A novel educational model based on "knowing how to do" paradigm implemented in an academic makerspace

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Abstract. The design discipline is faced with radical changes related to new technologies and to an increasingly globalized world with more and more competitive markets. These factors are profoundly influencing methods and processes of design, and the knowledge and skills related to the designer's role. Consequently, the design educational models are radically changing. Today, one of the most impacting evolutions is related to rapid prototyping techniques, which are bringing design practice closer to the auto-production. This emerging trend cannot be anymore supported with traditional didactic approaches, but it is necessary to create spaces for allowing students to learn, design and experiment in a shared way. This paper presents the Polifactory Lab at Politecnico di Milano, an innovative makerspace established with the aim of creating a new research and teaching space. In this paper, the authors present the Polifactory Lab, its theoretical purposes, and some examples of didactic activities carried out in the lab.

Keywords: Innovation in education, Design Educational Models, Makerspace, Rapid Prototyping

1 Introduction

The design discipline could be considered as a bridge element that integrates and acts as an intermediary among several fields [1] and, in particular, between art and engineering. Similarly, to art and engineering, it is characterized by a purely theoretical dimension and a more practical one. In both dimensions, design is faced with radical changes related to representation, communication, manufacturing technologies, and an increasingly globalized world with more and more competitive and demanding markets. All these factors are profoundly influencing the role of design and the methods and processes that characterize it. Also, these changes have impacted on the knowledge related to the traditional designers' role within the product development process, but also on their skills and working practices. Consequently, also the design educational models are radically changing. They get closer to the engineering disciplines, due to the need of accessing technical knowledge, but also of moving towards courses and educational paradigms that are increasingly based on the "knowing how to do" than on the simple "knowing".

In the Italian context, design education has a relatively short history, which traditionally began at the schools of architecture, where architects were trained. During the '50s, the growing demand by companies of professionals able to manage the design of industrial products boosted the advent of the first courses in furniture design and, later on, in product design. At present, considering the many different degrees in this area, such as product design, fashion design, communication design and so on, *design* represents the integration of art, architecture, engineering, and craftsmanship.

Today, one of the most impacting evolutions we are witnessing is related to new manufacturing technologies (3D printing techniques) and new skills of designers, which are bringing design practice closer to the auto-production. This emerging trend cannot be supported anymore through traditional didactic approaches and the use of traditional "Labs", but it is necessary to create spaces for allowing students to learn, design and experiment in a shared manner.

This paper presents the case study of the Polifactory Lab at Politecnico di Milano, which is an innovative makerspace established with the aim of creating a new research and teaching space. The Polifactory Lab comprising in-house staff and Faculty members of reference aims at stimulating the exploitation of new creative approaches to design, and the development of innovative projects and products. The Polifactory Lab is equipped with several technologies and facilities (i.e., for subtractive and additive manufacturing, physical computing and so on), and is accessible to researchers and students of specific courses and graduating students. In this paper the authors, who are Faculty members and technical staff members of the Polifactory Lab, describe the Polifactory Lab, its theoretical purposes, and some examples of didactic activities carried out at the Lab.

2 Literature review

Traditionally, designers were associated to artist, due to the "creative" approach used in their activities. Over the years, the evolution of the technological and manufacturing aspects has led to the reconfiguration of processes and roles. According to Buchanan [2], concerning the relation among technology, art, manufacturing and design: *"[...] twentieth-century orientation toward technology as a new science of art, where theory is integrated with practice for productive purposes and where art is no longer confined to an exclusive domain of fine art but extends to all forms of making. Nonetheless, the themes of rhetoric have merged in twentieth-century design precisely because they provide the integrative connections that are needed in an age of technology."*

The design discipline begins to play an important role in the Italian context during the post-war period, due to the increasing demand for mass products, which boosted the industrial development. In the same period, a first module concerning furniture design was established at the Faculty of Architecture of Politecnico di Milano, and the Italian education system began to think about teaching *design* [3]. Subsequently, a design module named 'Artistic design for industry' was established.

Later, in the ‘80s, both industry and academia started being in need of professionals with specific skills and knowledge, and of separating the discipline of industrial design from architecture, in order to adapt industrial design to the requirements of industry. So, in 1993, Politecnico di Milano established the first Master degree course in Industrial Design in Italy, integrating key elements of the Architecture and Engineering courses.

In the meanwhile, and specifically in the last decades of the 20th century, several social, political and infrastructural changes occurred on a worldwide scale, which led to a new technological development. This process refers to the phenomenon defined by Toffler with the term *Third Wave* [4]. Subjected to these changes, European industry started facing a particularly critical moment in its evolution: it needs to remain competitive compared to low labour cost countries by introducing more design, technology and sustainability in traditional products and in the production processes. In the professional world, many changes have been carried out to manage and exploit these new technologies and fulfil users’ needs.

Likewise, companies, academia faced new challenges as growing competitiveness, market globalisation, rapid technological evolution and consequent rapid product obsolescence, etc., and needed to re-define the designers’ role, knowledge, and skills. Similarly, the issue of change in the designer’s educational models has for long been a matter of debate among many design theorists. Findeli [5] launched a discussion on rethinking design education in the 21st century by surveying the evolution of the teaching models first developed by the Bauhaus and based on the interaction among art, science and technology – an interaction which changes over time but in which designers must be “*interested in the origin and destination of their projects, then the complexification of the process and the product should be completed by the complexification of problem setting and by the complexification of the impact of the project*”. In the same period, Cross, on analysing the evolution of design practice and design education in the Information Age, expressly spoke of the "*Information Age Bauhaus*" [6].

