Additive Manufacturing and Value Creation

in Architectural Design, Design Process and End-products

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The objective of this paper is to clarify how value creation can be a part of architectural design and end-products when using the new emerging technology of additive manufacturing. Different kinds of values that have emerged from the research material have been analysed and summarised using selected case studies of recent building-scale projects. In applying this technique to architecture, the result can be visually and functionally novel, smarter and more sustainable buildings or products. A new individually manufactured or customised architecture can be created to serve different cultural and well-being needs cost effectively and without any waste. This new production method can lead to unique joint structures with the use of traditionally produced new or old building parts to enhance architecture, prevent climate change or aid environmental issues. However, most research projects and applications done by commercial companies are at the early stages.

Keywords: *Large-scale additive manufacturing, 3D printed architecture, Digital design, New materials, New production methods*

INTRODUCTION

In architecture, climate change, environmental issues, digitalization and resource conciseness can be seen as driving forces for compressing production and simplifying structures and materials. Utilization of digital design and manufacturing can be seen as one realisation of that. One prevailing variation, CNC-manufacturing, a method that removes material, has revealed several new possibilities for architects and designers. The opposite method, which does not waste material, is called additive manufacturing, and this has started to spread only in recent years. At the advent of this change, many projects sought to prove that this new way of constructing products can create added value to the manufacturing process and production. The benefits of the method have been predicted to be significant. In contrast, value creation in architecture and its end-products have not been researched much. In this paper the term value is described to mean valuation or usefulness through an evaluation. The evaluation is always subjected to time, place and the person who acts as an evaluator. Value creation can be based on social or economic aspects, but in architectural design, values can be seen also as a guarantee of quality. In architecture, value creation can be seen as a result of a series of selections. The selection making can be based on valuing, such as favouring a high-quality material or emphasizing environmental aspects during the design process. Value creation, conscious or unconscious, can be done also through evaluations of appropriate material features, such as surface structure, colour, form or composition. The architect or designer can also include intangible value-laden properties, such as feelings and individuality (Ashby 2014, 196). With these choices, an architect or designer can guide the design process in a certain direction. When the combining of a material and a novel product method is not yet established, different kinds of value-based aspects can be seen as a guide to creating meaningful and appropriate solutions for the future. In addition, when presenting the main value aspects clearly, as a kind of guarantee, the novel practice can be given a rationale. Quality or innovative thinking have been found in many current case studies and prototypes. If additive manufacturing is to become more profitable, it can lead to more innovative visual design and end-products. Although, additive manufacturing is a very novel method in large scale architectural structures, it might be a realistic way to create buildings or architectural-related products in the future. However, without demand, a conceptual design and adequate applications, the new manufacturing method will not be successful. The focus of this paper is on presenting different kinds of values that have arisen from the research material, to create understanding of how the production method can contribute to architecture in future. It is very clear that the benefits of the architectural possibilities are not yet adequately understood or researched. An emerging method can be seen as a risk when thinking of how to adapt the new method to the design process, or whether the new method will benefit the construction process enough compared to traditional methods, or even how additive manufacturing will change over the years. The investments costs of starting a new additive manufacturing business without examining thoroughly the possibilities of architectural design and favourable product applications or purpose-built concepts are huge. The hype is not enough to maintain the interest of customers. There have to be other methods, such as value-based research and business that create a long-lasting evolution of large-scale additive manufacturing.

Objectives, Methods, Data and Theoretical Framework

The objective of this paper was to find wider value-laden themes that can be found currently in architectural-related additive manufacturing projects. The selection process for the study cases was centred on the question: how additive manufacturing can create added value for architectural design and end-use applications. The framework for this research was defined under themes where architects can use selection or decision-making as a tool or method to creating values. Understanding has been based on comparing the data of projects which have used additive manufacturing to the current situation with more traditional manufacturing methods. The theoretical framework consists of a whole chain of design, from the basic elements of the design process to the finished outcome. Different kinds of printing method or material did not refine the sampling. The data have been analysed and structured using a qualitative method, more specifically, coding the data thematically using interpretation and classifications that generalise the phenomena under prominent themes. Knowledge of different kinds of projects and cases constituted the research material and it was found using the news groups of additive manufacturing. Publications such as books on additive manufacturing did not have enough information, because the subject has only recently emerged. Non-scientific news groups were harnessed to find up-to-date material and relevant research or the design projects of universities and commercial companies.

