York, pp72-74 material thickness definitions, and the networked fabrication workflow that left the time and place of fabrication open to the determination of the consumer and fabricator. The analysis produced a roster that streamlined consistencies within AtFAB's system of relationships, and could enable the system as a whole to respond to new conditions (Tables 1 and 2).

Table 1 Attribute roster of AtFAB objects

Object	Pieces & Joints		Structural Assembly	Contextual Behaviour
	Kind	Total		
One to Several Table	6/3	13/22	Shear	Stand Alone
5 to 30 Minute Chair	6/2	10/13	Shear	Flock
Beside Table	6/2	11/12	Torsion	Sidle
Rotational Table	5/3	10/17	Rotational	Stand Alone
Cat in Bag i Table	2/2	5/8	Rotational	Aggregate
Cat in Bag iii Table	5/3	5/12	Rotational	Aggregate
Rotational Cabinet	6/3	13/20	Rotational	Stand Alone
90 Minute Chair	7/3	9/18	Shear	Flock
Silver Lining Bed	9/3	30/200	Torsion	Sidle
Cellular Screen	3/2	n/n	Vierendaal	Flock
Walking Chest	11/3	39/100	Rotational	Sidle
Open Cabinet	7/3	11/14	Vierendaal	Sidle

Table 2 Attribute roster of AtFAB object transformations and limits

Object	Transformation min/max				
	Kind	x	y	z	other
One to Several Table	Dimension	450/1800	450/1800	650/1000	
5 to 30 Minute Chair	Dimension	430/1000	565	800	0°/10°
Beside Table	Dimension	450/1000	450/1000	405/1000	
Rotational Table	Dimension	400/2400	400/900	600/2400	
Cat in Bag i Table	Shape	900/2400	900/2400	350	
Cat in Bag iii Table	Shape	900/2400	900/2400	500/1000	
Rotational Cabinet	Dimension	400/2400	400/900	600/2400	
90 Minute Chair	Dimension	880/2400	782	873	0°/10°
Silver Lining Bed	Modular	200/200x	200/200x	350	
Cellular Screen	Modular	400/400x	400/400x	300/300x	
Walking Chest	Dimension	400/2400	450/500	400/2400	n
Open Cabinet	Dimension	400/2400	400/500	600/2400	n

4 Implementation: Results and Analysis

With system physicality, fabrication, and interactions defined and functional, the investigation proceeded with an implementation phase that field-tested AtFAB's design and multi-agent workflow with both fabricators and users. We sought to refine the design of the object system and the interactive parametric and decentralized manufacturing system that affect and are affected by the object design. To gather the most generative insights to test and refine the project, we worked with both small, intensely engaged test groups, as well as very large, but more casually engaged, groups.

4.1 Fabricator Testing

During the first phase of research, AtFAB pieces were successfully tested in-house with laser cutters, but CNC router prototyping encountered early fabrication failures, with parts not fitting together. The team made tolerance adjustments to the cut files, and after successful re-testing, proceeded with the next phase of fabricator testing on remote machines. We forwarded a digital package of cut files and instructions to different fabricators using CNC routers, industrial laser cutters and waterjet machines who were cutting wood, acrylic sheet and aluminium, respectively. We discovered similar fabrication failures that resulted in pieces not fitting together, but learned that the extent and nature of failure were varied depending on machine and material. We also found moments in the process where communication challenges led fabbers to take unnecessary steps and/or misinterpret which profiles in the file required which kind of cut. We issued a second cut-file/instruction package to each fabricator. It included a small “test piece” that we designed for fabbers to repeatedly cut prior to full fabrication, until their machine beam/bit width was calibrated to achieve a proper fit between AtFAB parts (Figure 6).

