High performance 3D printed façade with integrated energy: built works and advancements in computational simulation

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Figure 1: Rendering of AMIE enclosure concept design and PUV (Printed Utility Vehicle)

Abstract

AMIE (Additive Manufacturing and Integrated Energy) was a collaboration to 3d print a building enclosure prototype that was designed and built to showcase the capabilities of additive manufacturing and its application in high performance buildings facades. The design integrates low cost vacuum insulated panels that are sandwiched between two layers of a 3D printed shell. The structure was 3D printed using the Big Area Additive Manufacturing (BAAM) technology. AMIE incorporates next generation modified atmosphere insulation panels, self shading windows, and the ability to produce, store and share solar power with a paired hybrid vehicle in an effort to reduce or eliminate reliability on the power grid. It establishes for the first time, a platform for investigating solutions integrating the energy systems in buildings, vehicles, and the power grid. This paper is intended to outline our methodology in successfully designing for these innovative strategies, with a focus on the use of computational design tools as a catalyst for design optimization, integrated project delivery, rapid prototyping and fabrication of building elements using additive manufacturing. Future work is proposed that plans to develop component and system models from the innovative strategies applied on AMIE for use in a wider range of system design applications.

Keywords: AMIE, 3d Printing, BAAM, Vacuum Insulated Panels, Dynamic Facades, Co-simulation.

1. Introduction

The AMIE (Additively Manufactured Integrated Energy) demonstration project was the result of a broad collaboration between members of national labs, design industry, and academia. It was these partnerships that ultimately made AMIE possible, given the wide range of expertise and resources required to realize a project with this magnitude.

The AMIE demonstration project, shown in (Figure 1), utilizes additive manufacturing to connect a natural-gas-powered hybrid electric vehicle to a high-performance building enclosure designed to produce, consume, and store renewable energy. All components of the demonstration were designed, tested, built, and assembled in nine months. Components of the building and vehicle were additively manufactured (3D printed). The vehicle's natural gas engine provides complementary power to the building. The photovoltaic panels on the building roof harvest solar energy and store it and can be shared with the vehicle. This concept can potentially enhance the resiliency and cost-effectiveness of two major challenging demands in our cities worldwide namely housing and transportation.

The use of additive manufacturing or 3D printing at full scale in architecture application is still at a very nascent stage. While there are other efforts to explore these areas of rapid prototyping of building construction using traditional materials like concrete, the work presented in the paper focuses on printing using carbon fibre-reinforced ABS (Acrylonitrile Butadiene Styrene) material similar to desktop 3D printers with one major limitation. The system used during this research doesn't allow for printing overhang parts since BAAM (Big Area Additive Manufacturing) does not use additional support material that would allow for this. The AMIE research project focused on testing the performance of the 3D printed exterior wall assembly paired with the modified atmosphere insulation panels. Additionally, the advanced modelling techniques and the geometry optimization that were used during the design of the enclosure and the assembly process of AMIE.

New endeavours by the team plan to develop component and system models from innovative elements of the AMIE demonstration project for use in a wider range of system design applications. The method will compile discrete models which represent a given element, such as the heat transfer behaviour of the 3D printed wall construction and modified atmosphere insulation panels, for use in building energy modelling tools through co-simulation.

2. Enclosure design and assembly

AMIE is a single-room building unit that was designed to showcase the capabilities of additive manufacturing and its application in high performance buildings. The design integrates low cost vacuum insulated panels that are sandwiched between two layers of a 3D printed shell. The structure was 3D printed using the Big Area Additive Manufacturing (BAAM) technology [1] (Holshouser et al., 2013). BAAM technology enables rapid production of sturdy, lightweight composite parts that are 5 times stronger than wood.