BACKGROUND

Additive manufacturing or 3D printing as it is also called, has been used commercially on a small scale since the 1980s, when the first commercial 3D printer was patented by Charles Hull for 3D Systems (Hoskins 2013, 30). Since then the technique was used, for example, to speed up product development processes by providing design teams with prototypes quickly for evaluation and further development. Today the technique is used in a great variety of industrial fields such as medical, automotive and aviation industries and the scale of the printed object can be from the nanoscale to quite large structures. Several types of additive manufacturing techniques have been invented to serve different needs, industrial fields, and printing materials. The technique is based on three-dimensional computer data that is then transformed into a specific format for the printer and objects will usually be created using computer controlled nozzles, layer by layer. Lately the printing technique has been applied also to a wide variety of projects in the construction industry. However currently there are not many building-scale 3D printed products on the market, just some prototypes and on-going research projects. Projects differ from each other by material, product type or printing technique.

Techniques related to construction industry

Fused Filament Fabrication (FFF), stereolitography and robotic arms are the most common additive manufacturing techniques when large scale architecture-related objects are printed. Printers are often custom made for the specific materials.

Materials

Almost all materials, such as concrete, plastic, steel and wood that have been traditionally used in architecture are used in large-scale construction industry-related printing projects. Most of the large-scale printing projects do not focus on developing environmental friendly printing material, though recycled waste material has been used at least in some cases as a concrete-based printing paste.

Large Printers

The size of a printer determines the size of a printed object. In addition, printers can produce small modular elements that can then be used to create larger structures. If large and continuously printed objects are desired, gantry based or movable printers can be used, which can continuously manufacture walls or other large structural elements.

VALUES AND APPLICABILITY IN ARCHITECTURE

In this paper, the question of how additive manufacturing can create added value in architecture has been considered through two different themes. The first theme describes how added value can be created by the selection process for using the basic elements of architecture. The three sub-themes are aesthetic aspects, the possibilities of the materials and the design of structures. The second theme is value creation through end use applications. Value creation is researched through themes such as new product properties, novel frameworks of design, new product fields and applications themes. Each sub-theme includes case examples that clarify the applicability. The analysis of values considers how the selected case studies contribute to the new production method. The same cases could be used as examples also in other themes or sub-themes. The themes also entail connections, such that value can be created by combining structures and materials, when designing functional and novel end-use applications.

VALUE CREATION FOR ARCHITECTURAL DESIGN

This section presents how the basic elements of design, in addition to tools used in architectural design projects, can create added value when additive manufacturing is chosen as a method (also refer to Figure 1).

Aesthetic

In additive manufacturing, it is possible to enlarge the aesthetic scope. The digital design and manu-

