This paper presents an integrated workflow for interactive design of shell structures, which couples structural and environmental analysis through a multi-agent systems (MAS) for design. The work lies at the intersection of architecture, engineering and computer science research, incorporating generative design with analytical techniques. A brief review on architectural shell structures and the structural logic of reciprocal frames is described. Through the morphological study of reciprocal frames locally we seek to inform the behavior of a MAS, which integrates form-finding techniques, with daylight factor analysis (DFA) and finite element analysis (FEA) on a global configuration. An experimental design is developed in order to explore the solution space of large span free form shells with varying topologies and boundary conditions, as well as identify the relationships between local design parameters of the reciprocal frames (i.e. number of elements, profile) and the analyses (i.e. stress distribution, solar radiation) for enabling the generation of different global design alternatives. The research improves upon design decision-making latency and certainty through harnessing geometric complexity and structural form finding for early stage design. Additionally, the research improves upon design outcomes by establishing a feedback loop between design generation, analysis and performance.

**Keywords:** Generative design, computational design, multi-agent systems, shell structures, reciprocal frames, form finding, parametric design
fordist perspective on the possibilities for architecture, namely a rejection of modernisms' over reliance on the self similar and an acceptance of the contemporary condition for mass customization. However, the work does not take the position of difference for difference sake but rather more importantly sees differentiation as an indicative of performance and natural design evolution. It furthermore situates itself intentionally in a discourse of emergence and of the viability, tenability and even perhaps enhanced characteristics highly complex and intricate geometry and tectonic systems may have for architecture. The availability of parametric and associative geometry systems has allowed for the invention and proliferation of non-Euclidean and un-variegated geometries and has facilitated design variation in accordance with designer intent and here, most critically, where complexity can be substantiated as higher performing. The research furthermore takes into account an era for architecture of an increased interest in performance based design models which combine analytical and evaluation processes with digital processes of form generation and rationalization (Gerber 2007). Yet our research sees performance as needing to be balanced with the synthetic, aesthetic and communicative aspects of all great design, in other words, the informing of form through both the design exploration and solution space thinking intrinsic to associative parametric and algorithmic generative design with that of complexly coupled empirical objective functions found in our engineering cousins analytical methods (Mitchell 2005).

Research has shown that empirically validated simulations and visualized information can assist designers in making better design decisions. Examples include when environmental analyses simulations are used during design development in order to enhance environmentally-conscious and cost effective design solutions (Roudsari et al. 2014, Eastman 1994). Another recent precedent includes the interactive design exploration of shell structures through form finding which demonstrates that complex structures can be more efficient than reduced and simplified systems, when the form-force diagrams are visualized and made accessible (Rippmann and Block 2013). Despite advances, the literature indicates there remains a lack of integrated and extensible workflows combining multiple analyses and generative design early in the design process. The necessity of such workflows for design through to construction of bespoke structures challenge existing tools and methods in part due to the complexity of the design constraints, parameter sets, and often conflicting and complexly coupled objectives (Shea et al. 2005, Scheurer 2010). Our work in part seeks to tackle this pervasive problem by providing a prototypical integrated workflow but also seeks to further the integration and adopting of computer science techniques of great interest and relevance to architecture, that of agent based models or here more specifically the multi-agent system (MAS).

