Chapter 23

The Sustainable Potential of Digital Fabrication Process and De-standardisation of Architectural Products

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Abstract Digital fabrication processes consist in a parametric designing and in a product manufacturing by computer numerical control (CNC) machines.

At the design stage, the architectural object can reach a great grip with the environmental and cultural context, because the parameters measured by the environment become the engine of the virtual model. In this way a change of external parameters results in a change of the project.

In this chapter the possibility to optimise, through this method of project generation, is investigated. Parametric design increases the performance of the architecture in terms of structural, thermal and functional needs, with a reduction in resources, material and energy, ensuring greater sustainability.

In the production stage, the use of CNC machines ensures the realisation of the objects, designed with parametric methods, that, for intrinsic reasons, cannot be standardised and thus they are unique.

This feature of digital fabrication could radically change the industrialised society.

23.1 Introduction

Nowadays, in the automation of information era, the mass production of objects gradually loses importance in favour of the operating cycle, controlled by a set of logically arranged and automated instructions that can be preprocessed or are instantly able to be processed within the organisation: the organisation takes, therefore, the upper hand.

The technology of power automatism and automation of leading control, ordered according to a plot governed by automatic processing of information, tends to free itself from the slavery of the industrial series, defeating the importance already

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attributed to the “quantity” factor so as to provide the product with intrinsic values rather than with accessory values.

The electronic progresses, applied to automation, transform the notion of standard, as formal milestone of objectual series, into those systems of informative stimuli, able to give birth to continuously different objects, manufactured in many or few copies, or even, into a unique piece [2].

This is the prophetic thought of Giuseppe Ciribini, which in the mid-1980s describes, with efficiency and precision, a phenomenon that will emerge in the decades to come: what we now call the digital fabrication.

Nearly 30 years later, Achim Menges argues: the opportunities of contemporary computer numerical control (CNC) fabrication technologies have … superseded the paradigms of serialisation and repetition that were predominant in the twentieth-century architecture [7].

Digital fabrication is a complex process, which has great potential in the context of sustainable development. In this chapter the phases, tools, properties and some experiments are analysed.

23.2 Digital Fabrication Phases

Digital fabrication is divided into two phases: the first one is the designing phase, and takes place with digital software; the second one is the manufacturing phase, which transforms the virtual project into a real object through the use of CNC machines or robots.

Both phases evolved in recent decades and promise a steady growth in the coming years.

The first tools for the design are limited to representation and are based on a computer-aided design (CAD) system, widely used today.

It is known that CAD is used in computer systems to assist in the creation, modification, analysis or optimisation of a design [8].

CAD software has the advantage of increasing the productivity of the designer and improving the quality of design and communications through documentation, and is quickly creating a database for manufacturing [8].

CAD output is often in the form of electronic files for print, machining or other manufacturing operations.

In recent years, CAD tools have been joined by computational design (CD) tools, based on the theory of computational complexity. The CD software enables the processing of the input data through a complex method; it uses algorithms and advanced computational techniques not for drawing shapes, but for creating formal possibilities. It deals not with producing a solution, but with generating a family of possible outcomes. This software is not only a support for the representation, but it is also a real way to design: it is parametric design.

The field of parametric design is generating geometry from the definition of a family of initial parameters and designing the formal relations they keep each other.

The use of variables and algorithms generate a hierarchy of mathematical and geometric relations that allow to generate a certain design, but also to explore the whole range of possible solutions that the variability of the initial parameters may create.

The benefits of this process are immediate. It is a huge quality leap for users, since tools do not constrain them anymore; now it will be the users themselves who design their own tools. On the other hand, parametric design is fundamental in order to minimise the effort needed to create and test design modification. The automated process eliminates tedious repetitive tasks, complicated calculations, and possibility of human error, and can generate huge shifts in the outcomes with slight variations of the original parameters. It is the difference between using the “Cube” command 1,000 times, entering center point and dimensions and customising the design of a “Group of Variable Height Cubes” that command out of our own predefined variability rules [16].

The generative tools of parametric design are expressed in the field of virtuality; and only in the second manufacturing stage, when a real model is created, the process can be completed.

