Sauro Longhi · Andrea Monteriù · Alessandro Freddi · Emanuele Frontoni · Michele Germani · Gian Marco Revel
Editors

The First Outstanding 50 Years of "Università Politecnica delle Marche"

Research Achievements in Physical Sciences and Engineering

UNIVERSITÀ POLITECNICA DELLE MARCHE

Springer

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Foreword

Università Politecnica delle Marche (UNIVPM in short) celebrates its 50th anniversary as an institution in 2019. It is a young, dynamic, and active University on multiple fronts, which in the first half-century of its life has been able to achieve important goals in many scientific areas. Hence, the idea of proposing a book is for celebrating the first 50 years, "UNIVPM50", and the natural choice is to divide the book into three thematic volumes: "Social Sciences and Humanities", "Physical Sciences and Engineering", and "Life Sciences".

The contents of these three volumes document the research activities of our University, both fundamental, applied, and clinical. "The ability to think together and to produce research, through differentiated thought and culture collaboration, is the main reason for the existence of an academic structure"—from "L'Università di Ancona, 1969/1989", a book celebrating the first 20 years of our University. The objective of "UNIVPM50" is therefore to present the most important research results achieved so far by our scientific community, with particular attention to the current frontiers of research and what future prospects might be. The contributions collected in the book summarize the main research efforts undertaken by the current faculty members and represent the outcome of a constant effort in the present, supported by past experiences, with the perspective to new emerging ideas in the three scientific areas in which UNIVPM plays a significant role.

The book, however, is not to be considered only as a collection of research works: the contributions also represent a sample of the knowledge which is daily taught in our classrooms and laboratories. Indeed, from the research, the University constantly draws inspiration for high-quality teaching and has the great responsibility of preparing young people for the world of professions. To train professionals, it is necessary that the link between academia and professional world is strong. The relationship with the territories is strengthened with actions to boost research and innovation, the so-called third mission, made up of technology transfer, patents, and entrepreneurship. These activities have led to the development of a contamination lab, followed by an incentive and promotion policy for university spin-offs that draw ideas from the best research results.

Founded 50 years ago as "University of the territory", UNIVPM must now confront itself in a perspective as broad and international as possible. Our research was, and still is, inspired by the territories, with the aim of increasingly open to the world. Internationalization is therefore a key to the present and future development of our University: international research, active student/teacher mobility policies, and the start of international degree courses, even as double degrees, are all measures aimed at projecting the University into an international dimension.

In conclusion, "UNIVPM50" presents the main goals achieved in the first 50 years of story of our University, and imagine a future of which UNIVPM will, hopefully, be an integral part.

Ancona, Italy

Sauro Longhi
Rector of the Università Politecnica delle Marche

Preface

Università Politecnica delle Marche (UNIVPM in short) celebrates its 50th anniversary as an institution in 2019.

Historically, UNIVPM was first established in Ancona in 1969 as Faculty of Engineering, followed by the Faculty of Medicine the next year. In 1971, the University was granted the status of State University, with the name of "University of Ancona". The Faculties of Engineering and Medicine were later merged with the Faculty of Economics and Commerce in 1982. Further on, in 1988 and in 1991, respectively, the Faculty of Agriculture and the Faculty of Sciences were established. In 2003, the name of the University was changed to "Università Politecnica delle Marche".

Focusing on the present, the Faculty of Engineering is composed of four Departments: "Construction, Civil Engineering and Architecture", "Materials, Environmental Sciences and Urban Planning", "Information Engineering", and "Industrial Engineering and Mathematical Sciences". The Faculty of Medicine and Surgery has four Departments: "Biomedical Sciences and Public Health", "Experimental and Clinical Medicine", "Molecular and Clinical Sciences", and "Odontostomatologic and Specialized Clinical Sciences". The Faculty of Economics is composed of two Departments: "Management" and "Economics and Social Sciences". Finally, the Faculties of Agriculture and Sciences count a Department each, "Agricultural, Food and Environmental Sciences" and "Life and Environmental Sciences", respectively.

UNIVPM is placed fifth in the 2018/2019 Censis Italian University Ranking among the medium-sized Public Universities. Being a "young university" this must be considered as a good result. On the other hand, there is still a lot of work to do in order to position UNIVPM at higher levels of research, but thanks to our growing faculty's expertise, remarkable progress is being made each year.