The building exterior shell was designed as a series of 10 rings. The width of each ring is 2ft which is driven by the maximum size of the vacuum insulated panels. Also by keeping the ring width relatively small reduced the weight of each ring for the final assembly. The overall dimension of the enclosure is L 10.9m (36ft) x W 3.6m (12ft) x H 4.2m (14ft). AMIE design team tried to utilize the capabilities of the BAAM by creating a 3D printed panel system that incorporate all the elements of a wall sandwich including structure, insulation, air and moisture barriers, and exterior and interior cladding into one vertically integrated building shell. This approach allowed for efficient use of the material. The BAAM system also allowed for easily printing doubly curved surfaces or undevelopable surfaces [3] without the need of a custom mold for each unique ring not only for aesthetics, but also the curved surfaces reduce localized stresses on the exterior(Figure 2).

The printing was done as half ring at a time in a C shape which were then combined to form the full-ring and joined with a steel plate. 80 percent of the enclosure was 3D printed with carbon fiber-reinforced acrylonitrile butadiene styrene (ABS) plastic composite material using the BAAM system.

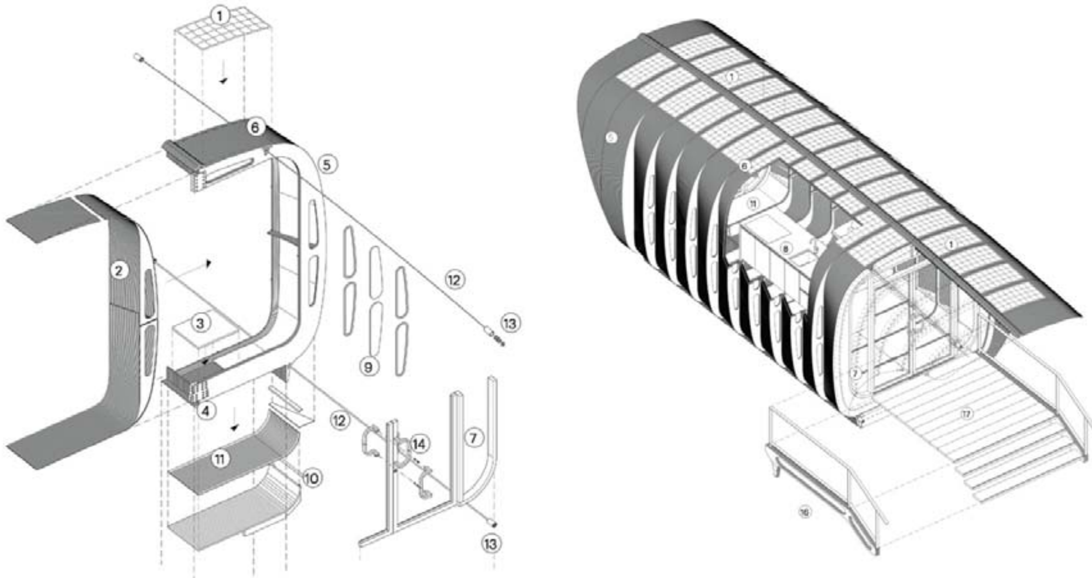

Figure 2: Left: Master ring components. Right: Assembly diagram of AMIE components

The printed half-rings were designed to standardize non 3D printed component such as the glazing. While each ring is unique as the result of the overall doubly curved surface that the main geometry was created from the, tear drop opening on the gills are all exactly the same size. At the same time, despite the small size of each side window, when combined together it floods the interior with natural indirect light. This also allowed the majority of the exterior wall to remain opaque and insulated, achieving a total overall window/wall ratio under 20%. The angled opening gills created visual phenomena in the interior where the user experiences the space differently based on the point of entry (Figure3).

Figure 3: Left: Joined rings from exterior; Right: Joined rings from interior.

During the design process two major constraints of the BAAM printer were considered. The first was the structural weakness of the printed parts in the z-direction. As consecutive layers of ABS were deposited building up the part in the z direction, the structure was always strongest in the x-y plane of the print bead, due to the partial cooling of the material between each printed layer. The team oriented the rings aligned to the x-y plane of the print bed, thus utilizing the strength of the x-y direction for vertical forces. Additionally, to prevent any separation of the layers, the structure team used a post-tensioned steel rod sunning the full length of the building keeping the rings and the 3D printed layers in constant compression.

