UNIVERSITÀ DI PAVIA

A strategic plan proposal for UniPV

3D@UniPV

Virtual modelling
and
additive manufacturing (3D printing)
for
advanced materials

Project webpage	http://www.unipv.it/compmech/PSA_additive.html (constantly updated)
Project coordinator	Ferdinando Auricchio, professor of Structural Mechanics For a CV please refer to http://www.unipv.it/auricchio/

Project network	**UniPV**	**67** professors and researchers from **16** different Departments + **9** laboratories
	Italian University and **Research Centers**	**6** Universities + **3** Research Centers + **4** Hospitals
	Foreign University and **Research Centers**	**8** Universities + **1** Research Center + **1** Hospital
	Companies	**20** Companies + **4** Academic Spin-off

Project goal

Additive manufacturing is at the same time a disruptive, but extremely wide-spread and transversal, technology; in this context the 3D@UniPV project has the goals of giving an even further boost toward innovative applications, in particular combining current technologies with two other fundamental ingredients, such as virtual modeling and advanced materials, investigating also social, economic, and legal aspects.

The proposed concepts have immediately coagulated a huge interest from a very large part of our academic community as well as from research centers and companies (from local up to international level) and, as a matter of fact, several project members are already actively working toward the project goals.

Henceforth, it is clear that the proposed activities represent a strategic direction, which our University could decide to pursue and ride.

Strategic view in the local, national, and international context

<u>Additive manufacturing (3D printing) technology</u>

The term additive manufacturing (**AM**), or 3D printing, indicates a technology where components or complete structures are constructed through sequences of material layer deposition and/or curing. If compared to conventional production technologies (such as casting, stamping, milling, etc.), AM opens the doors to complete different design and manufacturing approaches.

However, despite its already wide availability (3D printers are nowadays even sold with periodicals!!), we are just at the initial exploitation of such new approaches, with many future innovations, uses, and impacts to be explored.

It is in fact clear that AM will soon drastically change not only the production paradigms, but also the distribution chain, leading to whole new implications from the technological point of view as well as from social, economic, and legal points of view.

<u>Some facts … which should really make you thinking!!</u>

- MIT Technology Review (May 2013): AM is one of the 10 breakthrough technologies in 2013, pointing out that "GE, the world's largest manufacturer, is on the verge of using 3-D printing to make jet parts".
- McKinsey (May 2013): in a document entitled "Disruptive Technologies: Advances that will transform life, business, and the global economy", 3D printing is listed as one of the 12 disruptive technologies of the future (with Advanced Materials being another one out of the 12!)
- Forbes (Sept 2014): "35% of all ads posted for engineering jobs in the last 30 days prioritize 3D printing and AM as the most sought-after skill" and "the number of job ads requiring workers with 3D printing skills increased 1,834% in 4 years and 103% when comparing August 2014 to August 2013".
- McKinsey Quarterly (Jan 2014): "The advantages of 3D printing over other manufacturing technologies could lead to profound changes in the way many things are designed, developed, produced, and supported". Moreover, data shows that in 2013 the 29% of 3D printers is used for the production of end components (see Fig.1).
- Up today to our knowledge in Italy (unlike other countries, among others USA - Fig.2) there is no industrial district or university, which has set AM as a target activity!!

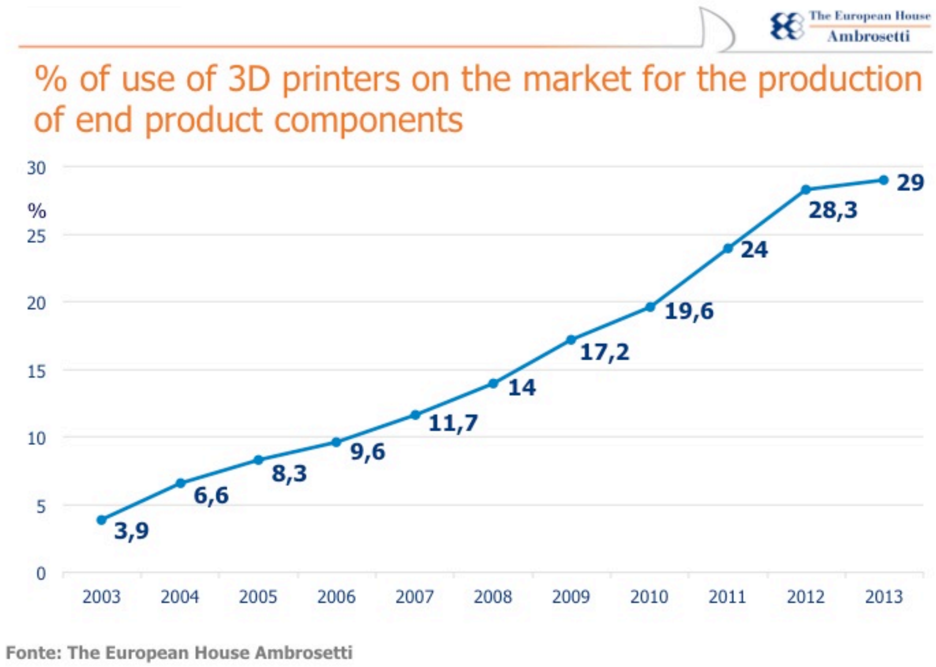

Fig.1: Data on the usage of 3D printers for the production of end product components (courtesy of the European House Ambrosetti).

Fig.2: USA investment on AM research centers (courtesy of the European House Ambrosetti).