This book is dedicated to the celebration of 50 years of UNIVPM and has been motivated by the desire to present the most representative research results of our scientific community achieved so far, with particular attention to the current frontiers of research and to what the future perspectives could be, in order to build a better society providing a dynamic road map for the future. The contributions

collected in the book summarize the main research efforts undertaken by current faculty members, from a vast range of researches. They represent the outcome of a constant effort in the present, supported by past experiences, with the perspective to new emerging ideas in the three major cores where UNIVPM plays a significant role, namely, Life Sciences, Physical Sciences and Engineering and Social Sciences and Humanities.

This volume covers the main research achievements in the different disciplines of Physical Sciences and Engineering. Several research lines developed at the Faculty of Engineering of UNIVPM are described in the fields of electronic and information engineering, telecommunications, biomedical engineering, mechanical engineering, manufacturing technologies, energy, advanced materials, chemistry, physics of matter, mathematical sciences, geotechnical engineering, circular economy, urban planning, construction engineering, infrastructures and environment protection, technologies and digitization of the built environment, and cultural heritage. The volume shows the international relevance and multidisciplinarity of the results achieved and the planned research lines for the next years.

In particular, in the field of information engineering, research activities cover all the modern fields of the information and ICT era, going from microelectronics to nanoelectronics (chapter "From Microelectronics to Nanoelectronics: Fifty Years of Advancements in Electronics"), to the birth and development of the "Electromagnetic fields" research group (chapter "Birth and Development of the "Electromagnetic Fields" Group"). The area of digital signal processing for audio applications is presented in chapter "Digital Signal Processing for Audio Applications: Then, Now and the Future", with background and future perspectives in the field. Chapter "Telecommunications in the ICT Age: From Research to Applications" describes research and application of telecommunications in the ICT age that has been studied in the last decades from the local research team. Control systems theory, robotics and automation, and intelligent manufacturing are other challenging research fields that were investigated and that are described in chapter "From the Control Systems Theory to Intelligent Manufacturing and Services: Challenges and Future Perspectives" together with future perspectives. Chapter "From Artificial Intelligence and Databases to Cognitive Computing: Past and Future Computer Engineering Research at UNIVPM" covers all the computer science area, going from artificial intelligence and databases to modern research themes of cognitive computing, showing past and future computer engineering research at UNIVPM. The last part of the information engineering is described in chapter "Fifty Years of Biomedical Engineering: From Origin to Smart Technologies" and covers the last 50 years of biomedical engineering, with an overview that is going from origin to recent and future smart technologies.

In the field of industrial engineering, research activities are focusing on strategic issues for improving people's quality of life, focusing on products, processes, and materials that strengthen sustainability along its main lines: environmental sustainability, social sustainability, and economic sustainability. In chapter "Citizen-Oriented Technologies in the Cities of Tomorrow", it is emphasized that the city of the future will have to be designed and structured to facilitate the life of citizens,

and the energy aspects are taken up and extended in chapter "Energy Scenarios for the Future of Mankind" where the scenarios of the future, to obtain an energy-sustainable ecosystem, are widely described. The sustainability of cities also means the use of new materials and buildings for which the circular economy paradigm is undoubtedly a driver on which to concentrate research efforts. Chapters "Environmental Sustainability of Engineering Works: Geological and Geotechnical Aspects"–"Sustainable Engineering for Resilient Built and Natural Environments" focus on these latter topics, extending the aspects of research to those of new engineering figures training. From the standpoint of purely industrial processes and products, the main research engine is the application of advanced ICTs both in the process of designing solutions and in the physical realization of products. In this context, the Life Cycle Thinking approach and the virtuality of the designed systems are becoming established. The virtual model allows simulations and verifications, chapter "Integrating Advanced CAE Tools and Testing Environments for the Design of Complex Mechanical Systems", which lead to obtaining advanced solutions and very often with high sustainability and where customization and the centrality of users become key aspects (chapter "Smart, Eco-Sustainable and Human-Centered Product Development Processes: 21st Century Manufacturing Industries"). Finally, the field of the new materials and the production processes that can derive from it is fundamental to investigate because it allows to arrive at disruptive technical solutions with respect to the state of the art. In this context, the chapters ranging from 10 to 12 touch on the topics from basic research in chemistry and physics and these turn into innovative production processes (chapter "The Role of Advanced Materials in the Development of Innovative Manufacturing Processes").