The second constraint was that the BAAM system does not include any secondary support material deposition for the part. This doesn't allow printing any overhang parts or undercut in the model. The team experimented with different build up angles that can allow the extruder to print partial overhang pieces especially at the joint rim between each ring. Later the team realized that if any travelling angle made by the extruder are greater than 40 degrees, the print layers start to sag and result in a failed print. This constraint dictated the angle of elements such as the exterior shell detail shown in (Figure 4).

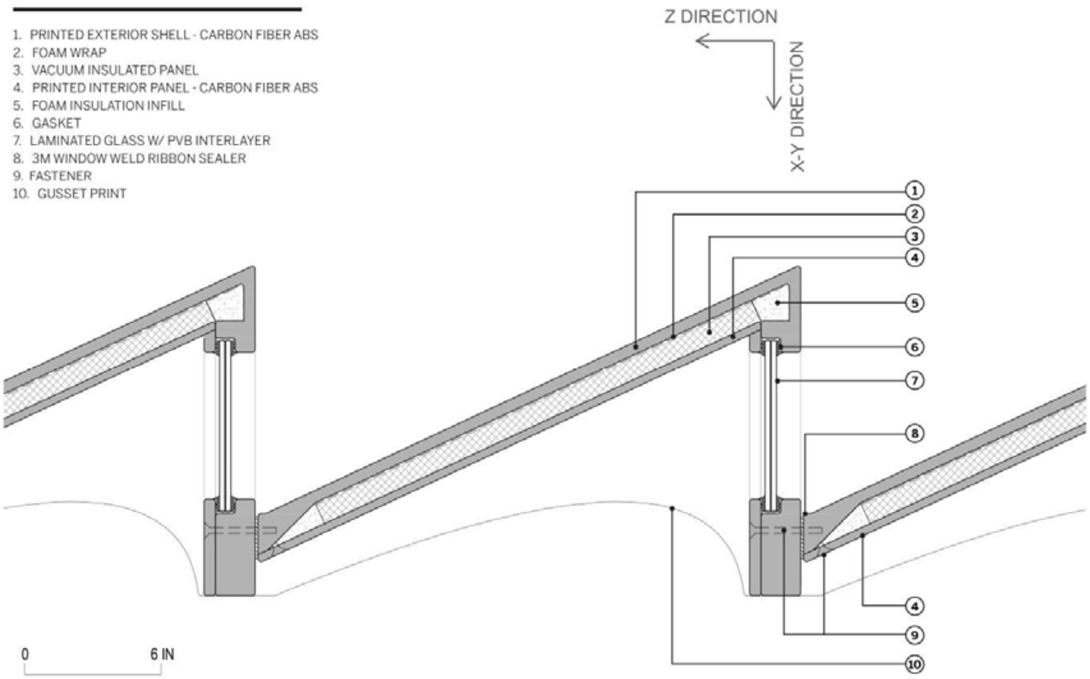

Figure 4: Plan details of ring connection and glazing.

The use of rapid prototyping and the direct design to print approach enabled flexibility/power in design by removing constraints of traditional methods. The total weight of the printed enclosure is approximately 13,500 lbs. At a rate of 60 lb/hr, the total print time was estimated to be four weeks: 13,500 lbs. * 60 lb/hr = 225+ hrs., not including machine setup time, etc. (Figure 5) shows the printing of the ABS rings and (Figure 6) shows the process of exterior rings assembly.