Regional, national, and international context

Manufacturing industry is a key pillar for developed economies. In Europe it represents the first non-financial sector for added value and number of employees. In particular, Lombardy is the first manufacturing region in Italy in terms of turnover, added value, and the third in Europe by number of employees, preceded by Bavaria and Baden-Württemberg, for a total of 100,000 businesses with around 1 million employees and a 250 billion euro turnover, with an added value of 60 billion euro.

With the goal of improving and coordinating manufacturing activities in terms of innovation, research, and technology transfer, Lombardy has seen the born of AFIL, an association between companies, research center, and public entities. A recent AFIL document has stated that "efficiency, sustainability and competitiveness of the manufacturing system depends largely on the ability to operate innovative and technologically advanced processes and to take advantage of them in the design, manufacture and assembly of products and their components", pointing out that "the research priorities in this area will be directed to the improvement of the potential of innovative industrial processes and their improvement in a wide range of applications", highlighting AM as one of the priority themes.

Furthermore, at the international level Lombardy is part of the "Vanguard Initiative New Growth through Smart Specialization", a strategic project that among other goals "aims at the construction of a network of industry-led demonstrators across Europe to enhance the uptake of solutions provided by 3Dprinting technologies in international value-chains".

UniPV is partner of both AFIL and Vanguard Initiative. Prof. Ferdinando Auricchio is member of the "Additive Manufacturing" Thematic Group Steering Committee within the Lombardy Association for Intelligent Industry.

Project structure

The 3D@UniPV project activities are organized into 5 pillars (Figs.3-4), briefly discussed in the following and detailed in the section "Project tasks".

Modeling and Simulation

This pillar deals with the development of models and simulations for a better comprehension of materials and product performances, as a basis for the development of high performance materials, more effective production systems, and innovative applications. Great attention will be given to the simulation of different phases of the manufacturing process within different AM technologies.

New Materials

This pillar concerns the investigation of highly performing or advanced materials to be used in innovative applications. In the medical, prosthetic and pharmaceutical field, main interests regard biocompatible, light and mechanical loading resistant materials, suitable for cell-culture as well as the printing of living cells, to be used in regenerative medicine or for drug delivery systems. A further target could be the combination of different materials into specific patterns, for the development of products with mechanical and functional properties that cannot be retrieved through other technologies.

Manufacturing

This pillar concerns the optimization of printing processes for specific target applications or for new printing materials. An example is related to the printing of highly deformable materials with FDM[1] technology. Other examples are represented by the rapid prototyping of metal alloys with particular mechanical characteristics, such as Shape Memory Alloys (SMA), whose mechanical behaviour is highly dependent from the processing temperature and of components realized with advanced ceramics materials.

Socio-Economical Impact

AM is completely changing production paradigms and new product developments, drastically shortening the time from the idea to the final product. Thus, there is a growing interest in topics like patenting and proprietary issues regarding AM processes and applications, as well as in all the managerial, social and economic implications, for example in terms of technology impact on the job market, economic sustainability of revenue models, and cost structures.
Furthermore, the rapid production of prototypes offers new and interesting problems to cognitive, epistemological and ethical reflections.

Applications

The rapid diffusion of 3D printing is a key indicator of its versatility. As a consequence, the project lists a wide range of target applications, some requiring the definition of a specific strategy for the application of an existing technology, while others need the development or optimization of printing materials and the adjustment of the prototyping process. Project

[1] FDM: Fused Deposition Modeling

target applications involve many different fields, from biology, medicine, chemistry and pharmacology to more industrial one, like jewelry, architecture and cultural heritage.

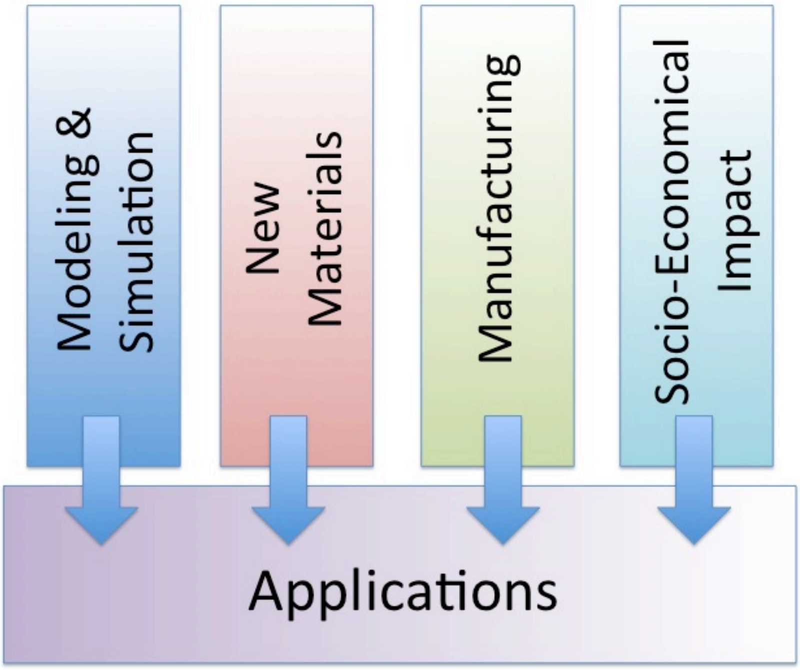

Fig.3: Project pillars.