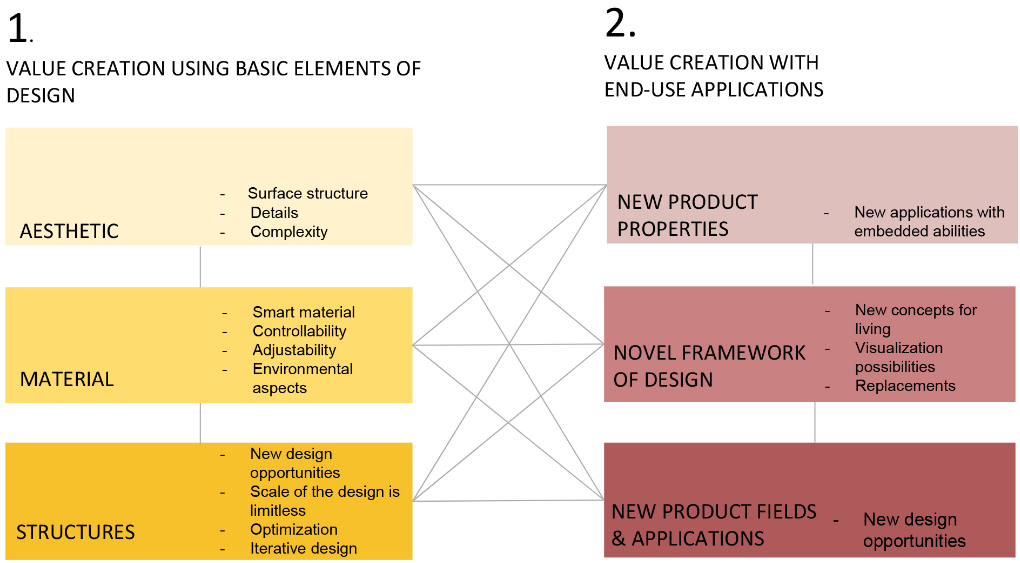

Figure 1
Two main themes with the three sub-themes and the connections between them. The themes emerged during the research process.

facturing method is flexible when creating complex forms and variations in the visual elements. Surface structures, colours, the haptic properties or material consistencies can be controlled and defined at the design phase. The surface patterns are not dependable on the original structural aesthetic of the material and the design can be very precise. Biomimicry, algorithm-based design or parametric design can be a source of a new kind of detailed design, where the scalability of the pattern can be almost unlimited.

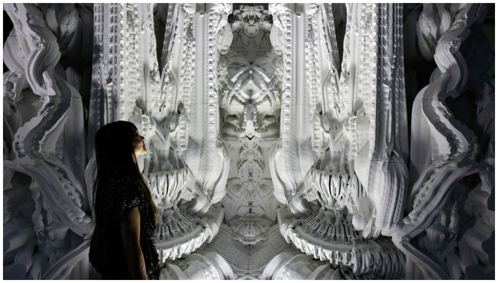

Figure 2
3D printed Digital Grotesque project, architects Michael Hansmeyer and Benjamin Dillenburger [1].

The case of algorithm-based design. The Digital Grotesque project (Figure 2) by two architects, Michael Hansmeyer and Benjamin Dillenburger, illustrates a new aesthetic approach. During the design process, the architects used an algorithm based technique for generating complicated forms and highly accurate surface structures. [2]

Material
Almost all traditional raw materials in the construction industry have been applied somehow in 3D printed prototypes. The printing material can be also a product itself, designed or developed as a commercial material.The benefits of an artificial printing material mixture is that the material features can be controlled beforehand and the design can be material driven. A deep understanding of the material features and physical behaviour opens up new possibilities in product design and architecture. The adjustable or controllable qualities of the printing materials can add extra value to the end products. When adding smart components directly to the printing

material, smart materials can be developed. It is also possible to print on electrically conductive material or to include printed parts. Nanotechnology can be applied to the printing material creating products, which become, for example, fire resistant, very stiff or easy to clean. Focusing on the tactile and aesthetic aspects of the material can generate added value in the end products. In other words, concentrating on the design shapes, colours, scents, haptic warmness, hardness, softness or structure of the material itself can lead to something unpredictable and novel. Material development gives possibilities to think of the lifecycle chain of the material starting from the beginning, from the manufacturing of the raw material. Recycling or using recycled printing material can give added value to end-use applications. Future possibilities may lie also in renewable, more reusable, bio-based construction materials. The technical and functional aspects, such as moisture resistance, insulation abilities, sound insulation, air tightness, fire resistance and structural stability, are crucial properties when thinking about architecture-related building products. The emphasis regarding those features are on dependable defined product fields and regulations, legislation, certification and local methods of using building materials. The material properties are crucial in terms of the building's lifecycle in the longer term.