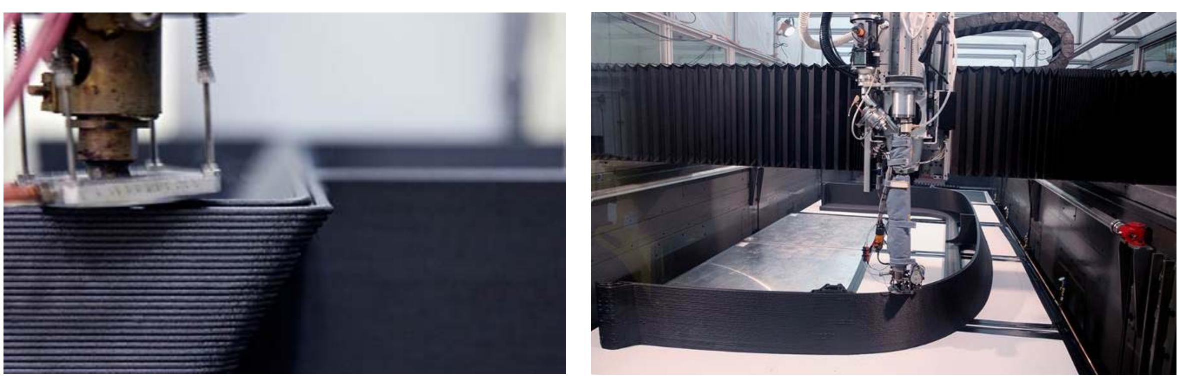

Figure 5: Left: Printing ABS layers; Right: Printing AMIE ring on the BAAM.

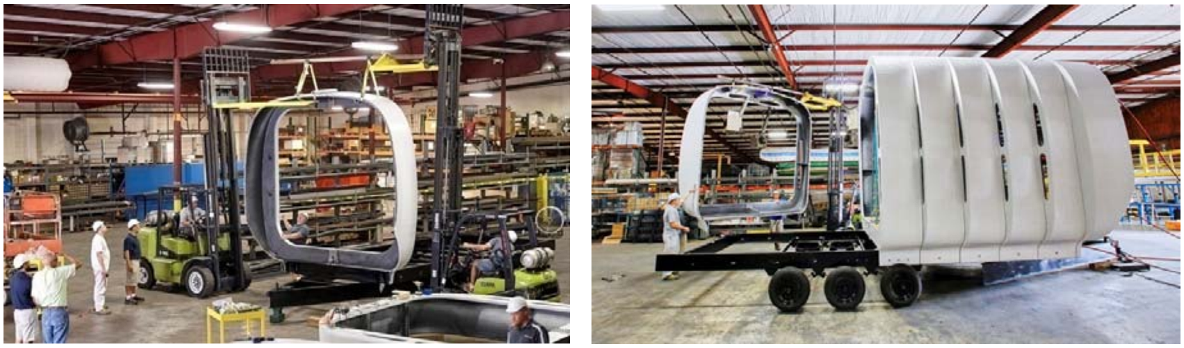

Figure 6: The assembly of AMIE enclosure

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2.1 Non-3D printed parts meets maximum flexibility of model alteration

Since the BAAM system allows for printing at high level of accuracy, the research team decided to utilize this capability to incorporate all the details of the hook ups, sockets, shrouds and sleeves, and to receive any non-3D printed parts such as glazing, light fixtures, tension rod, doors, and the HVAC system.

At early stages of the design none of the final products were yet specified, the algorithmic definition was designed to include a place holder for each known part with maximum flexibility to add any new elements as required to the model throughout the design process. For instance, the structure team addressed the weakness of the print in the Z direction by introducing a pre-tensioned rod that runs through the whole structure connecting both ends. A special sleeve was added to the model at the four corners of each ring. Additionally, a custom pocket was added to each end of the canopies to host the rod disk spring. All brackets for ceiling light fixtures, HVAC covers, doors and window frames were also dealt with in the same fashion (Figure 7).