The last part of the volume is dedicated to urban planning, construction engineering, infrastructures and environment protection, technologies and digitization of the built environment, and cultural heritage. Chapter "Research and Engineering for Resilient Infrastructures and Environment Protection" remains in the area of sustainability concepts with a focus on research and engineering for resilient infrastructures and environment protection. The connection between Università Politecnica delle Marche research and its territory is the concept behind chapters "An Overview of the Structural Safety-Oriented Research in the Region Marche Seismic Area" and "Earthquake in Italy: From the Past Decades to the Future. Strategies and Innovative Tools for Urban Planning and Territorial Regeneration": earthquakes in this seismic area were the main motivations of past, present, and future studies on the structural safety-oriented research and on strategies and innovative tools for urban planning and territorial regeneration. Relevant researches on novel buildings design, construction, and management strategies through sustainable technologies and digitization are presented in chapter "Rethinking Buildings Design, Construction and Management Through Sustainable Technologies and Digitization", while chapter "Cultural Heritage and Landscape: Analysis, Digitization and Design Aiming at a Resilient Future" reports an overview of modern research on analysis, digitization, and design of cultural heritage and landscape, aiming at a resilient future.

The last chapter of this volume is dedicated to education and communication in mathematical sciences, with a focus on new multimedia technologies for a modern approach to scientific communication and teaching.

Ancona, Italy

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Contents

From Microelectronics to Nanoelectronics: Fifty Years of Advancements in Electronics

Giorgio Biagetti, Massimo Conti, Paolo Crippa, Davide Mencarelli and Claudio Turchetti

Abstract Fifty years ago, when the Università Politecnica delle Marche (UnivPM) was founded, the minimum size of an electron device was about ten micrometers, today dimensions in the order of twenty nanometers can be reached by the current technologies. At that time silicon foundries were able to integrate about tens of components on a chip, after fifty years has passed, an integrated circuit (IC) might contain more than ten billion devices. As the need for increasing integrated density on chips continues and silicon technologies show their physical limits, the new era of nanotechnologies, that have the potentiality for circumventing these limits, is coming. The aim of this paper is to highlight some key aspects that determined this rapid advancement and to discuss the contributions given by UnivPM both in microelectronics and nanoelectronics during these five decades. In particular, in the context of microelectronics the paper focuses on research activity in the fields of device modeling, tolerance analysis, statistical analysis of ICs, statistical simulation and design of ICs. With regard to nanoelectronics, the recently discovered nanosize materials, such as atomic clusters, nanotubes/nanowires, and monoatomic layers, may constitute a new scalable platform for RF electronics, namely for switches, amplifiers, logic devices, frequency multipliers, rectifies, interconnects, and sensors. In this framework, the present contribution provides a view on the most recent developments in modelling and simulation of carbon based devices. Specifically, we describe rigorous multi-physics approaches for the analysis of quantum transport and electromagnetic

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fields in nanostructured materials. In addition, we show that the low profile and size of nanomaterials make them perfect candidates as test beds for novel experiments on single electron devices and quantum transistors. Finally, the paper will give a brief excursus of the activity in progress at UnivPM, taking a look at the future development in electronics.

1 Introduction

In 1969 a paper by Y. Tarui et al. was published on IEEE Journal of Solid-State Circuits [55], that reported the analysis and characterization of a high-speed large scale integrated (LSI) memory. The memory was fabricated using n-channel enhancement metal oxide silicon (MOS) transistors that operated at a higher speed than p-channel transistors, due to higher effective carrier mobility of electrons. A photograph of the memory is reported in Fig. 1. An 114-bit (16 word $\times$ 9 bit) n-channel MOS-LSI memory was fully integrated on a chip with an area of 4.3 $\times$ 3.0 mm, and operated with 40-ns write cycle time.

At the same time a study on the technological reliability and performance of integrated complementary MOS (CMOS) circuits, was published on the same journal [33]. The basic building block of these circuits—the complementary pair of MOS inverter—consisted of two enhancement mode MOS transistors connected in series, with their gates connected together (Fig. 2). Due to its characteristics—very low standby power consumption, high speed, ground noise immunity—the circuit became the fundamental block of subsequent silicon technologies development.