BACKGROUND
With the introduction and pervasive availability of reinforced concrete in the 20th century, an interest in the use of thin shells and funicular structures for architectural purposes becomes prevalent (Pietraszkiewicz and Gorski 2013). This is easily observed through a survey of the great number of large span shell structures that were realized in 20th century with functions that vary from stadiums, to factories and airplane hangars to name a few (Adriaenssens et al. 2014). Famously, architects like A. Gaudi and H. Isler developed apparatuses such as the hanging chain and fabric model methods in order to simulate, test and calculate shell structures (Chilton and Isler 2000, Ochsendorf 2010). In similar analogue fashion F. Otto, studied the behavior of grid shells and membrane structures, while structural engineers like P. L. Nervi and F. Candela investigated statics and construction techniques and by manipulating them achieved the construction of unique thins shell structures such as Agnelli Exhibition Hall in Turin (1948) and the Chapel Lomas de Cuernavaca (1958) (Tomlow et al. 1989, Burkhardt et al. 1976, Garlock et al. 2008). These researching
practitioners all are credited with laying the foundation of what is called architectural form finding today. More recently, researchers have been developing computational methods for modeling and solving or "form finding" structures to find equilibrium. Killian among other researchers developed interactive, real-time hanging chain modelling tools, using particle spring system solvers (Axel Kilian 2005). Piker, developed "Kangaroo" a tool for real time exploration of funicular networks using dynamic relaxation while Block has developed a methodology and tool for the exploration of funicular shells under compression based on Thrust Network Analysis (Piker 2013, Block and Ochsendorf 2007).

Our literature suggests that the future of digital design lies in considering the computer as a collaborative partner in the design process that is capable of generating design alternatives and evaluating different solutions in response to robust and rigorous analytical models of design conditions and performance (Gerber et al. 2012, Pask 1969, Mitchell 1990). Moreover, the literature indicates that in order to manage contemporary design demands, architects and designers need to shift away from reductionist models that rely on standardization and segmentation of functional requirements and use analytical simulation tools that provide designers with useful performance feedback (Oxman 2008, Malkawi 2005). Therefore, there is a need to develop interactive and integrative design tools that intuitively allow designer to understand the relation between geometry and performance, promote geometric, material and functional differentiation and provide a seamless data flow from design to construction for among all participating counterparts.

**RESEARCH METHODOLOGY**

Our interest lies at the intersection of architecture, engineering and that of empirical models to enhance performance criteria in broad terms. In designing systems and methods that enable architects to develop free form shell structures that are: computationally generated, intricate and highly varied geometries,

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Figure 1
Experimental workflow diagram illustrating the context, generation, analysis, and materialization and feedback steps of top down, generative, feedback and optimization, and then to material prototyping.
and that span continuous open architectural spaces. The research contributes to the discourse where the complex is embraced as opposed to reduced. Here our hypothesis states that by combining interactive form finding techniques with environmental analysis, via a MAS for design approach, designers can achieve the generation of alternative shell structures, which perform better across multiple performance criteria when compared to purely deterministic and or manual design exploration methods. The scope of the work presented here includes, the defining and optimization of structural components, the environmental efficiencies gained, and, and a discussion of the design decision making affordances for the designer. Another critical objective is to evaluate and argue further for how the non-standard can be found to outperform the standard structural system.

Our research methodology includes, the formulation of an integrated workflow for the design of efficient shell structures, which are based on the reciprocal frame structural system (see Figures 1-2). This is developed through a custom MAS which is validated through a series of incremental experiments and comparisons. These experiments include the generation of a set of shell models, which are expressed and prototyped as reciprocal frames, which are not solely driven by structural efficiencies but coupled with environmental considerations. The software prototype combines form-finding techniques using a spring based mesh relaxation solver (Rhinoceros Grasshopper/Kangaroo), with environmental solar radiation analysis (Rhinoceros Grasshopper/Ladybug, Radiance) in order to drive a multi agent system (Processing, IGEO). Both the global geometry (shell) and the local (reciprocal frame) are conditioned based on a set of user defined environmental parameters such as: geo-location, footprint area, support conditions and material. The research then studies the properties of the reciprocal frame design alternatives locally, in terms of different number and shape of elements, and explores which the relationship between each design parameter and the structural analysis. Globally different support conditions and loading conditions are studied. The system uses the analyses (i.e. stress distribution, solar radiation maps) and the relationships between different design parameters as inputs for the behavior of a multi agent system (MAS), which generates alternative morphologies of reciprocal frames (See Figure 4). The morphology of the reciprocal frames is informed by the combination of the structural and environmental analyses via a MAS driven optimization. The goal is the generation of more efficient structures, which span large areas with the use of short structural members (material economy) while providing improved environmental conditions beneath them (energy economy).
DESIGN OF THE EXPERIMENT