Case of cooling bricks. The material and structure of a specially designed brick (Figure 3, 4) can bind moisture and due to this, when warm air flows through, the brick gets cooler. The idea is based to the Muscateses tradition of cooling their buildings in a very warm climate by using evaporative cooling. The sponge-like fine structure of the tile and the large surface area would be difficult to achieve using other current manufacturing methods, such as traditional moulding techniques. [3]

Structure

The new manufacturing method in architecture can be an enabler of novel visuality in design structures, and can lead to the creation of structures that cannot be manufactured using traditional methods. Due to this, the structures can be an essential part of the design idea and visuality at an early phase. It is possible to design strength simultaneously with architectural design if using an iterative process of the optimal form creation. However, the design of structures go also hand-in-hand with the material development and aesthetic aspects.

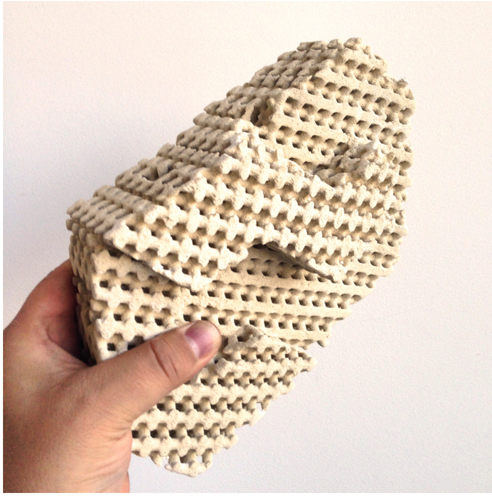

Figure 3
Cool Brick,
Emerging Objects
[3].

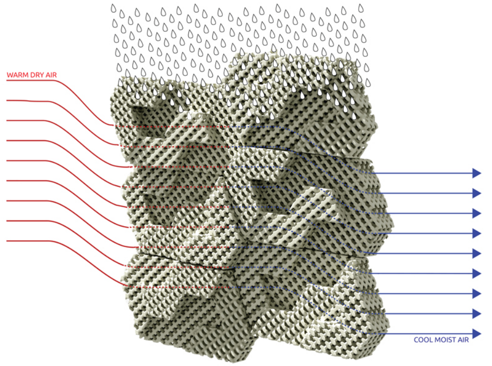

Figure 4
Function of the tile,
Cool Brick,
Emerging Objects
[3].

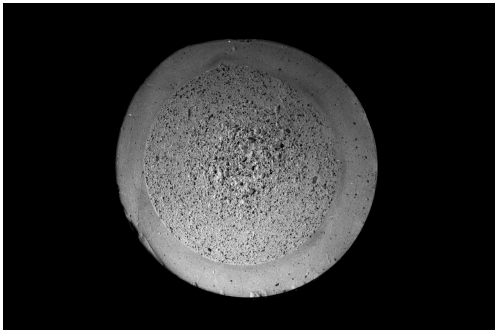

Figure 5
3D printed concrete and variations of density, MIT [4].

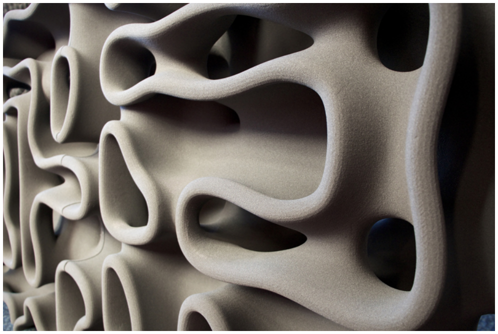

Figure 6
Involute wall, printed using sand, prototype, designers Virginia San Fratello, Ronald Rael, Emerging Objects [6].

Figure 7
Seismically resistant structures, Quake Column, Emerging Objects [7].