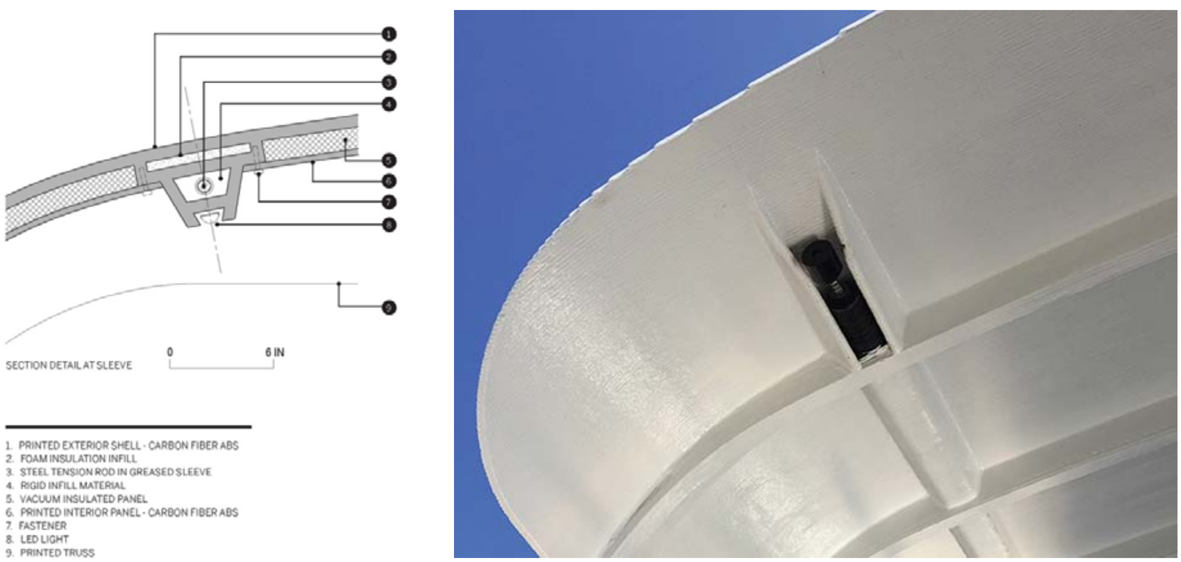

Figure 7: Right: details of pre-tensioned rod sleeve and light fixtures socket
Left: 3D printed canopy with incorporated disk spring pocket

2.2 The vacuum insulated panels

To create thinner wall sections, the use of vacuum insulation panels (VIP) [7], which exhibit thermal conductivity of about 0.004 W/m/K compared to ~0.03-0.04 W/m/K of commercially available building insulation materials, was considered. While VIPs have not seen widespread application in buildings, especially in North America, there are several studies discussing the potential of VIPs in buildings [8-10]. In AMIE, a novel, lower-cost version of VIPs, called modified atmosphere insulation (MAI), was used. Using MAI yields high thermal resistance in thin sections, enabling significant reductions in material required for the joints and structural members. (Figure 8) shows the installation of 1 inch thick MAI panels in a wall section of AMIE; some sections of the walls were insulated with 1 inch thick regular foam boards for comparison of heat transfer allowed.