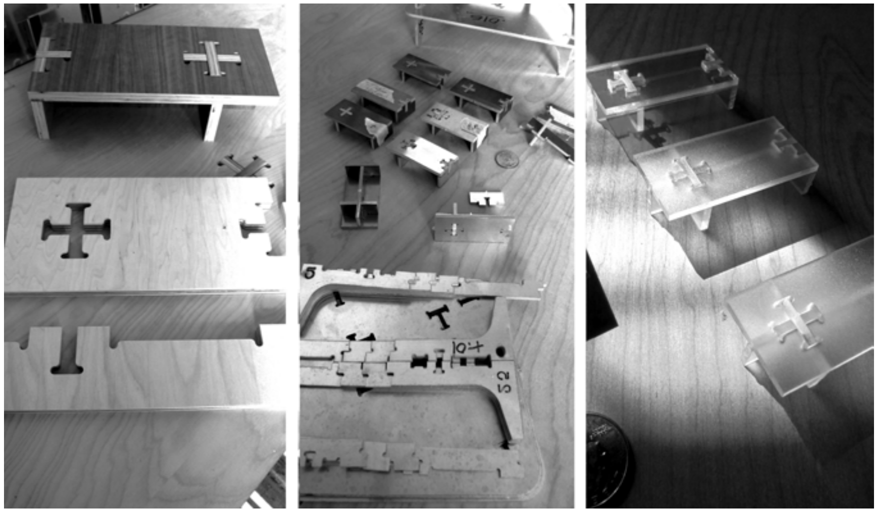

Figure 6 Test Pieces used by Fabricators (l to r) plywood cut by CNC router, aluminium cut by Flojet, acrylic cut by industrial laser cutter

The team had already simplified the cut-file itself so every piece required only 3 types of cuts (inside cuts, outside cuts and holes), we validated this decision as we saw how it this streamlined G-code for all fabricators to use three passes and a single router bit or beam setting. The test piece and simplified cut-file, accompanied by refined and clarified instructions, finally delivered successful outcomes of AtFAB from three kinds of machines and three kinds of materials.

This process proved our assumptions that designing relationships, in conjunction with designing objects, can improve design outcomes. In this particular case, designing the furniture and the workflow tools, which support its making, ensured that successful fabrication outcomes could be achieved in a variety of scenarios, ultimately without our involvement. The team had less design scope in determining the qualitative physicality of objects, but had significantly expanded scope in designing a fluid process and relationships between the system and multiple, unanticipated external conditions. The net result was that there was much more design for the team to manage, not less.

4.2 User Testing

To complete our field-testing of the multi-agent, distributed workflow, we shifted from ensuring ease of manufacturing and streamlining communication between remote agents, to focusing on enabling simple assembly, as well as the parametric customization that occurs at the front end. We tested the ease of user assembly with scale and scaled prototypes of all AtFAB objects. Even with bilateral and rotational symmetries and repetitive parts, we found that all objects

could be intuitively assembled, with the exception of the Cellular Screen. We added a system of "tattoos" etched by the CNC router, which eliminated confusion and enabled our student test subjects to quickly assemble the Screen.
To simulate AtFAB's parametric user interactions, we worked with students, colleagues and others to generate their desired iterations of several AtFAB source designs, while employing Rhino Grasshopper and other interactive methods to facilitate the process [Figure 7]. We found that our choreography of parametric definitions met user needs in the simpler objects (tables, side table, chairs), but we discovered our test subjects ran into challenges when they wanted to transform several larger objects to a dimension that taxed the construction integrity of the object. We were able to make minimal changes to the design, but more importantly, we established how choreography of parametric definitions must be precisely constrained to maintain AtFAB's system-wide structural assemblies. Our user group additionally identified gaps in functionality that could be accommodated by expanding our parametric constraints on several small objects so they could fulfil a wider range of needs.

Figure 7 Several examples of user-fabricated furniture

User testing results underscored our drive to productively affiliate user and designer in a manner that opportunistically capitalizes on the unique capabilities of each. We found that successfully choreographing systems and relationships demanded a grasp of when a designer should either let go or bear down, and we concluded that our place to bear down is when we can expertly design systems and define parameters that reside within limitless freedoms. These systems yield a framework that enables users to achieve consistent, quality outcomes that wouldn't otherwise be found with infinite latitude. By offering up a design (like a large storage object) and preserving key constraints and limits, which are critical to functional success (like preserving an object's structural integrity), we fulfil user desires. Equally, the development of a resilient systemic design, which adapts to user feedback, also fulfils desires. Since the designer can neither know every interpretation nor anticipate how prevailing conditions will inevitably evolve, a resilient and adaptable, open design strategy can address recognized areas of indeterminacy.