Case of varied density. In nature structures are often optimized and inherently aesthetic. A scaled or complicated imitation of nature can lead to a very small patterned design, with good strength or even resilient structures. At the MIT Media Lab, the Mediated Matter Group have studied 3D printed concrete of varying density (Figure 5). [5]

VALUE CREATION FOR END-USE APPLICATIONS

In architecture, additive manufacturing can be utilised in several types of product development projects. Nevertheless, due to the current phase of development, expectations of when the products could be launched will have a different time span and depends on the target applications. Currently, most of the projects concentrate on printing just a modular element, such as a tile, a building block or a wall element, creating added value for the existing product fields with this new method. In addition, 3D printing can be seen as a method of manufacturing unique pieces or industrial products that are not very easy to produce using traditional methods and where the size of the production line is limiting. In addition to these, additive manufacturing can, if successful, frame design in a new way in the future.

New Product Properties

The new type of production technique can enhance the three dimensional abilities of the products in architecture. New characters, such as printed functional features, can lead to something unprecedented in the construction industry. Novel functions can be added to the traditional or brand new building product, for example, products that have been printed using four dimensional printing. The fourth dimension is time, when for example the printed piece will change shape after the material reacts to an external stimulus. As a result, this can lead to programmable and movable prints.

Case of functionality in the designed object. An architect office called Emerging Objects has developed some prototypes of functional products, such as the Involute Wall (Figure 6). The curvy forms of the surfaces absorb and redirect sounds. The three dimensional design creates shades on the wall and the structure stays cool on a sunny day. Other wall structures, the Quake Column (Figure 7), is also optimized three-dimensionally. The tile is designed to be seismically resistant, and reacts optimally to movements during an earth quake. The idea is based on the interlocking stones of the Inca culture, where tiles were allowed to have slight movements, without falling apart. [6, 7]

Figure 8
Low-cost replacements for obtaining an impression of the original idea of the decoration [8].

Figure 9
Detail of the facade, Anne Pheiffer Chapel, original design Frank Lloyd Wright. The mould of the replaced tile has been 3D printed. [10]

New Framework of Design

In recent years there have been some visions where additive manufacturing can be applied to serve daily life, ease life after natural disasters, or create cost-effective living environments for poor areas. The changing situations of environmental or political issues affect new standards for living environments, ways of working, and the needs of end-users. Since the advent of hi-speed data transfer and the rise of information technology, an architectural design can be global, but resources or manufacturing can still be local. In additive manufacturing the printing material can be produced locally, and even respect local building material traditions. The local way to production means that design can once again respect and arise from local traditions, cultures, resources and needs. In addition, the manufacturing method can create new methods for architectural-scale rapid prototyping or three-dimensional visualisation that strengthens and supports the design process.

Case of three-dimensional visualisation. Additive manufacturing has been used in walls to visualize previously destroyed historical decorative parts and recreating already lost visual information. In Castello di San Martino dall'Argine, Mantova, Italy, conservation has been carried out on a missing putti-figure's head (Figure 8). After generating a 3D image of the head, the missing part was printed three-dimensionally to obtain an impression of the putti-figure with the head on. [8]

Case of emergency housing. Instead of moving building parts or element from the factory to the site, the factory can be seen also as the mobile unit. There have been many projects that have considered the question of how additive manufacturing can be applied in rebuilding projects in disaster areas. An expected added value can be created when low cost and rapidly constructed sheds or buildings are needed. With the co-operation of other partners, the University of Nantes and L'institut de Recherche en Communications et Cybernétique de Nantes began a research project where emergency houses are printed in 20-30 minutes apiece. The area of an insulated shed is 3 m^2, and the height is 3 meters. [9]

New product fields and applications

As mentioned before, when using this novel production method, value can be achieved through the strengthening of current product lines or through totally new product concepts. In addition, the technique can be used to produce customised products or spare parts, joint structures with old products, or to complete parts for the existing products. The technique can also be applied to replacing the manufacturing techniques of products lines already on the market. Reasons for doing this can include better and unique design possibilities, easier manufacturing processes, a need for customisation, or environmental issues related to the printing material or production. Additive manufacturing can be seen as a possible method when the moulds are made for large structures. The technique has been used extensively on a smaller scale. Moreover, using design thinking, totally new products based on new needs can be invented. The novel production method has a great possibility to create unique joint structures, with traditionally produced new or old building parts. However, designing new 3D printed parts to complete old products that have been manufactured earlier or that have a more traditional appearance can cause visual or usability malfunctions. That can be prevented by design thinking at the early phase. As time goes by, the 3D-printed products will age and aging will change how the product is valued, with the value fading or even growing (Ashby 2009, 66). Design concepts should support the aging of printed structures or building parts, and replacing a printed part or repairing prints needs to be considered in advance.