CNC machines and robots are tools able to translate a virtual project into a real object.

The CNC machines, in the most basic versions, are available from the middle of the twentieth century, but only after the creation of a universal language, the G-code, these mechanical instruments had a direct dialogue with the software tools.

The CNC machines can realise both projects defined by CAD software and computational design software.

The application field of these machines is wide, and in recent years several research groups had drawn their attention to them. It is easy to preview that, in a short time, the performances of these tools will be greatly improved.

But what are the CNC machines?

In modern CNC systems, end-to-end component design is highly automated using CAD or computational design and computer-aided manufacturing (CAM) software.

These software produce a computer file that is interpreted to extract the commands needed to operate a particular machine via a post-processor, and then loaded into the CNC machines for production [17].

CNC machines can be divided into several groups, depending on the technology used to transform the virtual file into the actual product: cutting, subtraction or adduction.

Lamination process, which is based on cutting, is divided into two categories:

- The simple cutting (by blade or laser) of material panels and the various parts of the element, which will then be manually assembled by the operator.
- Laminated object manufacturing (LOM): Layers of adhesive-coated paper, plastic or metal laminates are successively glued together and cut to shape with a knife or laser cutter. Machining or drilling, after printing, can additionally modify objects, printed by this technique. Typical layer resolution for this

process is defined by the material feedstock and usually ranges in thickness from one to a few sheets of copy paper.

The subtraction process in CNC machines is based on the removal of matter from a solid block of material. CNC machines usually employed for these technologies are the milling machine and the lathe:

- The milling machine is a machine tool used for the machining of complex shapes in metal parts or other materials.
- The lathe is a machine tool used for the machining of a work piece placed in rotation.

The CNC machines that work with the method of adduction of the materials are divided into two groups, depending on the technique of processing the material: in the first case part from solid material moulded by melting, and in the second case, part of a liquid material transformed via solidification.

The first group, which is based on fusion, uses different techniques:

- Selective laser sintering (SLS): SLS uses lasers as its power source to sinter powdered material, binding them together so as to create a solid structure. The main materials used with this technique are thermoplastics, sand, metals and glass.
- Selective laser melting (SLM) is similar to SLS, the difference being that the materials are not only sintered after having put together but are also able to achieve a full melt.
- Fused deposition modelling (FDM) works on an “additive” principle by stratifying down material in layers; a plastic filament or metal wire is unwound from a coil and supplies material to produce a part. They use mainly thermoplastics.
- Laser deposition technology (LDT) is a process in which metal powder is injected into the focused beam of a high-power laser under tightly controlled atmospheric conditions. The focused laser beam melts the surface of the target material and generates a small molten pool of base material.
- Syringe extrusion works by extruding a fluid material. The syringe is connected to a carefully controlled air compressor. As the printer begins its print, the pressure in the syringe is manually raised, and continuously extrudes material until the compressor is shut off. This technology uses different materials that can be rendered fluid, such as the clay and earth, but also chocolate.

In the second case of adduction, there is only a methodology.

Stereo lithography apparatus (SLA) production separates one layer per time by curing a photo-reactive resin with a UV laser or another similar power source. The term “stereo lithography” was coined in 1986 by Charles (Chuck) W. Hull, who patented it as a method and apparatus for making solid objects by successively “printing” thin layers of an ultraviolet curable material, one on top of the other. Hull’s patent described a concentrated beam of ultraviolet light focused onto the surface of a vat filled with liquid photopolymer. The light beam draws the object onto the surface of the liquid layer by layer, and using polymerisation or cross-linking to create a solid.