The project explores a design methodology for shell structures, which combines form finding informed with environmental parameters and the application of a modular structural system that of reciprocal frames. The principle of reciprocity in structural design and construction i.e. the use of load bearing elements to compose a spatial configuration wherein they are mutually supported by one another has been in use since antiquity. The design of the experiment includes the analytical study of the reciprocal unit and the application of reciprocal frames on form found shells. The form finding process is occurring though a MAS based approach where a physics particle engine is informed by user specified environmental parameters (longitude, latitude, orientation, sun position). The generated shells are populated with reciprocal frame units which are analyzed structurally both locally and globally. Based on the structural analysis on a local level key design parameters of a reciprocal unit such as: a) the length, and b) thickness of elements are adjusted in order improve the structural performance globally. In this experiment we focus only on two aforementioned design parameters, in Figure 4 we illustrate all key parameters of the reciprocal frames(see Figure 4). The research then implements the above methodology by developing the computational workflow (see Figure 2) that in-
includes both a generative and an analytical component informing each other. The generative part of the workflow is developed using Processing and the IGeo libraries while the analytical part is developed in Rhinoceros 3D software using Grasshopper and specifically a) Kangaroo b) Karamba, and c) Ladybug plugins (see Figure 1). The workflow is tested by developing an experimental design case study, that of the long span hangar in its global form. The experimental design process includes the definition of a covered area, support conditions and amount of elements to be used, as well as structural parameter such as elasticity, connectivity between mesh points (particles as frame elements) and friction. A shell geometry is generated based on the combination of force distribution (self weight) and solar path positions (shading). Once the geometry reaches equilibrium, reciprocal frames are applied on the surface.

Figure 4
Design parameters for reciprocal frame and stress distribution of different units based on the number of elements.
at every point of the geometry where the architect and design team controls the valency (number of elements in one reciprocal unit), as well as the parameterization in the generation of varying element profiles (i.e. sectional profiles). The generated geometries are analyzed both locally and globally where the design has a graphical overview of the stresses induced in the profiles assuming a certain material and load condition (see Figures 3 and 4). For this experimental run we kept this constant as Douglas Fir South Wood and 1kN load distributed over the entire surface area of each beam element. The geometric properties of the results are visually assessed by the designer in correlation with their structural performance (see Figure 5).

**Case Study: An informed reciprocal frame long span shell structure**

In order to validate the systems and methodology, the MAS is applied on the conceptual structural design of a large span hangar structure. We use our approach for the design of reciprocal frame structures with different topologies that span 50m and we compare it with a recently built structure of the same size. We use the comparison between the different cases as a means for benchmarking efficiencies of our methodologies and for drawing conclusion for the further refinement of our system.