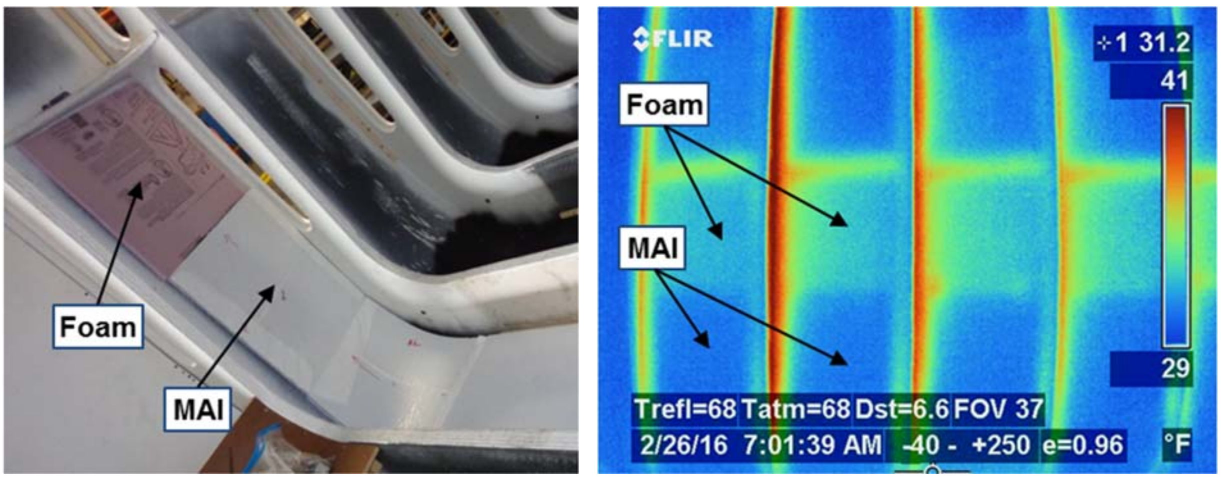

Figure 8: Left: MAI in AMIE. Right: infrared image distinguishing the heat transfer through AMIE sections containing MAI and foam insulation.

2.3 Rapid model adaptation for major design changes

Initially, the design team chose to use reinforced fiberglass ABS for its durability during the initial tests and for its natural white finish, eliminating the need to paint the final print. However, after the first full C ring was printed, a major layer delamination problem occurred, and the research team started to question the structural integrity of the material for that scale. More tests were done and it became apparent that ABS reinforced with 30% carbon fiber (black) is a better choice, resulting in much more durable printed sections and no layer delamination occurrence when printed at full size scale.

16 different models with various offset increments (0.35, 0.36, 0.37 and 0.38) and different mesh density/quality for each one (50%, 60% and 75%) were tested using tool path simulator software. A total of 48 models were tested to determine which increment translated the best -especially when only using a two-bead thickness for the warped wall shell- and to find the balance between speed, resolution and the quality of the final print (Figure 9). Increasing mesh quality to the finest level of mesh resolution resulted in eliminating all the gaps in the prints, but it significantly increased the printing time. So the team was trying to find a balance between mesh quality and printing time. Next, the team updated all the offset dimensions in the model based on the new tested increment. This mesh optimization resulted in reducing the printing time from 14– 15 hours per C section (half ring) to 7 – 8 hours (a 48% reduction in production time). The team also tested different mesh translators to get better control of mesh density distribution. Algorithmic modelling [3], [4], [5], [6] played a significant rule in rapid model adaptation. Using traditional modelling techniques this task would be virtually impossible, requiring complete rebuild of the model every time one of these changes was made.