One of the most important effects of this process on the Italian educational institutions concerns a new balance between the use of deductive and inductive approaches. In fact, until the ‘80s, in the Italian academia the deductive approach, fundamental for creating solid theoretical basis, was largely used within Architecture, Engineering and Design Faculties. On the opposite, few courses were based on the deductive approach, which was at the basis of the Bauhaus and Ulm Schools and also of many European Design Schools [7 - 9]. The deductive approach, in which students directly experiment and “produce” their ideas, better supports the integration of the “knowing” and the “knowing how to do”, theory and practice, areas [10 - 12]. Nowadays, also in the Italian academia the inductive process is considered crucial. This is implemented through different figures – academic lecturers, professionals and entrepreneurs – collaborating and providing students with the necessary skills and knowledge to define and develop design projects.

At the core of the deductive approach are the design studios, in which students are asked to define and develop design solutions for a specific problem, by integrating and managing knowledge and skills acquired during theoretical lectures. In order to perform these activities, nowadays it is becoming essential the role of labs and workshops as places where practicing and experimenting.

Actually, labs and workshops have always played a central role in design education by enabling experiments through a deductive learning process based on action-research and practice [13]. The main historical examples, which have become archetypes in the 21st century, are provided by Ecoles des Beaux Arts, Arts and Crafts Schools and Polytechnics, but the modern concept of design lab is based on a genealogy created in the Bauhaus, and finally developed at the School of Ulm [14].

Today, these spaces are asked to support students in acquiring knowledge and skills about "crafts" techniques, about materials, such as wood, metal, ceramics, glass and polymers, and also about new technologies for representing ideas and for developing virtual and real working prototypes of design solutions, like physical computing, additive manufacturing, 3D printing technologies and so on.

Indeed, in these spaces it is possible to develop prototypes of the developed design solutions, where prototyping is a valuable tool in the design process of technological products [15], which allows enhancing physical interactions with the design idea [16], and evaluating in advance the product characteristics and its user interaction.

2.1 State of the Art of Learning Environments for Making

In the last years the importance of having spaces dedicated to making is increasing in the Design School [17-20].

Understanding and mapping makerspaces in the academic field arouses interest because these spaces:

- propose an open and peer-to-peer educational model, where learning happens through practical and experimental making/hacking/thinkering activities, often stimulated in a "collaborative self-learning" dimension, and developed by interacting with local or virtual community;
- stimulate multidisciplinarity and multispecialization of members;
- propose their own peculiar model of open and distributed education, which has as a reference the Fab Academy program;
- have easily configurable formats within different academic environments (e.g. reconfiguring, reorganizing or upgrading existing labs).

Therefore, in summary it is possible to assert that this kind of spaces are truly significant because they support individuals in identifying problems, building models, learning and applying skills, and above all enhancing and sharing new knowledge [21].

In order to appreciate and really understand the potential of these experimental spaces, it is important to better define the different kinds of learning environment that can arise from the different balancing of the internal peculiarities of design educational laboratories. As argued by Anderson [22] the concept of a space where people can make everything (makerspace) appeared at the first time with the spread of the maker movement, which started outside of the educational program as a following step of the Do-It-Yourself culture (DIY) [23].

From this very heterogeneous initial background, makerspaces have been progressively structured and evolved, permeating not only in DIY contexts, but also integrating and influencing workspaces and educational milieu. Nevertheless, fast configuration and spread of makerspaces, coupled with peer-to-peer management strategies, have led to the development of different organizational models with similar characteristics, but distinct peculiarities and missions. In order to better define the different typology and organization of these advanced labs for making practice, specifically in educational background, it is necessary to discover, sort and compare makerspaces case studies in university educational programs.

Over the last few years, the research on makerspaces and, more generally, on the making context has progressively been intensified by working on the following interpretations:

- the makerspaces as places for learning activities, also interesting for university education processes [21, 24];
- the makerspaces as places that enable, promote and speed up the simultaneous acquisition of extracurricular expertise such as hard skills, soft skills, technical skills, creative skills, digital skills, manual skills and entrepreneurial attitudes [25];
- the makerspaces as places that stimulate the integration between design activities and the materialization of artefacts [25];
- the makerspaces as places where the proposed activities stimulate new forms of socialization and new ways of living the study experience and university research.

Among the various, it is possible availing of the analysis conducted in [26] where there were construed the presence of these kinds of spaces in the Design Schools and Universities of Cumulus Network: 152 places were investigated and classified by scope with the desk research method. It is interesting to point out that from 2013 to today the nature of these spaces remains unchanged and physical or virtual makerspaces specific for design could be divided in: (a) Workshop, (b) Research Lab, (c) Hakerspaces and Makerlab, (d) Factory.

This type of interpretation is particularly challenging because it considers a finite number of structures belonging to the same type of network, but geographically distant and therefore subdued to very different policy and politics. In the following it is reported some few definitions of these spaces, which are examples in many European Design Institutes.

The *Royal College of Art London*[1] (RCA) Workshop (a) is one of excellence among the spaces of this typology. Workshops are used in order to learn specific prototyping techniques or to use specific materials such as wood, metal, ceramics, glass and polymers. Workshop is the most popular typology of learning by doing spaces. RCA gives great importance to analytic learning processes including

[1] Another interesting example is Design Academy Eindhoven (DAE), The design lab tackles every year a different topic usually finalized to re-establish a direct relationship between design practice and the public. Students work individually to design their own production lines creating machines, tools, or products. Furthermore the laboratory promotes a direct interaction with the public that can suggest to designers alternatives solutions to industrialization, production and consumption. DAE puts at disposal its own internal workshops (wood, metal, plastics, screen printing, textile, ceramics, digital technology, a photo studio and a library) while at the same time there are active collaborations with external enterprises and museums in order to promote local manufacturing techniques. Design Academy Eindhoven counts very much on the organization of international events where the presented projects (‘alpha phase’) are ‘pushed’ to become quickly efficient self-production business models.