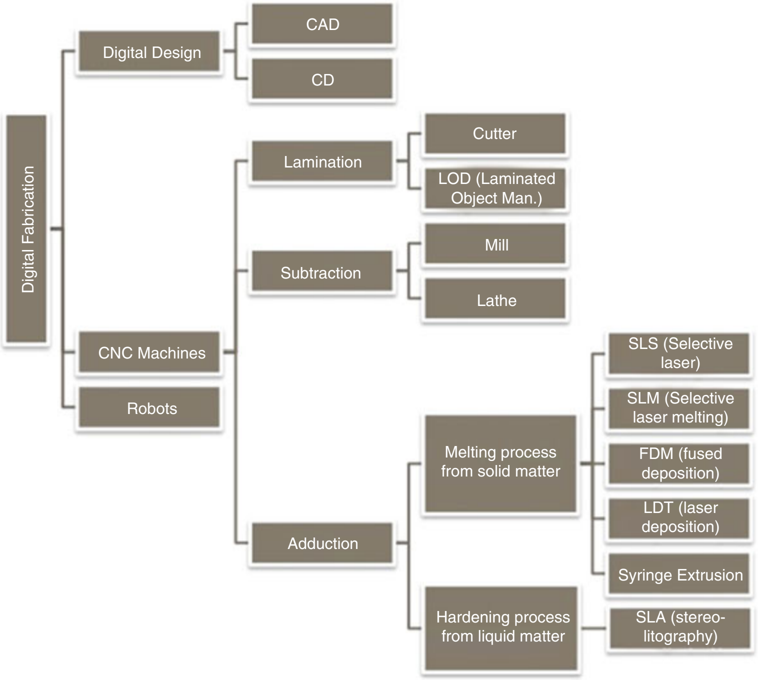

Fig. 23.1 Digital fabrication tools

Of all the CNC machines, those attracting more interest from the media are based on the process of adduction, commonly defined as 3D printer. They are the most recent, and also the most promising: easy to use and, in the basic models, easy to accomplish.

Digital fabrication takes advantage also by using robots. In this case their use is so varied that cannot be summarised. The design and programming of the robot is very wide and the only limits are the human imagination and technological feasibility (Fig. 23.1).

The materials used with these techniques are several. In cutting, we found mainly traditional materials such as wood, cardboard and aluminium foil. In the processes of adduction, the predominant materials have synthetic origin, made up with different types of plastic, but can also be metallic, or mixtures (powders of stone, wood, etc.) with a resin that glue all together.

The combination of these two phases produces different effects of considerable interest.

The first is the reciprocity between design and object: you can have a constant cross-reference between the virtual object and the real one.

In Computational Design Institute of Stuttgart Achim Menges defines and tests this property.

> The robot, being at the intersection of the binary and discrete world of the computer and material world in which exists, represents the interface between design computation and physical materialization. This opens up the opportunity non only to question the presumed unidirectional of the flow of information from file to factory, but rather to investigate the possibilities for reversing or short-circuiting this flow by informing the digital design tools themselves with the procedural logic of fabrication and the physical characteristics of material systems [7].

It is just the response of the materials that have attracted the attention of Menges in this study.

23.3 Digital Fabrication Properties and Some Experiments

> Structural design and form-finding process, allowing for the generation of design variation through adaptation to changing system-external and system-internal constraints, have to be closely intertwined. Using finite element (FE) analysis, the structural behaviour of the system can been simulated and continuously driven by the evolution of the design; in parallel, the load-bearing capacity of physical prototypes can be tested and the result thrown into the simulation, which in turn informed the global topology of the system. Through this integrative computational design process based on the reciprocal effects of fabrication, form, structures, material and performance the nominal material thickness could be minimised [7].

The material used in the testing by Menges is wood, but the logic of this process can be adopted for different materials.

The consequence of the material optimisation is directly related to the use of a lower quantity of material and, while still achieving the same performance, it follows the saving of resources. This is one of the first features that make this method a tool for sustainable development.

Till now in architecture the shape is expensive, while the material employment is cheap. With this new system the situation is reversed: the shape will be cheap and the material use expensive.

The material, for its intrinsic characteristics, becomes part of the parameters to consider in the realisation of the objects. Toni Kotnik and Michael Weinstock of EmTech programme at the Architecture Association (AA) in London gives another example of this trail of experimentation.

Even in this case, thanks to an interactive design process based on digital fabrication, that integrates material, form and force, digital fabrication has the potential to unfold a new generative logic of shape finding [5].