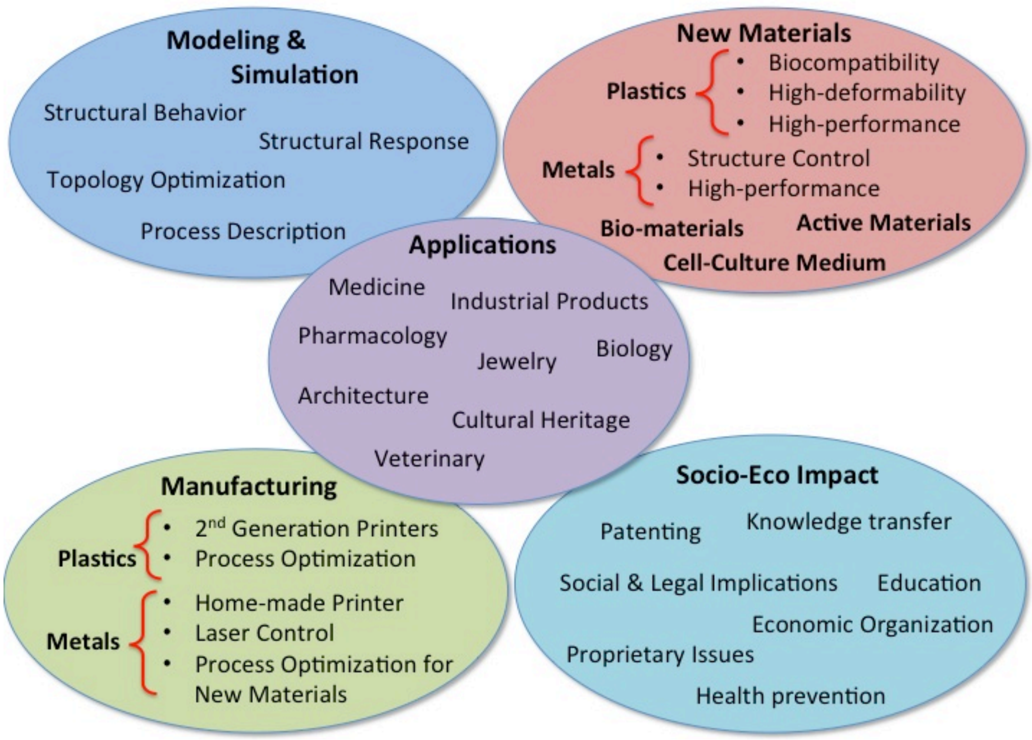

Fig.4: Project pillars and sub-themes.

Project network

The 3D@UniPV project has attracted a large interest from different actors (Fig.5), producing an enthusiastic response not only within UniPV (involving **16 out of a total of 18 UniPV Departments**, Fig.6), but also from several national and international research entities (Fig.8), along with a large number of companies (Fig.9), resulting in a quite balanced distributions of actors on the different pillars (Fig.10).

An overview of the contributing areas for each project team is reported in Figs. 7-8-9, while a complete and detailed description of each project team components and contributions can be found on the project webpage. It is important to emphasize that some teams have already been quite active in several project activities (e.g., refer to Gantt Chart in Fig.11).

Fig.5: Representation of the project 3 main actor groups

UniPV Department	Acronym
Department of Biology and Biotechnology	Bio_Biotech
Department of Chemistry	Chemi
Department of Civil Engineering and Architecture	DICAr
Department of Economic and Management Sciences	Economics
Department of Environmental Sciences	Enviromental
Department of Humanities	Humanities
Department of Industrial and Information Engineering	DIII
Department of Internal Medicine and Medical Therapeutics	Int_Med
Department of Law	Law
Department of Mathematics	Math
Department of Molecular Medicine	Molec_Med
Department of Musicology and Cultural Science	Music_Cultural
Department of Pharmaceutical Sciences	Pharma
Department of Public Health, Experimental Medicine and Forensics	Pub_Health
Department of Physics	Physics
Department of Surgical Sciences	Surgical