'discovery phases' based on prototyping and materials testing, which are considered crucial for the realization of any project. Therefore, RCA puts at the students' disposal a range of maker facilities, which combine both digital and traditional fabrication[2], enabling designers to become professional self-producers. The Royal College of Art has also organized several exhibitions attracting numerous visitors during the Milano Design Week. Finally, some designers are now part of the Craft Council network as designer-craftsmen (http://www.labcraft.org.uk/, last accessed on 15 November 2017).

Research Labs connect education and research activities experimenting with technological, methodological and instrumental aspects of design and making. An example of Research Lab (b) is offered by the *D.School at Stanford University*. D.School is an innovation hub devoted to creating transformative learning experiences.

The approach is learning by doing: the question is not how to solve a problem, but how to define what the problem is. The Basic Training course is a hands-on session practicing with tools to bring ideas to life. To develop the project, the School has partnerships with corporate, no-profit and government-sector organizations [27].

Another type of learning space is the Hackerspace and Makerlab (c). This third configuration represents an evolution of electro-shops, physical computing and interaction design labs. Makerlabs is an evolution of hackerspaces and can be organized as Fab Labs or out-and-out Fab Labs. The most interesting example in this field is *EPFL+ECAL Lab at ECAL Lausanne*. Its mission is to explore the potential of emerging technologies through design, and to offer new areas of creativity to designers. ECAL Lab also works with other renowned partners and designers depending on the specific theme and requirements of each project. The Lab involves industrial partners to ensure that the best results may better benefit society as a whole, in terms of services, products or economic development. The Lab also develops continuing education programmes to investigate new practices.

Moreover, (Design) Factory (d) are structures that include maker-places and combine them with co-working spaces and other functions linked to research, production, promotion and incubation. *Design Factory at Aalto University*, for example, is a 3.000 m^2 working environment that enables creative work, knowledge sharing and experience exchange. All facilities are designed for flexible uses, with free interaction and prototyping made as easy as possible. Spaces can be easily modified and rearranged for various set-ups and different purposes of use, and to encourage open communication and spontaneous encounters. In 2012 the community was composed of: more than 700 students, 30 staff members, 30 teachers, 20 researchers, 35 collaborating industry partners and 5 in-house companies [28].

The educational experiences developed in these spaces testify to the transition from 'stereotyped' educational processes to the simulation and testing of real design, production, distribution and entrepreneurial processes (from idea to market and from

[2] Personal work space in the studio, traditional facilities for woodworking, metalworking, plastics and resins, computer-driven 3D milling equipment, Apple Mac and PC based 2D and 3D modelling programmes, and finally Rapidform RCA, the College's rapid prototyping centre.

idea to business). The first important finding is that Design Schools and Universities are no longer exclusively dedicated to teaching activities, but are also suitable for micro scale production activities.The mapping activity highlights the predominance of traditional workshops and vertical specialization in *design through making*. In these places a sort of *crafts knowledge* facilitates the product development, but at the same time the presence of specialized technologies and technical capabilities (often linked to the local context) tends to standardize the design-production process (routine). But many workshops are not connected either to each other or to local or global 'designers and makers communities'.

3 Polifactory, the makerspace of Politecnico di Milano

Politecnico di Milano has many typologies of learning laboratories: besides four workshops that make the Design School System Labs, there is a new research lab named Polifactory, which is a makerspace where students and researchers can work on educational, experimental and innovative projects.

Since 2011 the Design Department has begun a process of investigation and experimentation on design for digital fabrication and distributed production. In particular, many PhD theses have been developed on this topics (e.g. Design for Additive Manufacturing, Design for distributed self and micro-production, etc.).

Back in 2002, the Design Department funded a research project named "MakeFactory". The project aimed to explore the role and potential of design within an emerging production scenario where new practices of making interact with education, industry, distribution as well as self-production activities. The results of this research have been fundamental to provide knowledge, data and information for the subsequent Polifactory project.

MakeFactory focused on two main investigation areas:

- the relationship between design and new fabrication technologies, in addition to the impact of the latter on the design processes, the presentation, production and distribution of goods.
- the relationship between design and traditional and emerging manufacturing networks. In particular, the impact on collaborative processes between design and enterprises and on emerging urban locations, where design and production take place.

The research investigated the emergence of a new production scenario from a phenomenological point of view, focusing on the rapid growth of maker labs in Italy and worldwide [29, 30]. Eleven makerspaces[3] have been visited and analyzed as case studies in order to explore: their relationship with public or and private institutions, their activities, services and business models, their research and experimental initiatives (and the role of design). Subsequently, an experimental activity named Making@Polimi (M@P) has been conducted. M@P was designed with the dual purpose of verifying the relationship between "making" and design, and promoting an

[3] Fab Lab Amsterdam and Fab lab Eindhoven (Holland), Time Lab Gent, Fab Lab Genk, BXL Fab Lab Brussel and Fab Lab Leuven (Belgium), Fab Lab Barcellona (Spain), Fab Lab Torino, Mediterranean Fab Lab - Cava De' Tirreni, Fab Lab Reggio Emilia and Fab Lab (Italy).

open event and setting-up and prototypimg a temporary makerspace in the basement of the Design School, an area commonly used by around 4.000 students. Such location highlighted the strategic role of M@P in reconfiguring the normal workflow of the design labs

A techno-scientific group have supported six selected design teams providing them advice and access to digital fabrication facilitates, enabling the rapid prototyping of their projects (the M@P motto was "*from ideas to market*"). Some outcomes from MakeFactory have been used to define the following features for Polifactory:

- a first network of contacts with digital fabrication manufacturers, fab labs and makerspaces and other universities interested in these topics;
- a specific approach named "pre-incubation of talents and ideas" involving design labs, researchers and incubators to stimulate the students in the prototyping of their product-service ideas;
- a first prototype of the makerspace settings (digital fabrication equipment, required skills for the technical staff) and business model.

