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3D printing of HVAC systems

3D-Printing (additive manufacturing) has been a paradigm change for the manufacturing industry especially on the last decade. It is expected that it will be used in the enterprise within the following 2-5 years. We predict that additive manufacturing will be the primary method for the production of HVAC systems; firstly, components such as heat exchangers (3D-CM), followed by the Equipment Manufacturing (3D-EM), and finally the technology will be adopted to the integrated design and 3D building construction (3D-BC).

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Introduction

3D-Printing (additive manufacturing) has been a paradigm change for the manufacturing industry especially on the last decade. It has basically been used as a hobby tool and for the production of non-functional parts to aesthetically control the design, it is also being used for manufacturing functional parts in the prototyping phase in a very wide range of industrial fields. As the technology has been developed, additive manufacturing has also been used for production of fully functional parts, even in the aerospace industry. There are many organizations and collaborations to study the technology and environmental impact of additive manufacturing and build the industrial standards. It is expected that additive manufacturing will take the place of today's industrial production methods and affect value chains to a significant extent within the next decades, along with the development of relevant design theory and tools. Especially, the future of industry shaped upon "cloud manufacturing" and "mass customization", relies on additive manufacturing the most. The Hype Cycle of Gartner on emerging Technologies reports that enterprise 3D printing is to be used in the main stream industry in the following 2–5 years.

One of the areas that additive manufacturing will have a significant impact will be the Architecture, Engineering and Construction (AEC) industry. The hot topic about building technology is integrated design that includes the overall design of a building including all of its components in harmony. This was also a hot topic in the old times. Two examples of integrated design solutions of the past are Ondol and Hypocaust systems. Ondol system is an example from the eastern world that was used in the traditional houses of Korea for cooking and underfloor heating simultaneously. Hypocaust is an example of integrated design of Greco-Roman World, which is a kind of central heating system in a building that produces and circulates hot air below the floor of a room, and may also warm the walls with a series of pipes through which the hot air passes. The hot air carried by the pipes can warm the upper floors as well [1].

The hypocaust system was built by bricks, which is a kind of additive manufacturing process (**Figure 1**). Therefore the Hypocaust system can be assumed as the ancestor of the near future's buildings, which will be constructed in a holistic approach. The buildings of the future will be constructed at once by additive manufacturing with all of their architectural elements, HVAC systems, and sanitary systems, as their ancestors were built.

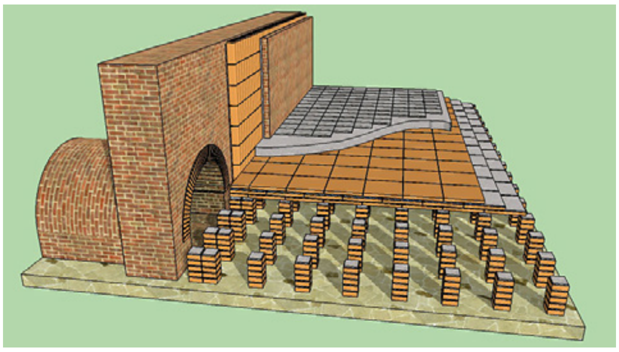


Figure 1. A Hypocaust system construction. [2]

An early example on additive manufacturing of buildings is by the group of Khoshnevisk [2] in 2004. They named the method as "Countour Crafting" which is an additive manufacturing application for building construction. The method is said to be most useful for emergency reconstruction by disaster and relief agencies working in third world nations devastated by earthquakes, floods, other natural disasters and war. However, they worked on developing technologies on this subject including a project (together with NASA) on using the additive manufacturing for building space colonies. They also mention about the integrated design needs and the possibility of manufacturing HVAC equipment together with the building itself.

More recently, in 2015, World's first 3D printed apartment building was constructed in China. In 2016, world's first 3D-Printed and fully functional office building was constructed in Dubai. All of the furniture of the office were also printed. There are many other examples of 3D printed houses and structures around the world. Some are modest to utopian shelters and the other are fully functional buildings for different purposes. There are also many interesting and/or functional designs waiting to be built [3]. What is more, some of those are designed to be constructed in a modular way which is a very efficient method of using additive manufacturing. Factories having a number of 3D printers for this purpose may be set up and manufacture the modules in the construction site. The modules then will be used to build up the building. The integrated design of a module will probably include some or all of the HVAC and sanitary components and we can imagine that they will be produced during the additive manufacturing phase.

Is the HVAC industry ready for the change?