Fig.6: UniPV Departments involved in the project

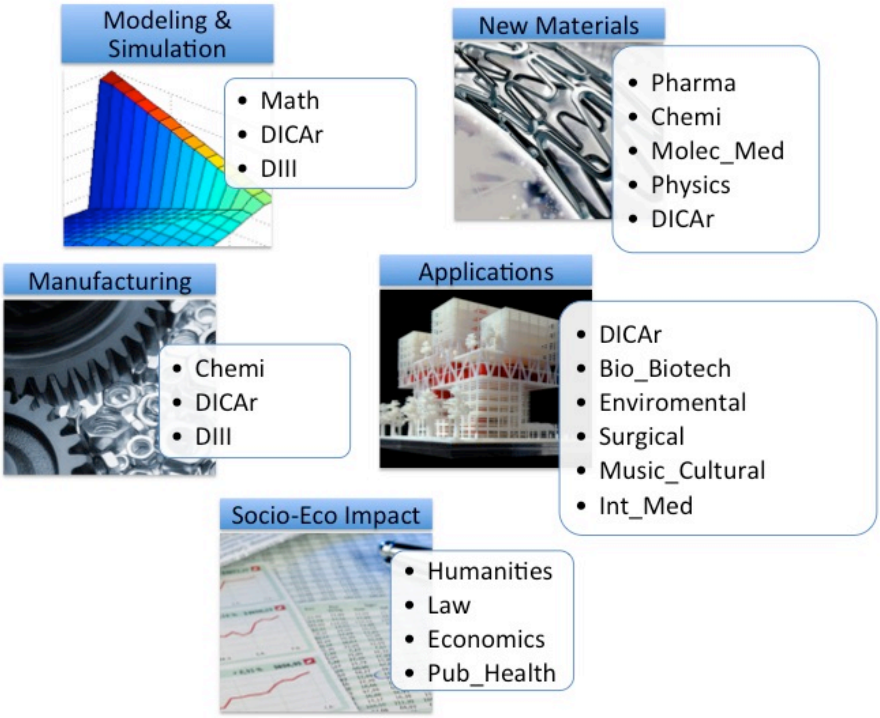

Fig.7: UniPV Department main contributions to project pillars

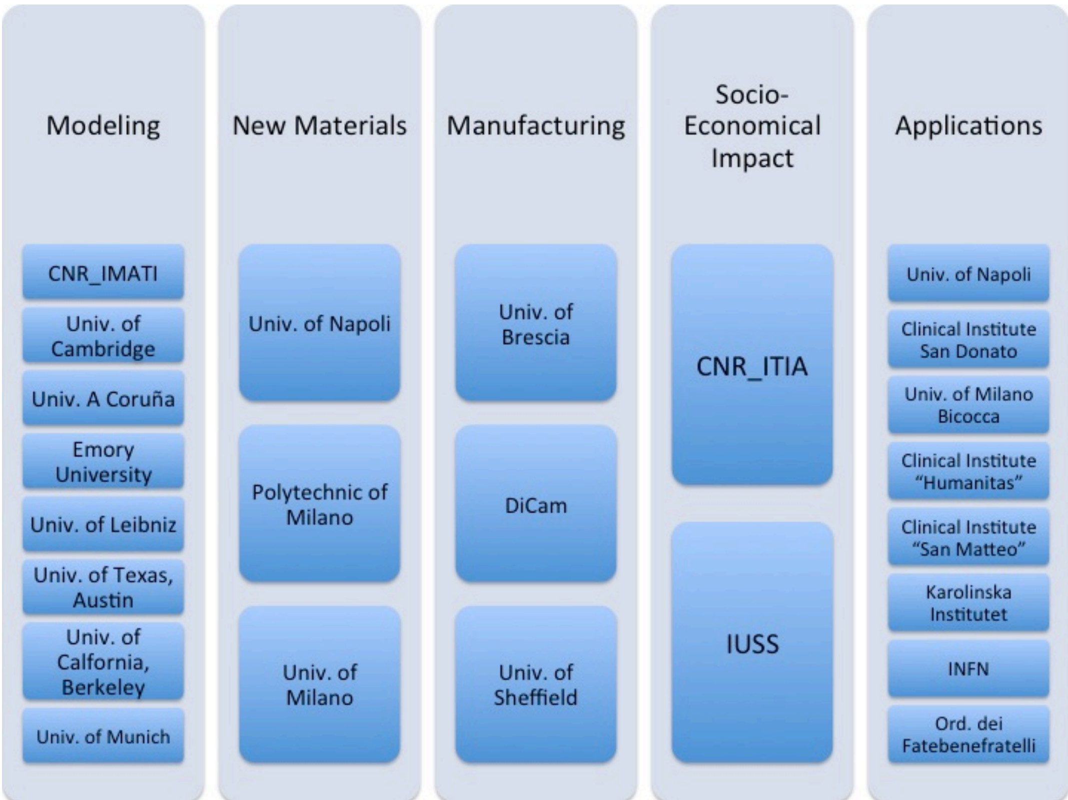

Fig.8: Main contribution of national and international Universities and research centers to project pillars. *DiCam stands for Dutch innovation Center of additive manufacturing, *INFN stands for National Institute of Nuclear Physiscs.