Therefore, in order to systematize and develop further this topic, Politecnico di Milano has established the Polifactory (www.polifactory.polimi.it, last accessed on 15 November 2017) makerspace-fab lab to investigate the relationship between design and the change of production models developing research, pilot-projects and experimentation. It has been officially launched in March 2015, supported by the Design Department together with the Department of Mechanical Engineering and the Department of Electronics, Information and Bioengineering.

The mission of Polifactory is to explore and investigate the relationship between design and new scenarios of manufacturing, and to develop experimental research and educational activities related to: (i) new practices related to independent innovation, self-production and personal fabrication, (ii) new fabrication technologies related to the emerging forms of open and distributed manufacturing, (iii) the new production places of (factories of the future) and spaces related to the concept of small urban manufacturing.

Polifactory supports the pre-incubation of young talents. Every year, doctoral and graduating students in design, mechanics, electronics, computer science and bioengineering are selected through Open Calls and hosted for three months in the makerspace. During this period, they work to materialize their own projects and collaborate (peer-to-peer) with other people participating in the makerspace activities.

Beside this educational and research space offers a consultancy for bodies and enterprises. Polifactory organizes hackathons and workshops together with authorities, institutions and companies in order to explore new scenarios for several manufacturing and service sectors and facing different issues/challenges related to the integration of design, manufacturing and digital/analogic technologies. Polifactory offers a service that includes the planning and organization of hackathons and workshops: scenario building, open calls organizations and giving support in the concept development and prototyping phases.

Polifactory is a member of new multidisciplinary and independent innovation communities created through the development of pilot-projects such as Next Design Innovation (www.nextdesigninnovation.it, last accessed on 15 November 2017) and Fabric-Action (www.fabric-action.org, last accessed on 15 November 2017).

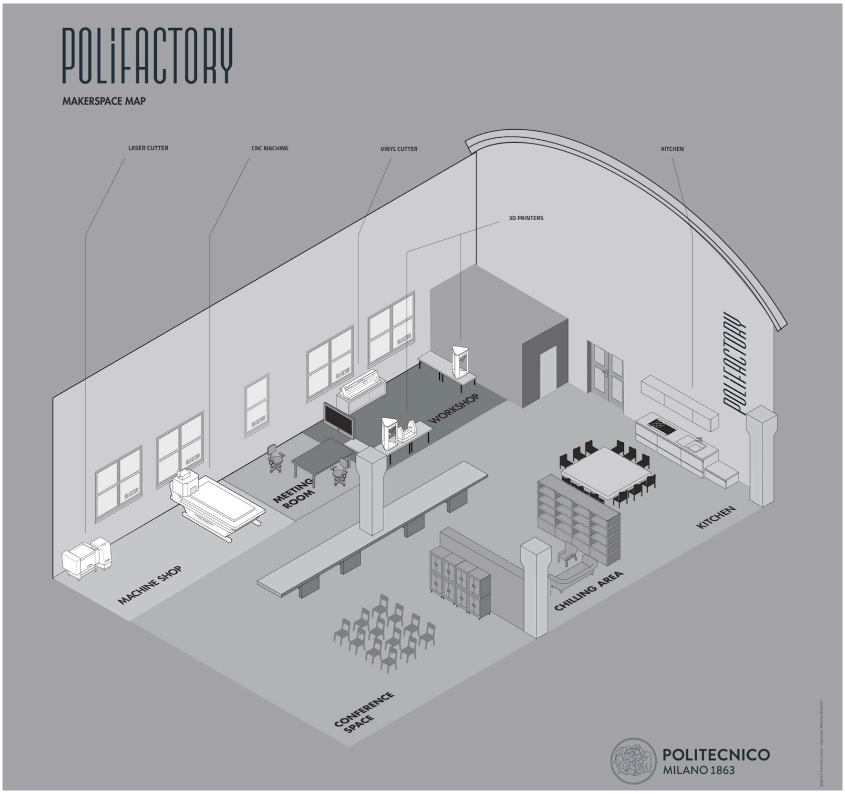

Fig. 1. The Polifactory space

In order to support young talents to improve the level of performance in their autonomous learning processes, Polifactory offers a range of coaching services. By definition, makerspaces are places that stimulate collaborative peer-to-peer and social learning (then the form of peer coaching). Polifactory follows this philosophy providing a coaching service that supports individuals and groups to develop strategic, design, technical-technological, micro and self-entrepreneurial capabilities:

- set up a production scenario which include technological trends, market trends, production system configuration (open distributed production);
- develop a whole pre-incubation process ranging from design phase to prototyping and the distribution strategy;
- learn how to analyse, evaluate and compare different technological options and solutions to set-up a sustainable micro or self-production process;
- self-assess the technical feasibility of ideas and self-organize the materialization processes;
- develop 2D and 3D models and set-up digital files for CNC and digital fabrication machines;
- learn how to set-up and use machines for additive manufacturing and cutting machines (laser cutters, desktop milling machines and vinyl cutter) autonomously;

- learn how to make small moulds and create objects using resins and silicones;
- learn how to design, prototype and program electronic boards in order to create interactive digital objects and devices (e.g. wearable devices).

It is possible to offer all these services and activities with the following facilities:

- subtractive manufacturing: laser cutting machine, 3 axis CNC big milling machine and 3 axis CNC desktop milling machine;
- additive manufacturing: FDM 3D printers of various sizes and a SLA (stereolithography) machine for high quality 3D printing;
- electronics and physical computing: microcontroller and microcomputer boards with kits of sensors, actuators and effectors and a workbench for electronics;
- tools and electro tools: a workstation equipped with hand tools and multifunction power tools.

But the real asset of Polifactory is the personal skills and human characteristics of the people who spend their time in there.