There are some signs of awareness on the topic, but not being discussed widely. Additive manufacturing is being used in the prototyping phase of HVAC components and equipment, especially by the fan manufacturers. Some researchers has focused on the heat exchanger technology. A team from University of Maryland used direct metal printing (DMP) to manufacture the miniaturized heat exchanger as a single, continuous piece using titanium [4]. Another example is the design, fabrication, and test of a plastic heat exchanger [5]. However, there is not any information about these research and development studies that they have resulted to mass production by additive manufacturing.

Two important studies on the possible status of additive manufacturing and integrated design are reported by Tibaut et al. [6] and Joplin [7]. Tibaut et al. [6] introduced the concept "Digital Fabricated Buildings" and reports that additive manufacturing has potential to be "the next big step forward" for the AECO (Architecture, Engineering, Construction and Owner-operated) industry. Although application of large-scale additive manufacturing systems in this industry is in early research phase, it is expected that are further parameterization of the interoperability demand function, BIM maturity, automation of workflow models, and new approaches for engineering of embedded building elements will be the important research and application topics of the near future [6]. New approaches for engineering includes freeform constructions inspired by the nature for the building construction elements and HVAC, sanitary, electrical etc. components. Joplin [7] reported the Innovations That Will Change HVAC Forever including 3-D Printed Air Conditioners as an expected consumer product of the future.

We predict that additive manufacturing will be the primary method for the production of; firstly components such as heat exchangers (3D-CM), followed by the Equipment Manufacturing (3D-EM), and finally the technology will be adopted to the integrated design and 3D building construction (3D-BC).

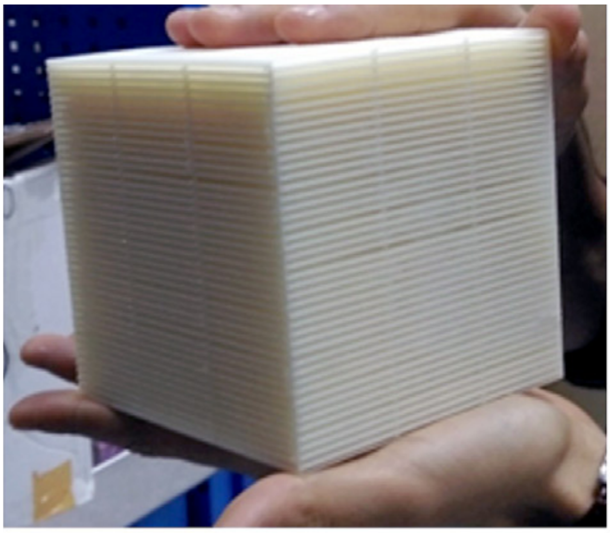
Preliminary R&D studies

A task force has been established to work on a project about implementation of additive manufacturing technology to HRV (Heat Recovery Ventilation) systems including all three phases of the progress as 3D component manufacturing, equipment manufacturing, and building construction in İzmir (Turkey). The first step is component manufacturing and we have started with the heat exchangers. Cellulose, pet, or aluminum heat exchangers are mostly used in HRV systems. A wide range of materials are available for additive manufacturing but ABS (Acrylonitrile Butadiene Styrene) was used to produce the air-to-air cross-flow plate heat exchanger material. As this is a conceptual study the material is not the primary matter of interest, instead producibility is the main concern.

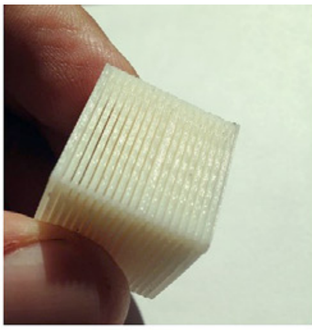
The main parameter that effect the producibility is geometry. A new approach to geometric design needed. Different than the conventional manufacturing methods, adding material in a discrete manner totally changes the dimensioning and tolerancing strategies during design. The critical geometric parameters are layer thickness, single wall thickness, and nozzle diameter while using the additive manufacturing method. There are a wide range of 3D printers in the market and the technology is in a very fast progress. Therefore, supply and demand balance will be ruled by the demand side in the near future.

In our case, heat exchangers always have gaps. Another question is question is how can we build gaps by adding material? Support materials or supporting structures are used during manufacturing. After the manufacturing process, cleaning starts either mechanically or chemically. However in tiny gaps mechanical cleaning is very hard. More time, material and money is used when supports are used. A more logical solution is constructing a self-supported geometry that can be manufactured without using any supports. Topology optimization is the keyword while determining the most efficient way of manufacturing process, and also having an optimized performance of heat exchanger by means of heat transfer and pressure drop. There many other problems waiting ahead. But the opportunities of the additive manufacturing by means of free form or non-linear geometric designs will certainly produce more efficient components. Same examples of the heat exchangers produced by additive manufacturing are given in **Figure 2**.