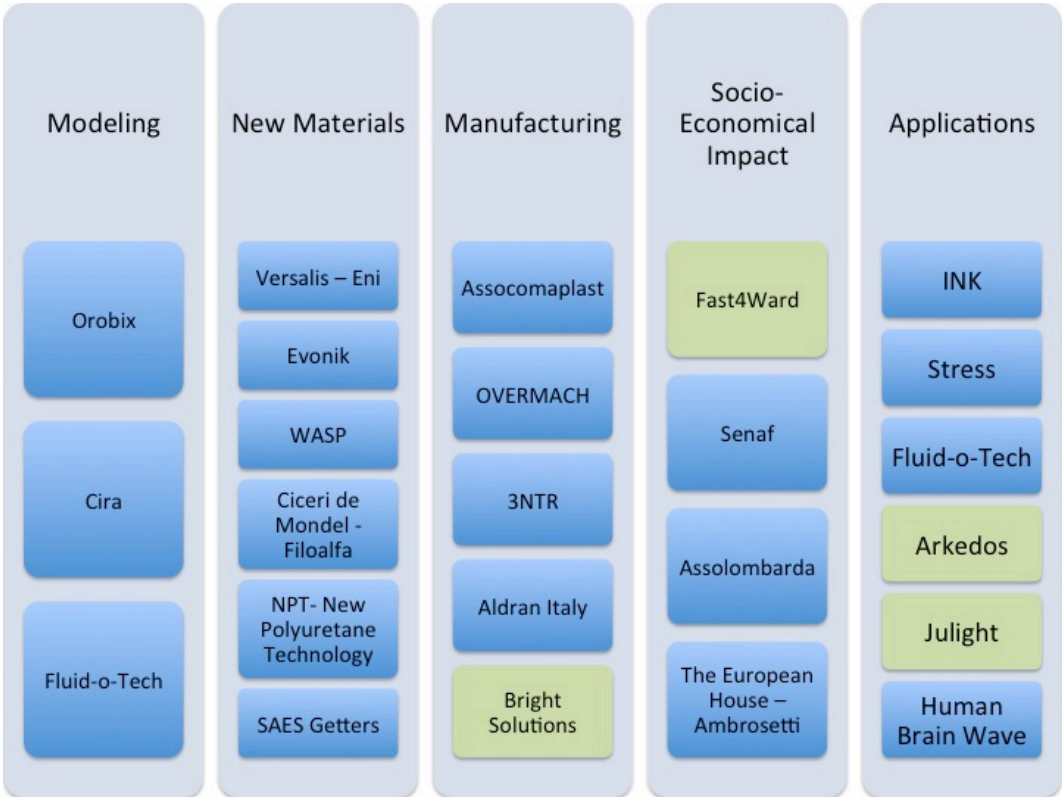

Fig.9: Main contribution of partner companies to project pillars. In green: UniPV spin-offs. Details on company activities in relation to the project can be found on the project webpage.

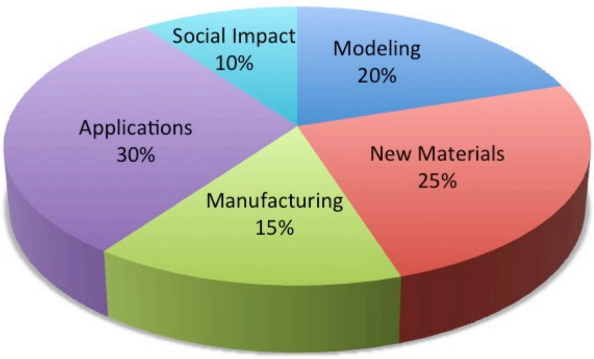

Fig.10: Distribution of resources in terms of UniPV participants, University, Research Centers, and company subscribers

Project Tasks

In this section we report tasks for each project pillar. Fig.11 indicates the contribution of each team to specific project tasks.

Modeling and Simulation

MOD_1: Advanced methods of discretization for integrated design, optimization and analysis of solids and structural components

MOD_2: Virtual and in-vitro simulation of anatomical geometries and biomimetic material properties, especially for patient-specific fluid dynamics in the human circulation (e.g. aortic aneurysms and dissections)

MOD_3:
a) Micro-macro multi-scale models to describe 3D printing processes
b) Non-Newtonian polymer models to describe 3D printing processes
c) Computational models to support and optimize metal print

MOD_4:
a) Numerical finite-element and isogeometric methods
b) Numerical "phase field" methods based on isogeometric analysis

MOD_5: Mechanical behavior of materials and processes (micro and macro scale), model validation, virtual simulation
Simulation of thermo-mechanical materials behaviour (both standard and advanced materials)

New Materials

NMAT_1: Materials for 3D printing of structural elements for buildings, using local and low environmental impact prime materials

NMAT_2: Highly-deformable and high-performance materials for FDM 3D printing

NMAT_3: Biocompatible materials for FDM 3D printing and application in regenerative medicine and cell growth, even under extreme conditions (space), or in veterinary for bone fracture healing plates.

NMAT_4: New materials and processes to print metals and ceramics using low-cost 3D printers

Manufacturing

MAN_1:
a) Innovative processes allowing the printing of alloy and ceramic materials
b) Feasibility of producing in-house laser melting metal printers

MAN_2: Optimization of FDM printing for highly-deformable and high-performance materials, even under extreme conditions (space)

Socio-Economical Impact

SOC_1: Health risks prevention for people in contact with nano-materials

SOC_2: Research and industrial patenting of new technologies or products realized through rapid prototyping

SOC_3: Knowledge transfer, with attention to target community

SOC_4: Ethical/philosophical analysis of technological advancement and products to be nested in cognitive theories, together with ethical and social consequences. Abductive cognition analysis in relationship to ethics, violence and technology

SOC_5: Future industrial scenarios on a local (Pavia2020) and global context, new frontiers for primary activity outsourcing. 3D printing for SME/startup, mass customization; role of FabLabs on innovation eco-systems, economic/financial sustainability/revenue models. Support to start-up covering "leading change" thematic

SOC_6: 3D printed models for educational purposes, in particular for students with severe visual disability. 3D educational contents to increase learning experience through manual exploration. Collaboration with SAISD (Servizio di Assistenza e Integrazione per gli Studenti Disabili) centre of UniPV.

SOC_7: a) Business models for 3D printing, including : source and origin of competitive advantage; sustainability analysis of cost structures and revenue; design of business model to protect business against imitation where patents & IP are not applicable; analysis of the scalability
b) Business models for integration of AM into hospitals

Applications

APP_1: AM for architecture
a) Architectural models and urban studies at smaller scales
b) Production through AM of entire buildings or building components

APP_2: AM for medical field
a) Anatomical models for surgical planning or in vitro-testing (e.g., general and vascular surgery, otolaryngology, orthopedics)
b) Prototyping of new devices for surgery, clinical practice and didactic activities
c) Devices for mechanical test on biological materials
d) Scaffold for cell-culture and tissue regeneration (e.g., dental surgery and orthopedics)
e) Personalized prostheses for limb amputations (possibly including sensory systems) and personalised shoes for foot deformations
f) Microfluidic channels for human locomotion energy harvesting