The first “stress test” to check the scientific-technical and operational model of Polifactory has been the project called “From Ideas to Market” funded by Regione Lombardia, which allowed the final technological setting of the Lab. The project aimed to simulate and demonstrate how the makerspace can work. A hackathon on interactive furniture has been organized in the new makerspace involving 3 companies and 15 among designers, architects and engineers. The Polifactory scientific team collaborated with 3 companies – Manerba, LuxSolar and Mobilitaly consortium – to define specific design challenges (interactive lighting, interactive living rooms and smart office) and asking them to donate three products (a sofa, a desk and a light) to be hacked by the participants in order to develop new interactive furniture products. The three new interactive prototypes developed during the three days of the hackathon have been presented at the European Maker Faire in Rome in 2015.

Fig. 2. Students working during the “Design From Ideas To Market” hackathon

A key aspect for Polifactory, as for the other makerspaces, is the development of its own creative community. In the case of Polifactory, due to its nature of an experimental research lab, this means the development of a multi-level research project:

- the development of initiatives to stimulate the creation of a multidisciplinary creative community capable of converging and collaborating in multidisciplinary projects integrating design, mechanical, electronic and computer engineering topics;
- the development of initiatives to connect the more technical culture of the Politecnico maker community with the mainstream maker culture.

In order to reach these goals, the Polifactory Faculty and staff have operated on three levels of research:

- the development of a theoretical-operational model of independent innovator named *designer = enterprise* [31], which represents the figure of a micro-designer and self-producer hybridizing the maker, the technical-scientific and the design culture;
- the development of a survey work to explore the features of the maker and independent innovation scenarios in Italy. This research, named Makers'Inquiry [30, 32], is the first study conducted in Italy on a sample of 150 *designers - makers* concerning the profile, skills, activities and skills of these subjects;
- the development of an *Open Call for Talents* initiative, a call that aims to select and stimulate design and engineering students of Politecnico di Milano interested in developing their Master Degree thesis at the Polifactory Lab.

Since 2015, Polifactory has analysed over 100 cases of international *designers = enterprise* and other 140 cases of *designers - makers*. Moreover, the *Open Call for Talents* initiative has been experimented with over 40 students. Finally, other initiatives such as workshops, summer schools, hackathons and computer clubs have involved more than 200 people.

4 Case Studies

There are numerous examples of didactic and research activities developed within the Polifactory makerspace. Among these, we mention the following:

- the Master Degree thesis in Design for the Fashion System of Margarita Medvedeva about a sportswear collection developed via Virtual Prototyping tools for fashion design [33 - 35] and 3D printing technologies;
- the design contest Fabric-Action, an initiative for the support of Valnerina promoted by Umbria Regional authorities and Fondazione Politecnico, and developed by Polifactory with the Museum of Hemp of Sant'Anatolia di Narco (www.fabric-action.org, last accessed on 15 November 2017), where students, young designers and recognized professionals presented innovative projects for hemp applications;
- "Phoenix, the rediscover jewel", a Master Degree thesis in Design for the Fashion System by Lavinia Scuderi, which explores additive manufacturing applications for jewellery creation, incorporating pieces recovered from scraps of art ceramic processing [36];

- the Ph.D. thesis of Weibin Ding about the design and development of Olfactory Displays for integrating scents simulation in multisensory virtual environments [37, 38].

The approach used at Polifactory is based on the observation of new trends in the design domains and aims in motivating students with different background in several design and engineering disciplines to:

- analyse company and users' needs, conceptualize and design novel design solutions and "materialize" them;
- experiment the use of new technologies for developing virtual and real prototypes in a very early stage of the design process, in order to evaluate their design solutions and improve them in a iterative process;
- work in a shared place, in which students and researchers can collaborate, create new knowledge and share it.

So, the Polifactory learning model is based on the technical knowledge already acquired by students through traditional theoretical courses at Politecnico, and integrates the deductive and experiential learning [13] with a peer-to-peer collaboration between Polifactory students, researchers and teachers, in which all the actors learn together.

In the following, three case studies are presented. These concern projects developed in the context of a "traditional" course of the Design School, a Master Degree thesis and projects developed during a one-week workshop of the Design School. These case studies have been selected because they represent examples of the three main categories of students' works usually carried out at the Polifactory Lab (a traditional course, an individual thesis and a workshop). Moreover, the design process of these case studies has been judged as accurate, complete and coherent, while the developed design solutions and prototypes have been selected for the annual students' design exhibition at the School of Design of Politecnico di Milano.

Although objectives, efforts and time could appear as far apart of each other, in all cases the deductive teaching approach and the used design processes is the same.

4.1 Design Concept course at the Master Degree in Product Design for Innovation

An example of activity that could be supported through the Polifactory makerspace can be searched within the course of Design Concept, situated at the first year of the Master Degree in Product Design for Innovation. Design Concept is a course structured in three different parts, where every single part has a specific teacher and each one explores a distinct theme. Within this course, the same year as Polifactory foundation, his scientific director, professor Stefano Maffei, conducted the module called "3D print the universe - additive manufacturing generates worlds".

The reason why the theme of additive manufacturing was presented to the students is because of the will to resize simplification and mystification, due to a generalized interest from the media on the theme of additive manufacturing. However, this interest often doesn't underline correctly the potential of this technology – which as industrial technology does not represent a new development at all: on the one hand, it doesn't give a complete idea of the real perspectives of improvement that 3D printing can offer in the development, manufacturing and distribution processes of industry; on the other it misses to list the real challenges between the vision of this technology.

So, the aim of the course didn't want to promote simple stylistic exercises, but was an opportunity to experience a reflective model of learning by doing, through the exploration of additive manufacturing technologies.