Fifty years later (2018), in the paper [35] a system-on-chip (SoC) was presented, embedding an ARM® Cortex® −M0 + MCU, 2 $\times$ 4 SRAM, an ultra-low power frequency synthesizer, a custom power switch, and a power management enabling active and sleep modes. The device shown in Fig. 3, has been fabricated using a 28 nm fully

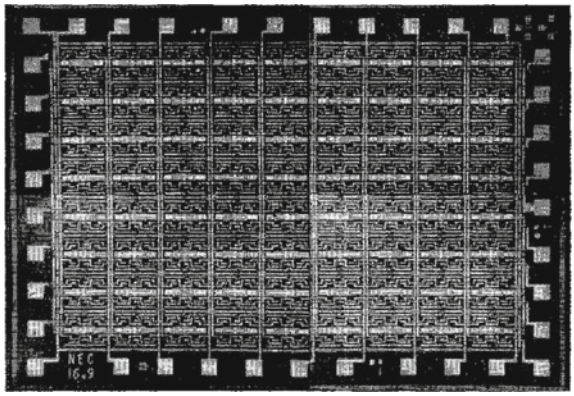

Fig. 1 The photograph of an 144-bit (16 word $\times$ 9 bit) n-channel MOS-LSI memory. The chip area is 4.3 $\times$ 3.0 mm [55] ©[1969] IEEE

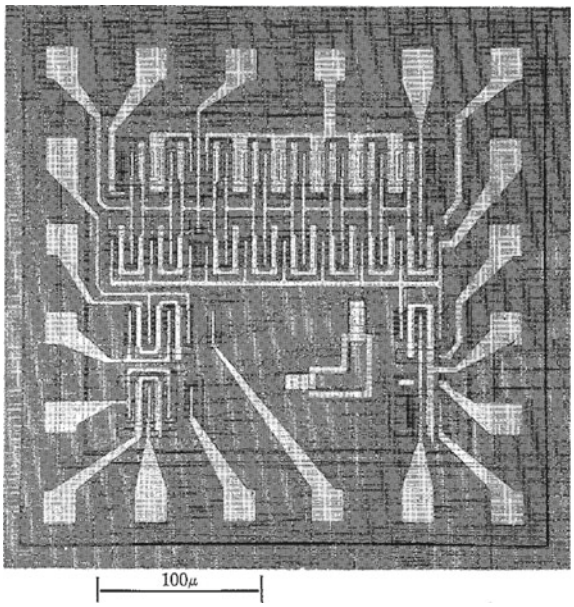

Fig. 2 Photomicrograph of the monolithic complementary pair MOS inverter test circuit [33] ©[1969] IEEE

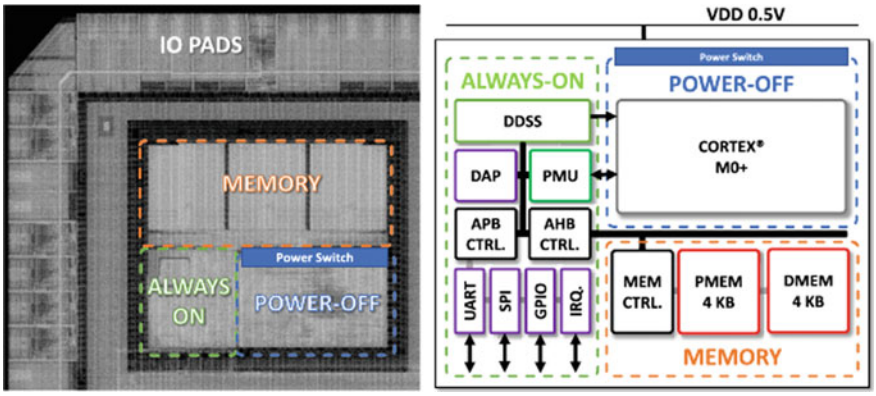

Fig. 3 28 nm FD-SOI SoC implementation and corresponding block diagram. Core area is 0.073 mm^2 [35] ©[2018] IEEE

depleted silicon-on-insulator (FD-SOI) technology, has a core area of 0.073 mm^2 and silicon measurements report an SoC's power consumption of 2.7 pJ/cycle at 16 MHz.

These three circuit examples clearly show the great advancements of silicon technology during the last fifty years. The key aspects that determined a such rapid progress are not only related to technological improvements but also to the development of design methodologies and techniques able to manage the increasing complexity of silicon circuits.