The ability to control the shape of the object using exogenous and endogenous parameters involves the monitoring of performance and the subsequent performance optimisation.

The stages of analysis and design are placed side by side; thus the project is processed and analysed at the same time, shaping the results on unique result.

The performances may be structural that are the most studied in the generation of optimised forms. But if the parameter is the energy, a project can be developed to generate devices for energy savings, increasing the sustainable potential of digital fabrication process.

But how is it possible to design architecture with energy parameters?

An example may be to provide a passive system, capable of interacting with the surrounding environment, modulating the action of climatic factors. Architecture can be “made”, taking into account the thermal comfort and indoor humidity: so as to allow a less energy use to adjust the internal comfort. This process is possible by the control of environmental factors such as sunlight, ventilation and precipitation.

While achieving the same comfort performances, you will consume less power, expressing energy savings.

A good example of this theme is a study project for the envelope of Piraeus Tower in Athens (MSc Dissertation of Ioannis Douridas) that is derived from an interactive algorithmic procedure with the environment. “Various lines of research within the Emergent Technologies and Design context examined the way that building and components may be utilised to contribute in effective way to environmental modulation” [4] (Fig. 23.2).

MArch Dissertation of Juan Subercaseaux shows an other interesting study about a second skin: “the overall geometry of the grid shell was subsequently elaborated through a series of environmental performance criteria within context-specific defined ranges of environmental condition, including the insulation of rainwater, ventilation and thermal modulation, as well as controlled sunlight exposure of the interior” [4] (Fig. 23.3).

Intents of performance optimisation, the research work at MIT by Neri Oxman, investigates the new design approach to digital fabrication that offers the potentialities to programme physical matter. In this research, form generation is driven by maximal performance with minimal resources through local material property variation [9].

With the use of a single material it is possible to satisfy different requirements (structural, insulating, thermal, etc.) varying the composition of the material itself. Let us take as example an external wall; it is traditionally composed by several layers, with different materials; each of them has a specific characteristic: flow, insulation and waterproofing. With the innovation proposed by Neri Oxman it is possible to design a stratigraphic variability of density (Fig. 23.4), elasticity or other characteristics within a single material, and thus to obtain different performances in the different layers of the product, without the need of adopting a plurality of materials [9].

This experimentation can be applied to many products that now require stratification with more materials.

The main benefits are the increasing of performances and the reduction of material, two essential aspects for the sustainability, but there is more: the use of a single material makes it more effective because the step of recycling or disposal will be cheaper at the end of product life. The recyclability increases the sustainability of the product.