At first, a field analysis was conducted through the collection of significant case studies to present emerging production forms related to 3D printing, after which students were invited to propose their own application motivated by real benefits in choosing additive manufacturing technologies instead of others. The course will have the ability to teach participants content, processes, and tools that make them able to make a quick & dirty prototype of their idea. In this way, and with the support of Polifactory know-how, students had the opportunity to conceptualize, to tell and to develop projects experiencing a hands-on approach. Teachers and assistants involved in the course are members of the Polifactory Faculty, and have work to recreate a sharing environment to foster the growth of creative, technical and soft skills, in a participatory way: the technical constraints of the digital tools and machinery available were not transmitted as obstacles, but as a potential to be exploited or as limits to overstep.

The class was subdivided into ten three-people groups, whose made so many projects. Some ideas were interesting design exercises, though not necessarily related to the peculiarities of additive manufacturing technologies; more over rely on the technology to make small-scale productions. One of the most interesting insights emerging from this learning activity linked to the makerspace is the lack of a shared method in the literature.

The two best projects are described below.

Fig. 3. "Sprinted Wheel" by Carlo Maestri, Alice Mastropasqua, Dario Panico. Dimensions: 52 x 52 x 42 mm, Materials: ABS e Filaflex, 3D printing technology: Double extrusion Fused Deposition Material (FDM)

Sprinted, by Carlo Maestri, Alice Mastropasqua and Dario Panico is a skateboard wheel printed in 3D with the technique of the double extruder. Due to it they chose two different materials: ABS, a rigid polymer with good resistance (the white part), and Filaflex, a mixed TPU based polymer that makes good grip (the green part). In order to guarantee the best performance either to made trick or to run in a city with the maximum control of the skateboards, the three students printed lots of sample to define print direction, slicing parameters, and infill pattern and amount. The hexagonal texture in the inner part identifies Sprinted, between the competitors' wheels, as the unique wheel for skateboard produced by 3D print, and the perforated part guarantees a much lower weight than those currently available on the market.

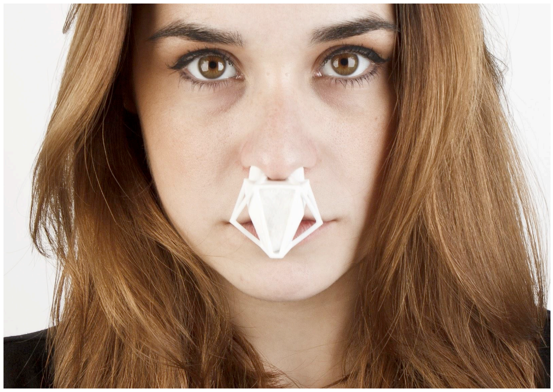

Fig. 4. "Traho" - nasal filter by Renato Ocone, Lucrezia Rescigno, Alice Scaringella. Dimensions: 39 x 22 x 44 mm, Materials: PA 3200, 3D printing technology: Selective Laser Sintering (SLS)

A radically different example is the project "Traho". It is a conceptual prototype whose main function is to denounce the daily levels of urban pollution by making it visible. Traho is forced to be worn out in a manner that differs from the accessories used for the same function by a strong aesthetic impact in order to cause, communicate and highlight the quality of the air we breathe every day. The main structure seeks to exploit the peculiarity of 3D printing both in geometry and in thinking about the adaptability to the measurements of each person.

Indeed, at present the majority of design experiences related to additive manufacturing are swayed by personal intuitions, either of the professional or of the amateur or even of the community involved. This is the reason why it is extremely important to set-up more educational milieu where students could grow up their own training with trial-and-error working alongside professionals and researchers who share knowledge.

4.2 Master Degree thesis: Innovation in the Montessori approach

At Polifactory it also possible to develop personal projects, including the thesis of talents in residence, students who choose to develop the experimental approach for their final project. Students attending Polifactory can freely use tools and technologies in space, in exchange for an active contribution during makerspace activities. For students, it is particularly beneficial to develop the thesis project within Polifactory because they can rely on constant support not only by teachers and experts who populate the space, but also by other students who are concluding studies. They no longer develop a project in isolation, but feel part of a group where they can share results, inconveniences and problems with people who are able to bring a wider and more strategic vision.

Many of the thesis projects that take place there give central attention to the experimental part, and an example of these is the Master Degree thesis of Deborah Fumolo [39]. During the setting of her thesis project, Dr. Fumolo deliberately chose to deepen the theme of the use of digital manufacturing technologies for the realization of learning tools.

Starting from an analysis of education systems, the student decided to focuses her attention to the lowest degree of education, where innovative elements are slower to root; the environments she analysed are nursery and primary school, these structures are rigid, not adapted to the current socio-economical context and not specifically based on the research provided by the educational science fields. The Montessori School is a system with specific characteristics able to remedy certain shortcomings in the traditional educational system. This entire methodology evolves around the teaching material, which is a basic element on it. Particularly, the student pointed out as the expense for materials is consistent and can stand as an obstacle to the spread of the method and the possibility to use these very important tools for the growth of the child (often the costs for a single class can spread around 5000 euros).

The method uses various wooden objects such as, for example, cubes of different sizes, wooden prisms of variable thickness, bars that differ in length, small coloured tablets - for the associations and combinations of colours -, geometric solids, bi-dimensional geometric shapes, tablets with different degree of roughness, tablets with different weight to develop the baric sense, tablets with bas-relief letters so that children can become familiar with the letter shapes, instruments introducing mathematical concepts such as the Pythagorean theorem and many more.

Fig. 5. Prototype of the learning tools for the Montessori Method.

In this framework, 3D printing is presented as a solution for the democratization of the material and the diffusion of it even outside of the Method in schools. Obviously, not all the tools used in Montessori schools could be produced with such processes (for example there are bottles containing different flavours to develop the sense of taste), so Deborah Fumolo's thesis focuses on the development of material taken from those available in the official catalogue and producing them in a way that can be approved from Montessori Official Committee. The thesis research also provides clues on how Montessori Method could be chosen among others and how it can improve and enhance both cognitive and social skills.