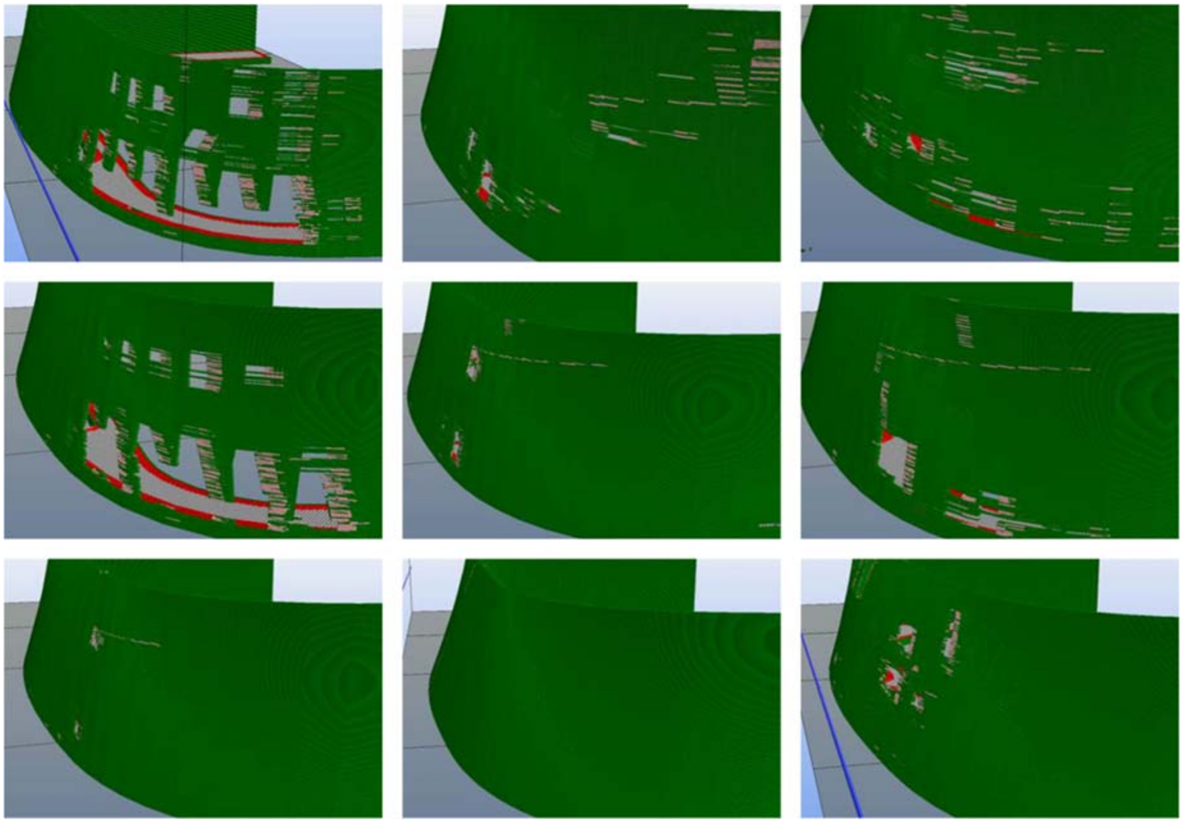

Figure 9: Testing of the various bead sizes and mesh density using the tool path simulator

3. Advanced project delivery

During the production of AMIE, an alternative process of building was demonstrated. Traditionally, architects design a building and provide drawings to the contractor. The contactor then prepares shop drawings for fabrication to be reviewed by the architect. The original design intent can be affected by multiple layers of drawings, reviews and communication exchanges.

However, with AMIE, the designers worked very closely with the researchers and the team responsible for the final assembly of the parts. Rather than issuing the typical 2D representational drawings, the AMIE deliverable was the actual 3D digital model shared directly with the printing team as an IGES data file (Figure 10).

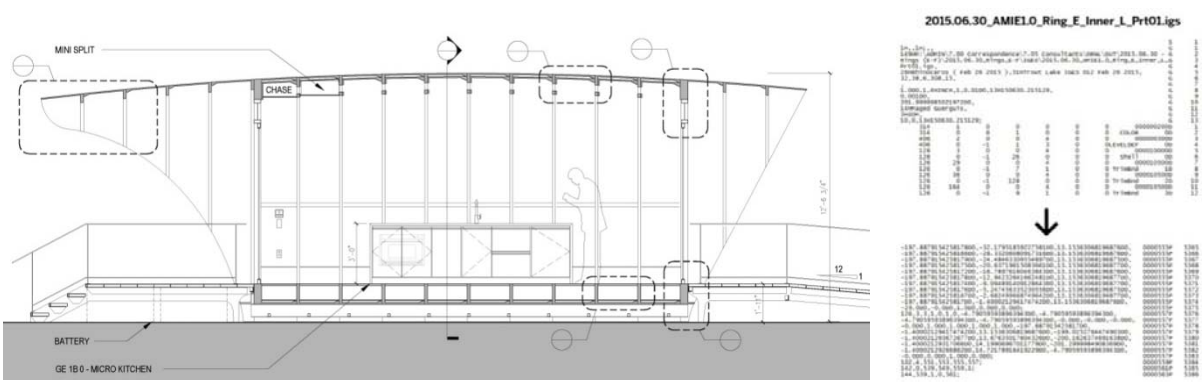

Figure 10: Construction document versus IGES data files

4. The integrated energies

AMIE features the world's first level 2 (6.6 kW) bi-directional wireless power transfer system. The transfer system allows driver to charge the vehicle wirelessly when parked over the charging pad. The smart control system is designed to decide which way the wireless power transfer should send energy and the origin of the energy (e.g., solar, wind, battery storage, the grid). This method offers a convenient and safer alternative to plugging the electric vehicles into wall outlets (figure 11).