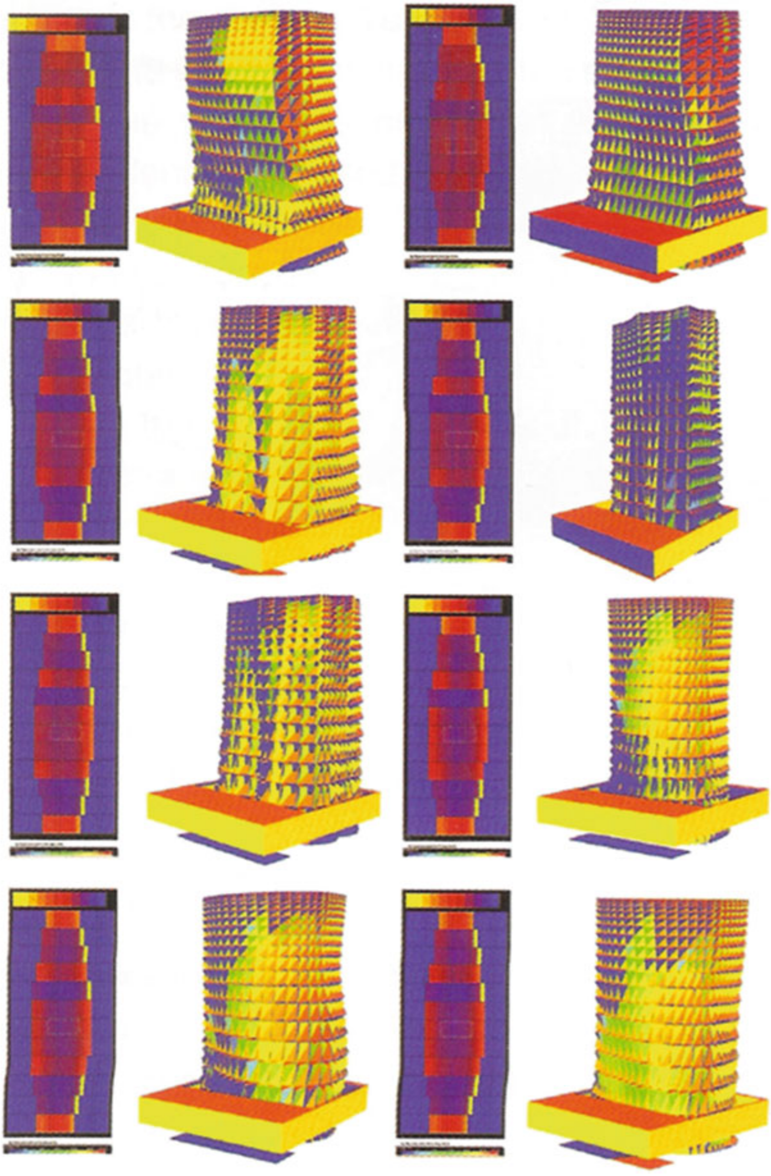

Fig. 23.2 Multiple generation of the Pireaus Tower's envelope is computationally evolved and analysed in relation to a number of environmental fitness criteria in order to explore the self-shading capacity of both the global envelope shape and local articulation of the skin components. MSc Dissertation of Ioannis Douridas. October 2005

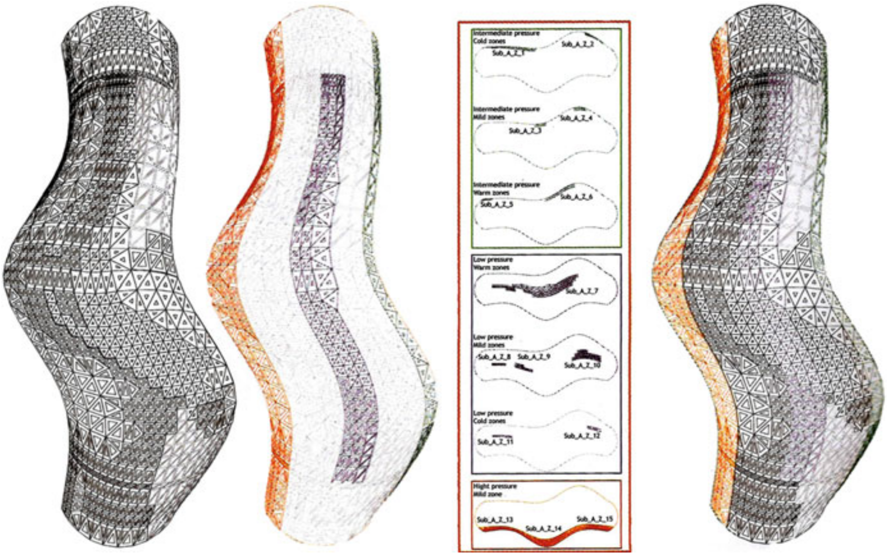

Fig. 23.3 Final tessellation and distribution of frames over the double-curved surface of the building envelope (*left*); air pressure zones and water-collection zones indicated on the envelope (*centre*); articulation of enveloper informed by the combined input parameters of light-exposure and air-pressure zones (*right*). MArch Dissertation of Juan Subercaseaux. February 2006

Fig. 23.4 Material tests for a concrete extruder head capable of dynamic density and aggregate control. Mechanical foaming techniques are automated using a six-axis robotic arm to produce lightweight, floating concrete structure with programmable porosity. Steven Keating and Timothy Cook, Variable-Density Printing, Mediated Matter Group, MIT Media Lab, Cambridge, Massachusetts, 2011

23.4 Accessible Test

An interesting aspect of digital fabrication process is the accessibility, both of information and instruments, in particular regarding the economic aspect.