APP_3: AM for biology, chemistry and pharmacology

a) Experimental in-vitro models for drug-delivery systems testing and 3D cell-culture systems. Polymeric scaffolds for tissue regeneration
b) 3D bio-scaffolds for tumour cell-culture endowed with vascularization system, to replace animal models in bio-distribution studies and to test anti-tumour drugs efficacy (e.g., boron vectors in BNCT applications)
c) Micro-chambers for in-vitro reconstruction of specific neuronal circuits
d) 3D model of bone marrow to study blood platelet production using silk based biomaterials
e) Microfluidic systems for energy harvesting. Micro-scale reactors for experiments in-operando conditions on catalysts using synchrotron radiation. Continuous flow (photo)micro-reactors for applications in organic synthesis
   Printing of crystal structure models in 3D

APP_4: <u>AM for new production system in the industrial field</u>
a) Personalized jewellery
b) High-precision fluid-dynamics valves for biomedical/industrial applications
c) 3D shapes to build custom footwear forms
d) Non-contact laser measurement techniques for low cost 3D imaging objects produced by 3D printers (quality assessment, defect detection)
e) Low cost microwave components and antennas of unconventional shape. Meta-materials based on micro-engineered structures, for compact and high performance planar antennas

APP_5: <u>AM for the arts</u>
a) Reconstruction of ancient cities for research in historical/philosophical /archaeological field and for exhibition purposes
   Study, preservation and exhibition of works of art, prototyping of architectural structures, decorations and frames for exhibitions
b) Integration of missing parts in sculptural and architectural restoration, replacement of sculptures located in open areas.
   3D acquisition system based on structured light technology, to acquire and process architecturally interesting images. Models for educational use or for museums during restoration works

Macro-Area	Task	Units
Modeling & Simulation	MOD_1	Math, Cambridge
	MOD_2	DICAr, Emory, CNR_IMATI, Orobix
	MOD_3	a) Math, Leibniz b) DICAr c) Munich
	MOD_4	a) Berkeley b) A Coruña, Austin
	MOD_5	Math, SAES Getter, Fluid-o-Tech
New Materials	NMAT_1	DICAr, Napoli, WASP, Stress
	NMAT_2	Versalis, Ciceri de Mondel, 3NTR, NPT, PoliMI
	NMAT_3	Evonik, Pharma, Chemi, Molec_Med, Physics, Milano
	NMAT_4	Chemi
Manu-facturing	MAN_1	a) Chemi, Brescia, DiCam, Sheffield, 3NTR, Bright Solutions b) DICAr, DIII, Chemi, Brescia, Bright Solutions
	MAN_2	DIII, 3NTR, Aldran, Overmach, Assocomaplast
Socio-Economical Impact	SOC_1	Pub_Health
	SOC_2	Law
	SOC_3	Assolombarda, Senaf, Ambrosetti
	SOC_4	Human, IUSS
	SOC_5	Economics, CNR_ITIA, Fast4Ward
	SOC_6	DIII, SAISD
	SOC_7	a) Economics b) CNR_ITIA
Applications	APP_1	a) DICAr b) DICAr, Napoli, WASP, Stress
	APP_2	a) DICAr, San Matteo, San Donato, DIII, Karolinska, Chemi, Surgical, Julight, Fatebenefratelli b) DICAr, San Matteo, Int_Med, Surgical c) Humanitas, San Matteo d) San Matteo, Human Brain Wave, Surgical e) DIII f) Chemi
	APP_3	a) Pharma, Med_Mol, Surgical b) Surgical, Physics, INFN c) Bio_Biotech d) Med_Mol e) Chemi
	APP_4	a) DICAr, INK b) DICAr, Fluid-o-Tech c) DIII d) DIII, Julight e) DIII
	APP_5	a) Music_Cultural, Arkedos b) DIII

Fig. 11: Scheme of the actors of the project tasks

Already available Project Resources

The project will be supported in terms of available resources by 6 laboratories at DICAr (**Proto-Lab, β-lab, Mate-Lab, Nume-Lab, Active-Lab, AML-Lab**), **lab Arvedi, Pharma-Lab and LAMSC** and the financial knowledge of the spin-off **Fast4ward**, for a total value of instrumentation of about 1.000.000 €. More details about laboratories and their facilities can be found on the project website. Here below some direct useful links:

- **Proto-Lab** (Link)
- **Mate-Lab** (Link)
- **β-Lab** (Link)
- **Activ-Lab** (Link)
- **Nume-Lab** (Link)
- **Fast4Ward** (Link)

Already On-Going and Future Project Activities

As previously discussed, several proposed activities are already on going. The following Gantt chart (Fig.12) highlights temporal distribution of project tasks from January 2013 to today (January 2015), and from today to December 2017.

The on-going activities regarding 3D printing are supported by 2 projects:

- "iCardioCloud" - Bringing cardiovascular virtual reality to clinical bedside practice through cloud platform: implementation of a US excellence paradigm into Lombardia SSR, **Regione Lombardia & Fondazione Cariplo**, 2014-2016
- "Fab@Hospital" - Hospital Factory for Manufacturing Customized, Patient Specific 3D Anatomo-Functional Model and Prostheses", **CNR (National Research Council)**, 2014

In the following we also list some planned events regarding AM themes, organized in collaboration with DICAr.

Past Events

25 Nov 2014 — Conference "3D Printing as enabling technology: development of new project ideas, from surgery to building industry", **Borromeo College**. Organized in collaboration with Pavia **Professional Association of Engineers**, giving **2 formative credits** for the attendance.