4.3 User experience feedback

To complement our work with small user test groups in evaluating customization and assembly, we sought to gather a large volume of anecdotal responses (rather than data) on AtFAB's designs, concept, and reliance on multi-agent distributed-fabrication. We exhibited prototypes at the 2011 World Makerfaire, a public ex-

24 Open GL, Adobe Acrobat 3D, and other programs are aiding interactions with visual information. Programming languages like Processing.js, which allows interactive, data-rich visualizations to be run by any HTML5 compatible browser
25 **Sanders, E.** (2010). ibid

position of technology and DIY culture. As we engaged over a thousand visitors in discussing the project, AtFAB provoked a generally positive response in its design and concept for customization. However, while many potential users were highly aspirational in their desire to engage fabricators and/or DIY fabrication, we found a barrier in actual implementation in our discussions. This was later validated by our website analytics, after giving ~800 event visitors a specific web address, 40% came to the website in the week that followed, and 20% of those online visitors downloaded an AtFAB cut file to fabricate. Some of this barrier might not be overcome, as many individuals will always desire finished objects. However, our team gauged from discussion that our implementation barrier should be overcome as digital fabrication networks and consumer resources become increasingly accessible.

As parametric tools are more easily being repositioned from architecture's internal toolkit into online interactive interfaces, we have an increasing capability to engage users in our designs.[24] We also have the opportunity to use these tools to provoke useful, latent knowledge about needs and desires[25] and to gather patterns of user input during the customization and downloading process. Instead of gathering user feedback in the manner we did at the Makerfaire, we could gather more specific data from online users in the process of transforming an object. After numerous downloads, we could conceivably gather patterns of user tendencies during the process of customizing AtFAB. Which pieces, material thicknesses, machines or combinations of transformations are desirable, what dimensions or shapes might be preferable or where, when and how many pieces are downloaded for fabrication. With a systemic design that is adaptable, this information can then be used to productively refine all aspects of AtFAB so it can always address user desires.

5 Conclusion

AtFAB is not a proposal for the best furniture design; so much as it's an endeavour to provide furniture design that is the best for the most. It doesn't embrace radical innovations, but rather productively leverages common technologies, like CNC, social media and interactive parametric tools, by rethinking our role, scope and position as designer. In contrast to the prevailing object-centric design processes that typically link one designer to one outcome, the development, design and testing of AtFAB demonstrated an evolutionary design process of generating systemic and networked relationships that link the designer with infinite others and infinite outcomes. AtFAB as a systemic design ensures that many furniture objects can be fabricated out of many materials, and found in many places, where they can be produced on-demand at any time. In designing responsiveness, we've found a method to achieve much, abundance, and adaptability.

Beyond the furniture design context, our research illustrates how an evolved design thinking can give architects the capacity to transcend transactional and formal technological agendas, and deploy innovations to inextricably link the interrelated systems within a project to the complex conditions that surround it. A shift is slowly under way in object-centric architectural education and design curricula, as evidenced by the growing number of inter- and trans- disciplinary programs.[26] The profession is slower to embrace the thinking, but could quickly find that by productively expanding design scope from the tangible to include the intangible, our design efforts have the potential to produce outcomes with more relevance, and empower our profession that has only seen its stature decline for decades.[27 28]

We see our next step as employing AtFAB's generative engines in the larger architectural context, and believe buildings possess a similar technologically dependent and systemic set of relationships, which are linked to an entirely different set of parts. The S/Z joint might become a basic conceptual or physical intercalated element, around which an entire architecture is organized. A set of generative elements analogous to AtFAB's structural or programmatic criteria could be seen as building systems, codes or performance criteria. Parametric definitions might literally be BIM families in an architectural scenario, and could also be a process design for defining constraints and numerous simultaneously competing systems. AtFAB's networked multi-agent user-tool-fabber-designer system could literally be translated to the Integrated Project Delivery (IPD) team or could be an example of how the boundaries between other kinds of multi-agent teams might be blurred.

Architects' design scope can extend beyond the building to involve the system within which architecture is realized as well as the tangible and intangible context within which it ultimately resides. Designing relationships as we design the architecture enables us to productively implicate the organizational bodies around a project, to influence the process of building, and to productively incorporate political, economic, and environmental conditions into the mix. By seeing beyond the object building, we can gain responsibility, and ultimately control, to generate an intercalated architecture that is fit to become a part of everything.

26 Programs like Parsons Transdisciplinary Design Program, Stanford's Design School, Konstfack University's Interdisciplinary Experience Design Group, and many others have emerged in the past decade to address the need to join design with business, humanities, sciences and other disciplines.

27 AIA Bi-Annual Firm Survey Series and internal reports on the Economics of Architecture has long tracked the trend of declining net revenues and increasing marginalization of the profession. The reports commonly cite the profession's inability to expand architectural services to proactively address the radical political, economic and organizational impacts on building construction.

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