4.3 The "From Mind to Reality" workshop

The third case study carried out at the Polifactory concerns a "Workshop", a one-week course that students of Master Degrees of the School of Design have to attend, named "From Mind to Reality". The Workshop was attended by 30 students from the Master Degree in Communication Design and 20 students from the Master Degree in Design & Engineering. The Design & Engineering Master Degree Course has been established by the School of Design of Politecnico di Milano in collaboration with the Mechanical Engineering and the Materials Engineering areas [40 - 42]. The main goal of this Master Degree is to train professionals capable to manage every phases of the industrial product development process, from concept to engineering phase, in order to manage independently the process and, at the same time, be able to collaborate with other professionals.

Students were asked to create groups composed of 3 students from the Master Degree in Communication Design and 2 students from the Master Degree in Design & Engineering. All the students were asked to work full-time at the Polifactory Lab. Faculty members and Polifactory research staff were available for supporting students in the development of the prototypes of their design solutions, and students were asked to use, in collaboration with the Polifactory research staff, the Polifactory facilities, consisting of machines for laser cutting, vinyl cutting, 3 axes CNC milling, 3D printing (ABS, PLA, resins, …), and also physical computing boards and components (Arduino boards, Particle Photon and Node MCU boards, sensors, actuators, LEDs, etc.).

The brief given to students was to "*design a domestic product that allows new tangible interaction with live-data streams, and develop its functioning prototype*".

So, students were asked to avoid using any kind of digital display in the final product and communicate digital data to be acquired from the net by using lighting effects, sounds, movements, changing the shape or the colour of some parts, etc.

This brief is derived from the intention to stimulate students in conceiving and designing novel products, based on the most innovative technologies, in which new modalities of user interaction, based on the interaction design principles [43], can be exploited. Students, instead of designing user interaction based on "screens" and "apps", which currently is one of the most common approaches used for controlling function of any kind of product, were forced to be creative and "think differently".

After the brief presentation, three lectures were given about real-time data to be acquired (from social networks, online banking systems and other services, like weather forecast, and so on); about physical computing techniques and the Arduino and Photon boards; and about rapid prototyping technologies (3D printing, laser cutting, etc.). Then, groups started defining the “design problem” of their project, which consists in identifying which data stream they intended to use as basis for a product supposed to help users in their daily life. Consequently, students focused on the definition of “product concepts”, where the meaning, the shape, the functions and the features of the *product to-be* were designed referring to the modalities used for communicating the selected data-streams. Then, the remaining days were dedicated to the project and the prototype development. In this phase, each group defined the rapid prototyping technologies to use in order to materialize their prototype (physical computing boards and components, laser cutting, 3D printing and so on) and, consequently, prepared the necessary 3D models and programmed the boards. Consequently, students have been involved by the Polifactory staff in setting the machines for subtractive and/or additive manufacturing (depending on each specific project). Once the components were manufactured, the students assembled them and verified the proper functioning of the prototype.

Finally, the last day of the workshop was dedicated to the presentation of the ten developed projects and their final working prototypes. Some of the most representative and successful projects are described in the following section.

4.3.1 Pollution indicator

The first example is a pollution indicator, named Pollenair. In this project, students took inspiration from the worldwide serious environmental problem of air pollution. Even this invisible phenomenon kills 3.3 millions people every year, many people are not aware of the impact that air pollution has on their health. Moreover, also if data about air quality of many countries exist, few people check them and, even if they read them, they have not a clear idea of the potential risks caused by air pollution.

Consequently, the idea of these students was to design a real-time air pollution indicator, which can be used for visualizing the existing air pollution levels in contemporary cities in a tangible way. The aim is to increase people's awareness about the pollution issue and to warn them if the quality of the air is too low.

Students decided to use the live-data stream from the website https://waqi.info/, which is dedicated to monitoring the air quality in 60 different countries around the world. The data stream provided by this website reports the AQIs based on hourly measurements of particles in the air. Also, the website index used the air quality according to six levels of pollution: Good, Moderate, Unhealthy for Sensitive People, Unhealthy, Very Unhealthy and Hazardous.

Regarding the shape, students decided to use a metaphoric language, consisting of a flower shape. The flower represents the heart of the city, which is affected by the air pollution level. If the air quality is good, the flower is healthy and the light inside is green. If it is Moderate/Unhealthy for Sensitive People, the flower starts bending a little bit, and the light becomes yellow. If the quality becomes poorer (Unhealthy/Very Unhealthy), the flower is very bended and the light is blue. Finally, if the level becomes Hazardous, the flower is completely folded down on itself (which means “dead”) and the inner light is red. The use of this metaphor is particularly effective, and the users can understand the air quality looking at the shape and at the colour of the flower. The prototype was developed by using a NodeMCU WiFi board for the acquisition and processing of the real-time data, and for controlling the LEDs and two micro servo-motors used for bending the flower (Fig. 6). Finally, the external structure was manufactured using mainly the laser cutting technology for the basis (made of Plywood, 5mm), while a 3D printing machine was used for manufacturing the main shape of the flower.

Fig. 6. The Pollenair prototype

4.3.2 Weekly expenses display

The second project, named Budgy, is a system for visualizing daily and weekly expenses. Students observed that today economic transactions are carried out mainly by using electronic cards or other electronic payment systems. Consequently, it is quite difficult to control the actual cumulated expenses vs. a predetermined daily or weekly budget.

The students' idea was to *help users in keeping under control economic transactions, which are often difficult and confusing*. So, they designed Budgy to transform digital data, acquired from online banking system and electronic payment companies' websites, from an abstract entity to a physical and concrete product.