Due to the low cost of the process, from design to construction, an emergent system of delocalised testing is dawning.

We are witnessing the birth of Fab Lab, fabrication laboratory [3], "physical locations where these new models of process and product are realised, are the places where it is possible to revolutionise the foundations of the goods' exchange process principles and ideas in order to meet the global sustainability and solidarity" [11].

Digital fabrication field is constantly and rapidly evolving, so part of the activities by Fab Lab is dedicated to research and test.

The experiments are no longer preserve of research centres and universities, but it is fragmented. Experimenting, but mainly making: these are the key words that move these small organisations of digital fabrication.

If you do something and you share it on the Web you are a Maker [1], so even without organising Fab Lab, the process of digital manufacturing is spreading more and more widely: just with the enthusiasm of a single person.

Digital fabrication teaches people to make and to repair too. "This new relationship between production and use seems to be a reminiscent of the pre-industrial culture, but instead of taking life from the local community, it tends to form itself a community, even global, which gathers around the single object. It tends to reduce, as it was for the craft, the changes of the finished product . . ." [11].

The information and the basic tools for the design and production are available on the Web.

The consequence of this phenomenon, in different aspects and even in the context of sustainability, is not to be foreseen. However, the multiplication of experimentation and research creates a competitive environment and a greater number of possible solutions; therefore it is desirable to promote sustainability, or at least to raise its different aspects.

Hereinafter two projects are shown: Cocoon Pavilion and Cocoon Evo Pavillion.

Cocoon Pavilion (Fig. 23.5) is a project born from the collaboration of Medaarch, Mediterranean FabLab, Co-de-iT and CRTS Cartotecnica, made by corrugated cardboard, and it was the result of a workshop organised by the Mediterranean FabLab [13]. The project gave the opportunity to investigate the processes that lead from design to manufacturing of architecture, until their physical realisation. The most interesting note is that the entire process is self-financed; all the partners have contributed to an aspect. It is a clear example of an experiment by small groups of individuals.

The second project is an evolution of the first. Cocoon Evo Pavillion (Fig. 23.6) is an installation presented at the Maker Faire Rome 2013 designed by Mediterranean FabLab, Co-de-iT and PicernoCerasoLab and realised thanks to the machines and professionalism of Tekla company [15].

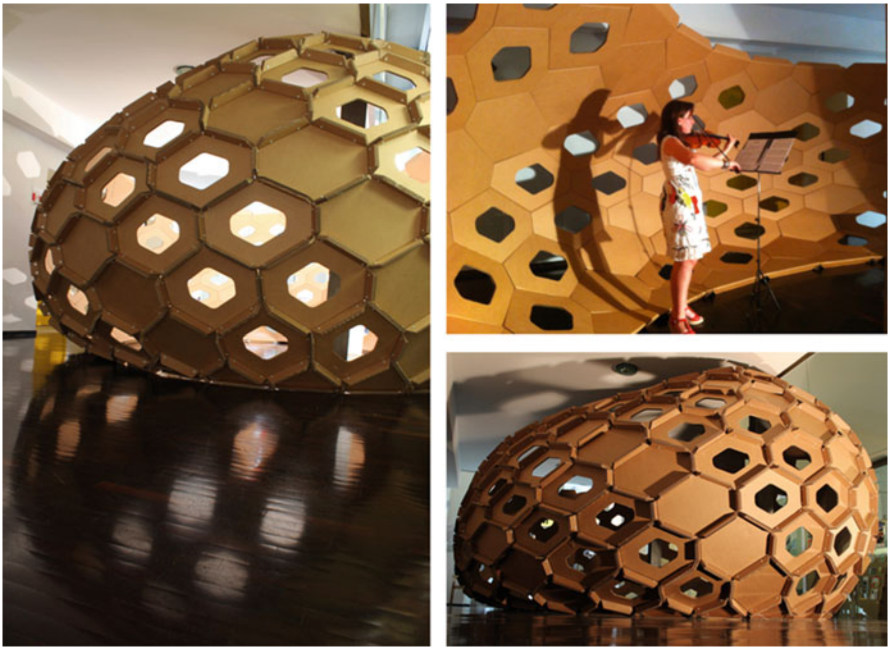

Fig. 23.5 Cocoon Pavilion is made by corrugated cardboard. It is born from the collaboration of Medaarch, Mediterranean FabLab, Co-de-iT and CRTS Cartotecnica