Case of replacing a traditional method. In the case of the restoration of the Annie Pfeiffer Chapel (Figure 9), additive manufacturing was used because the old and original artisan skills had disappeared. The building, dated 1941 and designed by Frank Lloyd Wright, faced a problem because the tiles were almost impossible to reproduce, while traditionally used methods were too expensive. In addition, not enough competent artisans were available. The original design of the facade consists of 46 different kinds of tiles, which were originally cast using wooden moulds. Using 3D-printed moulds, it was possible to manufacture the facade blocks with ease and at a reasonable cost [10].

DISCUSSION

At this moment in history, large-scale additive manufacturing industry is concentrated mostly on improving printers. For this reason, technical challenges restrict design thinking, the creative process, and also visions of 3D printing possibilities. Research and product development has basically fallen into two parts. Typically, engineers try to improve the technical abilities, while groups of designer-architects with a more creative approach develop end products and concepts. Most fruitful would be a co-operation between engineers, designer-architects, and commercial companies that would develop together new 3D printable product concepts, following a normal real-life design process. Some examples of co-operation have however already emerged. Presumably, in future the development of printers will be more dependent on future visions and the process will be more design driven. Design can also be material driven, when the environmental aspects and material selection will give added value to design applications. Currently the tendency seems to be that almost everyone wants to be the first to market. This eagerness will decrease the quality of printed parts, with concepts being under-developed and value aspects not given sufficient thought. If it is not clear how value is obtained and how the new technology is justified, catching up later might be difficult. Value creation can benefit architectural design by creating quality and precision in the basic elements of designed objects. The freedom of creating design patterns can be seen, for example, even as a new kind of craft. Printing will create added value also in designs where form, functions or shapes are not possible to manufacture by using traditional methods. Designers can present creative, even intangible feelings or reminiscences by means of additive manufacturing. The optimal form of creation of structures can imply less material, but also form-based imaginative architecture that is yet implementable. Currently there are no standards, norms or legislation to define the stiffness of structures, the use of 3D printed products or to guide 3D-printed construction projects. Calculating the added value is not yet possible. This broad, wild and open scene can be seen as an advantage, while almost anything is still possible and is yet to be strictly defined. On the other hand, without certified products, markets are difficult to conquer. There is a risk for companies in starting a new product line if the future standardisation is unpredictable. Appropriate concepts for architects and the construction sector need to be clarified, and the possibilities need to be articulated more precisely. Value-based analysis of architectural design and end-use applications can lead to the stable use of this new manufacturing method.

CONCLUSION

Additive manufacturing has great possibilities to enhance the quality of architecture and end-products. The potential is immense, yet the method is not commonplace, and research in architecture is still scarce. To sum, the potential lies in the properties of materiality and the possibilities to design complex forms and surfaces and to control or adjust different aspect during the design process. In the early stages, there is a significant possibility to develop products and find solutions using a more value-based approach. A flexible manufacturing method can be a source of inspiration as an enabler, and has the potential to create value through the design process. In future, a desirable research focus in architecture-related additive manufacturing could be to find new and more sustainable practical solutions and iterations. Additive manufacturing can also be seen as a fresh way to enhance architecture, the materials industry, and the construction industry, as well as a means to utilise information technology more efficiently without diminishing environmental issues. In the coming years, the interests of companies, researchers and designers can be expected to work to identify more clearly what the new trends are and where the real values lies.

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