Flyer: Link

Planned Events

13 Feb 2015 — **Business Day** - "Printers 3D / Virtual modeling / Advanced materials: state of the art and perspectives", addressed to the industrial world.

Flyer: Link

5-7 Mar 2015 — **3DPrintHub**, an event dedicated to the 3D printing world. DICAr will have an exposition area and will contribute with seminars and workshops also in collaboration with medical and engineering professional associations. Formative credits may be assigned for the attendance. Link

5-9 May 2015 **PLAST 2015**, an event dedicated to the industrial sector of plastics and polymers. DICAr will have an exposition area and will take seminars on the topic of 3D printing. Link

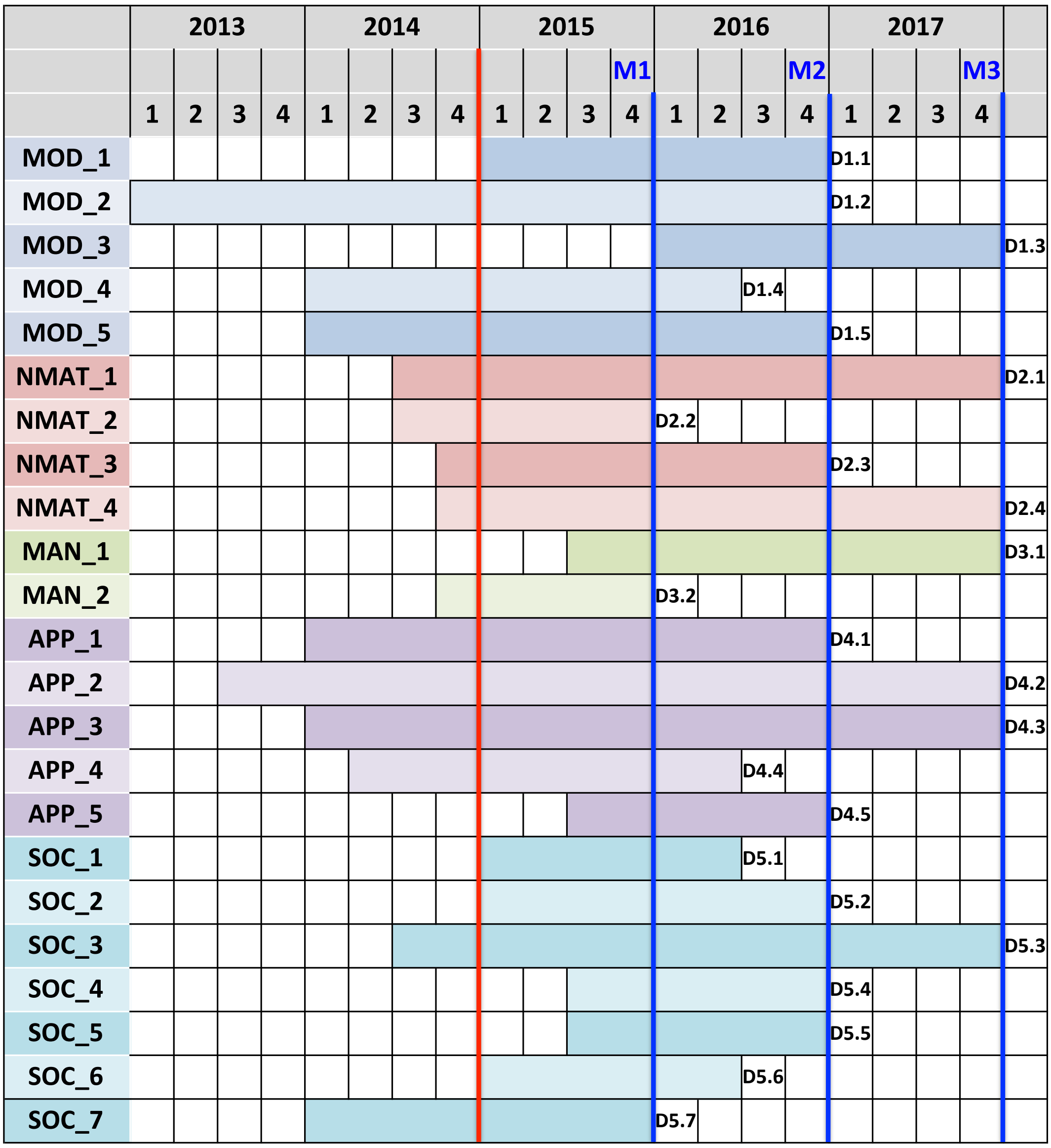

Fig. 12: Gantt chart of project activities. Vertical red line indicates project start, while blue lines stands for yearly milestones. At the end of each task, the deliverable of reference is indicated (see Fig.13 for deliverables).

Project Results

In terms of research activities

In accordance to the Project Tasks and the Gantt Chart (Fig.12), here we summarize possible project deliverables divided in 3 milestones (one for each year of activity), clearly to be properly modulated depending also on future funding.