Students used the concept of "stack of coins", usually used by people to visualize "money", as inspiration and designed a product made of different vials: an upper and bigger one for the weekly budget, while other ones, smaller and lower, represent the seven days of each week. The weekly vial is filled up at the beginning of the week with some small spheres, which represents the weekly total budget. Each sphere represents one euro. Then, for each bank transaction, Budgy drops the corresponding quantity of spheres into the daily vial, showing the daily activity. Every morning, the system moves the vials in order to place into the right position the correct vial. The system works this way: the bank information system receives data concerning expenditures and sends these data to the user's mailbox. Then, a commercial software, named Mailparser (https://mailparser.io/, last accessed on 15 November 2017), automatically extracts the data from the emails and create a CSV file. Then, a NodeMCU WiFi board gets the data from the CSV file and, via a specifically-designed software, turns them into inputs sent to three servo-motors. The first servo-motor shakes the spheres, in order to avoid their aggregation, while the other two servo-motors control the valve of the weekly vial, for dropping the spheres, and the rotating platform of the daily vials.

The physical structure was manufactured by using mainly the laser cutting technology for the flat sides (with Clear PMMA, 3mm), while a 3D printing machine was used for manufacturing the valve, leverages and gear wheels (Fig. 7).

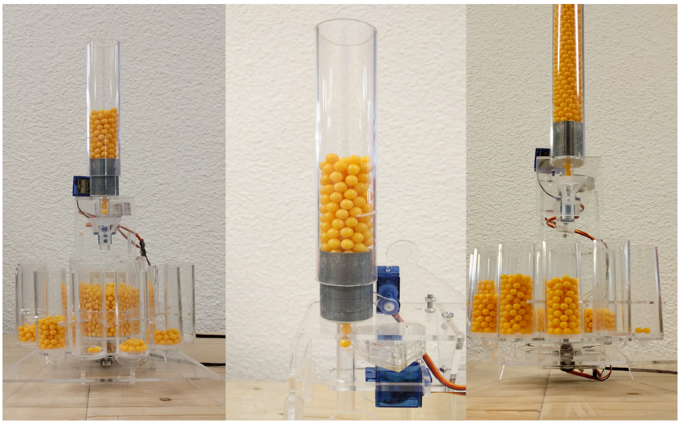

Fig. 7. The working prototype of the Budgy

4.4 Analysis of the case studies

Carrying out a comparison among the presented case studies, some important differences become obvious. These concerns a different topic for each case study, a different level of development required by teachers, different time frames, the possibility to develop these projects individually or in groups, and so on.

However, all these case studies present a learning process based on the deductive approach: starting from the students' technical knowledge acquired during the traditional design courses, they have been asked to apply it on a design problem, develop appropriate design solutions and create the corresponding working prototypes. Moreover, the deductive and experiential learning model commonly used in labs and workshops [13] is integrated and improved in the Polifactory experience by the peer-to-peer learning.

Specifically, the case studies have been analysed and compared with the Polifactory model and approach. Traditionally, students who apply to the *Open Call for Talents* are requested to have a residence experience ranging from 3 to 6 months. During this period they develop and prototype predominantly their projects by exchanging knowledge in peer-to-peer learning with other students, researchers and teachers in the Polifactory makerspace. At the same time, they are asked to participate in the Polifactory research, experimental, professional and cultural activities. In this model, a peer-to-peer collaboration between Polifactory students and research and teaching staff is carried out, overcoming, in the respect of roles, the traditional teaching-learning hierarchies to create a horizontal collaboration in which researchers, teachers and students learn together.

Also, if it is particularly effective in the case of Master Degree thesis, the same learning model is also identifiable in the case studies concerning the course of Design Concept and the "From Mind to Reality" workshop. In fact, even if the level of complexity, integration and learning is affected by the short available time and the greater number of participants, the peer-to-peer learning model and the horizontal collaboration are in any case carried out.

Finally, these case studies have been further analysed in order to define new skills that students can acquire during their experience at Polifactory:

- *experimental skills*, enabling the development of forms of craft and hands-on innovation that combine design, technology and science;
- *experiential skills*, enabling the systematization and enhancement of the learning that springs from the work-life experiences;
- *entrepreneurial skills*: enabling the design and re-design of a job or business activity;
- *heuristic skills*, enabling the use algorithmic processes to accelerate the development of systemic design solutions.

5 Conclusions

The Polifactory makerspace can support very different types of teaching methodologies and structures, as can be seen from the examples reported in the paper. Indeed, the wide set of digital tools and technologies for digital manufacturing, the possibility to rely on a very wide body of knowledge and competences, thanks to the availability of professors and researchers from different departments and of professionals with different background and the layout itself (which favours aggregation, collaboration and peer-to-peer dynamics) make Polifactory a very flexible and versatile structure, which is able to meet very different requests.

One of the most interesting features of a research space permeable to teaching activities consists in its versatility and, then, its ability to respond to extremely heterogeneous stimuli: medium-long duration activities run side-by-side with more immersive and time-limited experiences. Design and engineering students have also the possibility to work on specific tasks of external corporate projects, which enhances cross-fertilisation and mutual enrichment. It is thus possible to set-up initiatives that last some days, whose purpose can be the creative generation of concepts, which are verified only from looking at the operating principles. In other cases, students are given the opportunity to carry out all the phases of a new product development process, from conceptualization to design, to production testing and usability through rapid prototyping and direct digital manufacturing techniques.

This is very important if we take into account the scenario that current students will face once they have completed their studies: indeed, in an ever more flexible work environment, in which delivery times can vary to a great extent from project to project, the ability to adapt the approach to the different briefs is a fundamental skill. In addition, another very important distinctive skill consists in the understanding and managing rapid prototyping and direct digital manufacturing technologies, which are increasingly used by companies and professional firms, but are not given enough attention by higher education programs of most universities, still focused on traditional production technologies.

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