The next level is equipment manufacturing. An ordinary commercial HRV unit which is manufactured and designed for conventional production. Many processes exist during manufacturing of this unit. A hybrid approach is to produce the casing by additive manufacturing, which can be manufactured as a single continuous piece, and other components (heat exchanger, fans, filters, and electronic equipment) are assembled afterwards (**Figure 3-a**). A more **additive** approach would be to produce the body and the heat exchanger as a single continuous piece and assemble the other components afterwards (**Figure 3-b**). When you are free about the production method and supply procedures, you can free your mind and focus on the main problem, engineering. The second design (**Figure 3-b**) has a heat exchanger volume of almost twice the first one (**Figure 3-a**), when the outer dimensions are kept constant. Engineering and integrated design will be



a- A cubic cross-flow heat exchanger having an edge length of 10 cm



b- A cubic cross-flow heat exchanger having an edge length of 2 cm, gap thickness of 260 µm and wall thickness of 260 µm

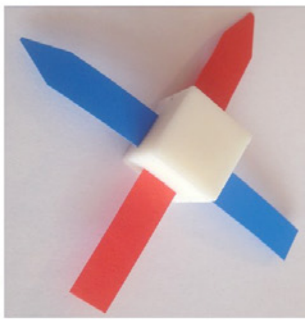


Figure 2. Same examples of the heat exchangers produced by additive manufacturing.

more important than ever when the method is fully available for the industry. We are on our way.

The last level of our future perspective is the building construction. By conventional methods we can calculate the loads and select a system from any manufacturer. Latest technology enables us to embed (immerse) the ducts into the building, while we are constructing the building. But when we go a step forward, together with the ducts embedded into the building elements, we will be able to embed units also into the walls or facade of the building. **Figure 4** shows the integrated design of an apartment for which we have calculated the loads, prepared a CAM model for additive manufacturing and the HRV unit embedded into a wall together with the ducts. It is ready for construction.

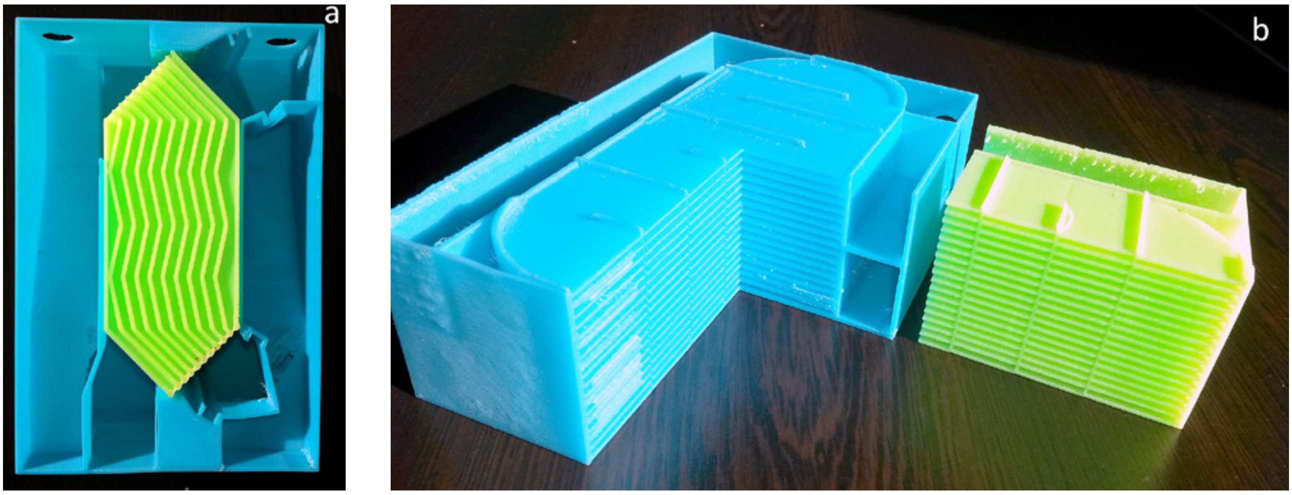


Figure 3. Samples of HRV units produced by additive manufacturing.