Year	Deliverable	Result
2015	D2.2	Definition of the best properties of high-deformable and high-performance materials for FDM 3D printers
	D3.2	New generation FDM 3D printers (optimized for high-deformable and high-performance materials)
	D5.7	Definition of a business model strategy for 3D printing applications
2016	D1.1	New formulation of discretization and optimization methods
	D1.2	Virtual and in-vitro simulation strategy for aortic aneurism and dissection
	D1.4	Results of application of isogeometric analysis
	D1.5	Analysis of mechanical behaviour of thermo-mechanical materials through simulations
	D2.3	Pilot application of 3D printing for implantable bio-scaffolds
	D4.1	3D printing service for architectural studies & pilot study for building components prototyping
	D4.4	Conclusion of pilot studies for 3D printing application in the production process of the listed industrial products
	D4.5	3D printing based facilities for cultural heritage, art works and ancient architectures
	D5.1	Health care lineguides for nanomaterials
	D5.2	3D printing products patenting guidelines
	D5.4	Analysis of the social impact of 3D printing
	D5.5	Analysis of the economical impact of 3D printing and of the different economical sustainability models
	D5.6	Support modeling service for blind students
2017	D1.3	Paradigm for 3D printing process simulation (FDM, metal printers)
	D2.1	Definition of optimal materials for building 3D printing applications
	D2.4	Development of innovative approaches for the printing of metals and ceramics using low-cost plastic printers
	D3.1	Prototype of home made metal 3D printer
	D4.2	Development of a prototyping service dedicated to medical needs
	D4.3	Definition of a new paradigm for bio-scaffold production for the different purposes
	D5.3	Definition of a structured cycles of seminars and academic courses

Fig. 13: Summary of possible project deliverables

In terms of teaching and didactic activities

Within the 3D@UniPV project different levels of training could be provided as described in the following.

- **Academic seminars.** Devoted to university students and open to auditors, to maximize the benefit of University presence on local context (Third Mission). Seminars are intended to introduce subjects but also to carry out training activities and they will be held both by professor engaged on the project and by industrial partners, also to bridge industrial activities and research. Seminars could be an important chance for companies to describe required working skills and for students to better understand required knowledge.

- **Business seminars.** Primarily addresses at the corporate world, to inform on the expertise and technologies available, as well as to encourage cooperation between companies and University.

- **Master degree.** Since the growing work market interest in AM skills, an academic program may be proposed to provide a specialization on three of the main topics of the project:
    - Computational Mechanics
    - Advanced materials
    - Additive Manufacturing

  Project of 1 year MS: total of 60 formative credits (40 credits: lessons; 20 credits: lab training, internship or direct activities) → 8 courses. Possible subjects to be scheduled are:
    - CAD modeling and introduction to simulation
    - Introduction to AM technologies
    - Metal printing materials
    - Polymeric printing materials
    - Fundamental of modeling
    - Structural computational simulation
    - AM business modeling and economic sustainability
    - Patenting and intellectual properties

  Other courses/subjects can be added, with credit/course to be defined in terms of relevance/impact/needs.

  Knowledge acquired during courses is going to be focused on specific application areas and subjects during internship or direct activities.

- **PhD Program.** Attention to the Additive Manufacturing topic will be included in the already active Ph.D. program in "Computational Mechanics and Advanced Materials", offered by the DICAr (Link).
  PhD topics will regard:
    - 3D printing strategies for surgical and bio-ordiented models and devices
    - Optimization of modeling strategies for AM technologies
    - Development and testing of new materials for 3D-printing

It is important to highlight that some important Universities have already activated PhD programs regarding AM themes (link).

Activities regarding AM are currently subject of bachelor and master thesis at DICAr laboratories, both on the use of 3D printer for specific applications and on the optimization on printing material and modeling strategies.

In this context the **Borromeo College**, a historical college in Pavia, has expressed a wide interest in logistically supporting the project teaching activities.

In terms of technology transfer and interaction with companies

- **UniPV-FabLab**: Opening of a city-university fab-lab, which should work as a place for discussion and development of innovation, with qualified personnel to support the development of new devices, new concepts and products. According to Fab-Lab philosophy, it will contain base equipment like 3D printers, 3D scanners, laser cut devices and CNC milling machines.

Project governance and monitoring

We plan to have one internal local governance body, namely a Local Scientific Committee (possibly made of 3 or maximum 5 professors with different expertises), plus an Advisory Scientific Committee, and an Advisory Industrial/Business Committee (e.g., Ambrosetti, Pirelli, a printer producer, a material producer, etc.)

Project website (http://www.unipv.it/compmech/PSA_additive.html) will be the reference instrument to monitor project progresses.

Resource plan

In the following we list a possible resource plan that will be partially covered by the PSA.

Human resources

- 1 position devoted to the management of a 3D-printer lab (technician oriented)
- 1 position devoted to the development of surgery/vascular/bio-oriented applications
- 1 position devoted to the modeling, simulation, and optimization of processes, materials, and applications
- 1 position devoted to development of new materials, optimized for AM
  1 position devoted to the study of legal/economic/human/social impact of AM

Hardware resources

Here we summarize main prototyping resources useful for project activities.

- **ProJet 260 C – 3D Systems** (Link)
  High-resolution multicolor 3D-printer. Cost: 31.000 €

- **ProJet 3510CP – 3DSystems** (Link)
  High-resolution wax 3D printer for lost wax casting applications. Cost: 77.000 €

- **XFAB – DWS Lab** (Link)
  Stereo-lithography printer compatible with opaque, transparent, rigid and deformable polymers. Cost: 5.000 €

- **PXS - Phenix System (3DSystems)** (Link)
  Selective laser meltig (SLM) system for alloy and ceramic prototyping. Cost: 200.000 €

- **Bioplotter – EnvisioTEC** (Link)
  3D printing system dedicated to the deployment of biologic material. Cost: 200.000 €

Space resources

- Creation of a dedicated space of around 150 m^2.