**RESULTS AND ANALYSIS**

The results of our work so far are on both a local and global level. On a local level we test different section profiles, which range from standard to not standard and observe that the structural performance of each reciprocal element is largely affected by cross sectional profile. Six different types of profiles are tested including: a circular pipe, a rectangular element, and 4 types of planar elements with different, a) proportions of width over height, and b) with one transformation (torsion along main axis and offset along main axis. We plot the stresses on the reciprocal elements with different geometries in relation to varying length and thickness (see Figure 5). We observe that only one type of element (twisted planar) fails to meet the requirements for allowable stress based on the American Building Code while the rest of the profile types show an almost linear relationship of their length and thickness to the stress. We note that as the length increases the stress also increase while as the profile increases the stresses on the element decrease. In terms of the unit we observe that as the number of elements increases (valency) the stress decreases (see Figure 5). For a unit (reciprocal frame) of n=3 and a pipe profile the stresses can be as high as 1620 kN while for n=6 it drops as low as 703 kN (66%) At this stage, for simplicity and clarity of the experiment we test only one pro-
Figure 6: Structural analysis of global geometries generated by varying agent behaviors. Figure 7 (below): Solar Radiation analysis of global geometries which have been generated with form finding and with different agent behaviors.
file type and reciprocal frame unit (n=3) for applying it on the global geometry. In terms of global geometry we generate 4 different topological cases based on the support conditions and whether or not the geometry has an opening. We test one of the topologies for both a span of 50 and 100 meters. We analyze both the form found and environmentally influenced geometries and measure the following: principal forces (compression, stress, moments, displacement and cross section utilization (see Figure 6). The utilization of the cross section is the ratio of applied stress over yield strength of the element and using a safety factor of 200% we size the elements in order to achieve a target utilization which is between -50% to +50%. Additionally, the maximum displacement is measured which is within limits (0.5 to 5cm). The structural analysis shows that geometries with a hole have a significant increase in moments (130-200% increase) while we observe that the amount of support conditions does not affect significantly the resulting principal stresses rather their position and shape (see Figure 6). The environmentally informed shells are subject to higher principal forces as their form is modified from the pure form finding however they are performing better in environmental analysis (see Figure 7). Although the designed workflow is controlled manually by the user in terms of generation and transfer of geometrical data for finite element analysis, the intent is to lay a foundation that can be automated for generation and analysis to form a singular structural agent, which has as an input the analytical results and as an output modifications on the defined design parameters. With proper automation, ample results can be generated for different profiles, different notch styles, varying material parameters, varying cross-sectional dimensions and varying frame morphologies. The next steps include the development of an autonomous structural agent, which will be able to analyze, visualize and evaluate structural analysis data from the generated geometries and communicate information to the generative agent in order to continually optimize the next generative iterations. The final objective is to develop a Multi-Agent System for architectural, structural and environmental optimization from design to construction.

CONCLUSIONS
This paper presents the application of a MAS for design approach that supports the integration of structural performance in order to inform the design decision making of a generative design process, leading to improved design solutions and in this case long span reciprocal frame structures in an applied hangar configuration. The aim of this work is two-fold, a) to explore how designers could implement non deterministic processes where the precise definition of local rules can be combined with analytical tools in order to lead to globally optimized geometries, and b) to develop an integrated design methodology based on MAS that provides designers with not only geometric feedback but structural performance feedback and thus assist them in generating and selecting among well performing design solutions. The presented experimental case illustrates how a MAS for design in architecture approach can be developed and tailored to specific design problems in order to assist architects and designers in generating higher performing design solutions in terms of structural and environmental performance.

Here the experimental results are presented in the form of three scales and investigations: 1) the reciprocal frame morphology (valency); 2) the cross sectional and element lengths; and 3) the global configuration of a shell structure, the hangar. The geometric configurations of the design solutions may vary but the coupling of the generative with the analytical and optimizing processes ensures the satisfaction of prescribed structural goals. Our objective has remained to demonstrate the value of the emergent, non-standard, and geometrically intricate as a viable post fordist solution for form finding and performative driven design. The system was able to generate shell as reciprocal frame configuration(s), which provided longer spans based on short self-similar elements. We have demonstrated that architects and designers can benefit by implementing an
integrated bottom up design approach for the design of building components that lead to optimal global configurations. By combining analytical methods with user data, properly formulating and passing such data automatically to a generative process, we provide designers with a larger pool of complex yet well-performing design solutions that could not be modelled manually. The experimental case study and results showed improvements both in terms of energy efficiency by generating solutions that increased the amount of available daylight, as well as in terms of design process as we provide the designer a methodology to augment an existing design approach, that of pure form finding while integrating environmental parameters as well. By analyzing and cross-comparing the results, the continued objective is to deduct heuristics and weighting factors to provide intuition and to further model behaviors for our agents in order for the MAS system to be able to automatically generate a series of design.

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