Fig. 23.6 Cocoon Evo Pavillion is an installation presented at the Maker Faire Rome 2013. Realised by Mediterranean FabLab, Co-de-iT, PicernoCerasoLab and Tekla srl, ALURAME

A new era is emerging.

In a first step, an increase in the creation of objects, dictated by the ability of having customisable products, seems nothing more than another tool of consumerism and is clearly at odds with the logic of sustainability. In fact many of the products, made using these processes, are in plastic material, fact that can brings to an increasing of pollution and wastes, in the realisation phase.

But one of the most desirable solutions, aimed at overcoming these problems, is the experimentation on materials with a low environmental impact and easy recyclability.

23.5 Relocation and Customisation Production

By the spread of small production companies, based on digital fabrication process, it will be possible to have access to a delocalised and custom manufacturing.

The products will have less need to travel from one continent to another, simply by sending projects via e-mail.

One of the solutions on which various experiments are starting concerns the possibility to create architecture with the parametric fabrication using local materials, as sand, earth or clay and so on. Such an approach, in addition to being considerably ecological, is definitely cheaper than traditional techniques.

The use of such a process will allow best performances, lower energy resources and lesser amount of material than traditional methods, and it will therefore be preferable from the sustainability point of view.

All analysed aspects consider the digital fabrication as a moderate factor of sustainable development. It is true that the optimisation of materials affects energy performances; it is also true that the relocation of production leads to the decreasing of transports, but in contrast, the growing flourish of objects of each type and material does not contribute to the increasing pollution and wastes.

So far, the balance of advantages and disadvantages seems to be equal.

The sustainability factor of digital manufacturing is not in the direct consequences, but in the indirect ones.

This manufacturing process makes it possible to create unique objects at no additional cost as much as create thousands and thus undermines economies of scale. The spread of digital manufacturing could have a profound impact on the world, as it was the advent of the industrial era. Just as nobody could have predicted the impact of the steam engine in 1750—or the printing press in 1450, or the transistor in 1950—it is impossible to predict the long-term impact of these new technologies. And probably it will subvert every field it will touch.

With this enthusiasm The Economist welcomes the advent of digital fabrication, with a focus on 3D printers [14].

So the principal quality of this process is the potentialities to compete with the economy of scale and replace it.

23.6 Conclusion

The current system is based on the industrial mass production.

Mass production is the production of large amounts of standardised products, and is an established and effective practice, because its inherent logic allows lowering the cost of unique product increasing the number of production.

The low cost of the product ensures spread to all sections of society. The spread of standardised products has expanded exponentially, as these products are more economically affordable compared to handmade products. Standardised objects invade today all fields of goods production. The standardised product fulfills the needs of the consumer universally and not particularly. Today the needs and performances have to undergo an adaptation, providing approximate results. The standardised products then provide standardised performances; they are neither adaptable nor flexible, and sometimes perform only in a minimal way as per the required needs.

This process lowers the quality of the industrial products, which are preferred to the handmade one for their cheapness. The market thus supplies the development of mass production. The production of goods increases, and the market becomes saturated and is no longer able to absorb that particular product. To deal with this gap there are several strategies in the system that maintain a high level of sales of that particular product.

A possible way to increase the number of consumers can be that of operating a constant market extension (to other territories, to other social groups).

Another possibility lies in increasing the need for that product.