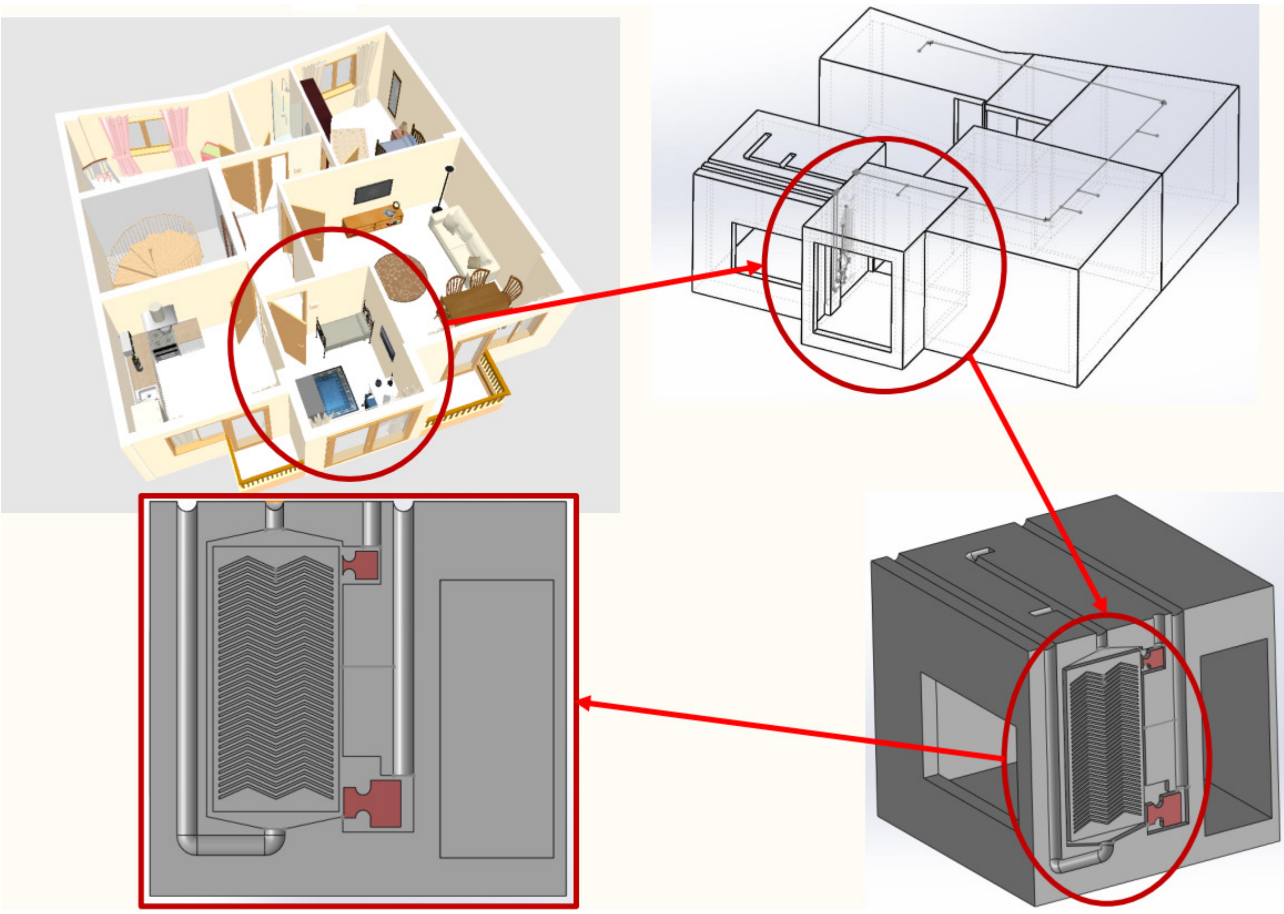


Figure 4. Integrated design of an apartment for additive manufacturing.

Conclusion

Our Perspective is:

1. Additive manufacturing will be an **alternative tool** for manufacturing firstly the HVAC components, then the units (HRVU, AHU, etc.) **in the near future**.
2. The days that additive manufacturing will be used for **production of all of the components** (walls, roof, ducts) of a building on site in a holistic approach is **not so far**.
3. Additive manufacturing will change the World from Cartesian design to **non-Cartesian (freeform, nonlinear)**. This will enable more compact unit designs with higher performance while keeping the capacity the same.
4. Additive manufacturing will **enforce** designers of **different disciplines** to cooperate for integrated design.
5. Integrated building design for additive manufacturing will arise **a new sector that will be developing software for 3D printed components** designed for both Cartesian and non-Cartesian geometries. ■

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[3] Khoshnevis, Behrokh. Houses of the Future: Construction by Contour Crafting Building Houses for Everyone. University of Southern California, 2004.

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