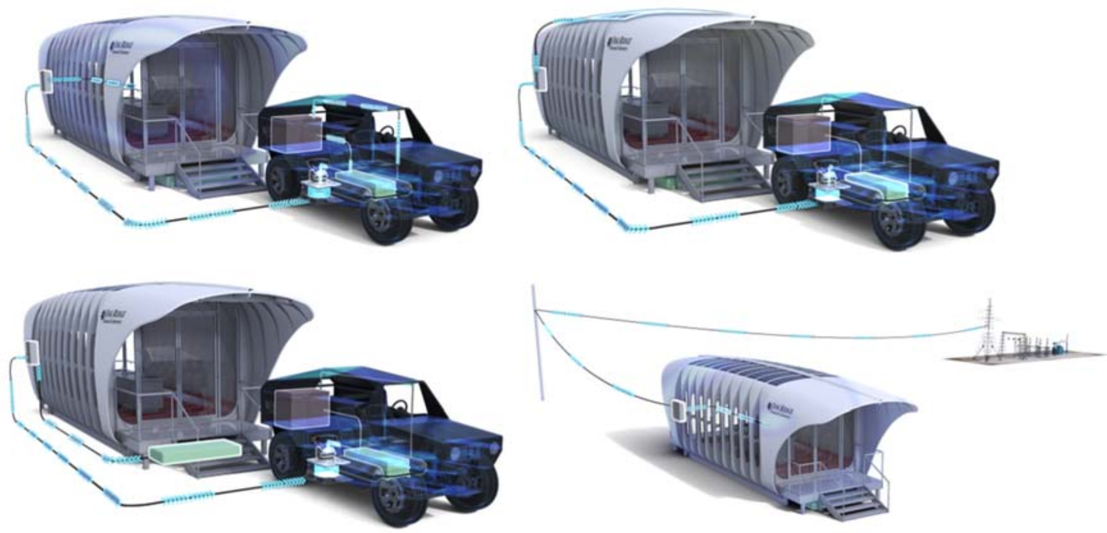

Figure 11: Building control and power management strategies directing electrical energy flow.

5. Conclusion and Future Work

AMIE (figure 12) is the world's largest 3D printed polymer structure that can share power with a vehicle. This research was completed in a period of nine months, AMIE is an examination of new ways and technologies to design and build energy efficient buildings that can also efficiently integrate with the grid and vehicles. In addition, AMIE's design explores the potential for 3D printed systems of building component to combine all of the wall elements such as structure, insulation, air and moisture barriers, and exterior cladding into one vertically integrated building shell eliminating the need of assembly of smaller parts while significantly reducing the wall thickness and achieving high insulation value.

The design, engineering and science generated in AMIE also provide momentum for other examinations of how large-scale additive manufacturing can be used in buildings. The high geometric control of additive manufacturing paired with algorithmic modelling allows precise openings for fenestration, sockets, and other details to be included in the model rather than being added later as separate elements greatly reducing waste in construction. With industry partners, the AMIE team will continue to investigate this and other opportunities to leverage the success of AMIE to achieve energy efficient building technologies solutions.

The AMIE demonstration project incorporated novel combination of building constructions, systems and controls into a physically deployed installation. Discrete systems of the AMIE demonstration will be made into computational models that are adaptive and deployable to a wide range of climates and building applications[8]. The physical demonstration provides the opportunity to take measured data from the deployment to calibrate and validate the accuracy of the computational models, allowing the development of system models closer to how the actual systems behave. The computational models will be coupled with building energy modelling tools, such as EnergyPlus, and co-simulated together [9] to assess the energy savings of the innovative strategies and the potential of integrating them into future design applications.

Figure 12: AMIE final assembled enclosure

6. References

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