When consumers are led to the need for replacing some goods they already own, we talk about planned obsolescence [10]. This process is triggered by the production of goods subject to a rapid decay of functionality and is realised by means of appropriate devices introduced in the production phase (use of poor-quality materials, planning of repair costs higher than those of purchase, etc.). Product's life is reduced to a shorter time of effetive technological possibilities, so as to push for purchases of replacement. Detailed further acceleration of planned obsolescence of the goods is made by the advertising of new models which have irrelevant changes in functional terms, but great ones in substance and form. This is particularly relevant in the advanced technology industries that operate in oligopolistic market structures, in which the positioning of companies depends on the ability to differentiate technological products which are homogeneous: in these market conditions, planned obsolescence is realised through sophisticated marketing strategies with which it is possible to create fashions and trends, aimed to elicit consumer needs to replace products [12].

These logics involve a higher economic use of resources and energy and a greater production of waste. As demands increase the profit rises and the system is repeated, growing to the infinity in a finite environment, threatening the balance of the ecosystem.

Just in opposition to this indiscriminate growth, different ideologies and strategies are born, including the need to adopt a “happy degrowth” [6] and a sustainable development.

If the digital fabrication is proposed as an alternative to mass production, which is mainly responsible for the increase of the ecological footprint of the industrialised lifestyle, it has the inevitable implications of sustainability.

Digital fabrication creates a customised product, which fulfills the demands with increasing accuracy, and varies the performance, with a return on investment-based materials and energy savings. The difference of cost between digital fabrication and standardised products is offset by the higher quality of performances. Finally customised digital fabrication products are cheaper than handmade ones.

However, these factors may not be sufficient to induce consumers to prefer customised products to those standardised.

Perhaps the crisis of Western consumption can be a contributory factor to a new model.

A decrease in sales, which is typical of a crisis, requires a reduction in production, which leads to an increase in costs of each product in the long term.

If the crisis will be enough strong to topple the mass production, maybe a minimum gap will result between the costs of standardised and digital fabrication products.

In short, until there are no tools to compete with the low costs of the mass production, it is not conceivable to implement a comprehensive sustainable development. Digital fabrication phenomenon seems to get characteristics suitable to perform this task.

In this case, there are many changes that industrialised society will have to face, including substantial changes in habits and consciences.

References

1. Anderson C (2012) 2013 Makers. II ritorno dei produttori. Rizzoli, Milano
2. Ciribini G (1984) Tecnologia e progetto. Celid, Torino
3. Gershenfeld N (2012) How to make almost anything. The digital fabrication revolution. In: Foreign affair, vol 91(6), November/December 2012
4. Hensel M (2010) Material system and environmental dynamics feedback. In: Hensel M, Menges A, Weinstock M. Emergent technologies and design, towards a biological paradigm for architecture. Routledge 2010, ISBN 10 0-415-49343-9
5. Kotnik T, Weinstock M (2012) Material, form and force: material computation. AD architecture design, ISBN 978-0-470-97330-1
6. Latouche S (2007) Petit traité de la décroissance sereine,. Tr. it.: 2008. Breve trattato sulla decrescita serena, Torino, Bollati Boringhieri, ISBN 978-88-339-1869-3
7. Menges A, Shwinn T (2012) Manufacturing reciprocities: material computation. AD architecture design, ISBN 978-0-470-97330-1
8. Narayan KL (2008) Computer aided design and manufacturing. Prentice Hall of India, New Delhi. ISBN 812033342X

9. Oxman N (2012) Programming matter. In: Material computation. AD architecture design, p 90–95, ISBN 978-0-470-97330-1
10. Packard V (1957) The hidden persuaders, trad. Fruttero C (1968) I persuasori occulti. Torino: Einaudi, Milano. 1989—I persuasori occulti rivisitati negli anni ottanta. In: Il Saggiatore. Einaudi
11. Pone S, Colabella S (2014) Maker. In: Op. Cit. Selezione della critica d'arte contemporanea n. 149—gen 2014
12. http://www.treccani.it/enciclopedia/obsolescenza-programmata/
13. http://www.medaarch.com/2128-cocoon-a-temporary-pavilion/
14. http://www.economist.com/node/18114327. The Economist. 10 feb 2011
15. http://www.co-de-it.com/wordpress/cocoon-evo-pavilion.html
16. http://www.parametriccamp.com/
17. http://en.wikipedia.org/wiki/Cnc