This paper is mainly addressed to this second aspect and aims to report the contributions given by UnivPM both in microelectronics and nanoelectronics during these five decades. In particular it is focused on these following subjects: (i) circuit simulation and device modeling; (ii) statistical IC design; (iii) system level and circuit design; (iv) graphene based field-effect-transistors and modelling perspective.

2 Circuit Simulation and Device Modeling

With the rapid increase of device density of integrated circuits, the development of computer aided design (CAD) techniques, became one of the key aspects in the design of large-scale (LSI) and very-large-scale (VLSI) integrated circuits. Due to their complexity, circuit simulation, that is simulation of circuit behaviour by computer, performing several analysis, i.e., DC, AC and transient analysis, was crucial for the success of CAD based design approach [50]. Circuit simulation is based on circuit analysis, that establishes general equations describing the behaviour of a circuit (f.i. modal analysis). A circuit simulator numerically computes the solutions, by using suitable algorithms, under different stimulus and initial conditions. The responses so obtained are useful to predict the real behaviour of a circuit bypassing the fabrication of samples for testing the performance, thus reducing the cost of the design. The Simulation Program with Integrated Circuit Emphasis (SPICE), written by Larry Nagel in 1972 and subsequently released as SPICE2 in 1975 [45], has been widely accepted for circuit analysis since its introduction and continues to be the framework in the more advanced circuit simulation tools.

Device modeling played a central role in VLSI circuit design because the accuracy of computer-aided circuit analysis results strongly depends on the accuracy of the device models used in the circuit simulator. As a consequence a great attention was devoted to MOS transistor modeling and a considerable effort was spent to model even smaller and more complex transistors, for several decades [68].

- A macromodel for integrated all-MOS operational amplifiers

In the eighties a great attention was devoted to fully monolithic PCM filters for telecommunication applications, and in this context the design of high-performance CMOS switched-capacitor (SC) filters was a main issue in analog ICs design. To this end a large adoption of CAD tools was required to simulate the behaviour in both the time and the frequency domain, and in particular to take into account for second-order effects such as (1) non zero resistance of the switches, (2) parasitic capacitances, (3) noise, (4) non ideal characteristics of the op amps (slew rate, settling time, gain, bandwidth, nonzero output impedance, etc.). However, as an integrated op amp was usually described at the device level and typically included about 20–40 MOS transistors, this complete description would lead to an excessive and impractical computing time for the simulation of the entire SC filter. To achieve both accurate simulations and minimum computer time, several authors [34] suggested simple linear models of the MOS op amps, taking into account only for a finite value of the

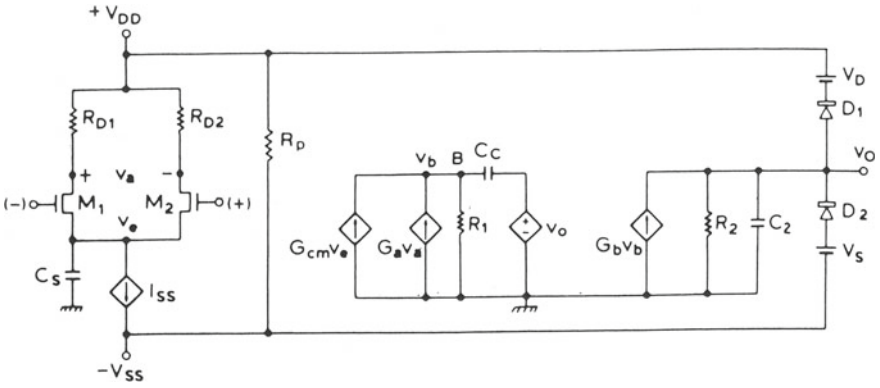

Fig. 4 The macromodel for integrated all-MOS operational amplifiers [57] ©[1983] IEEE

voltage gain, a nonzero output resistance and the presence of poles in the transfer function.

In the paper [57], C. Turchetti and G. Masetti, studied the problem of a whole and inexpensive modeling of integrated MOS op amps and presented a macromodel that met all these requirements. The macromodel, shown in Fig. 4, was able to adequately represent the main electrical performances of integrated all-MOS op amps and especially the settling time that is of particular concern for charge redistribution ICs, where only capacitive loads are considered. In the macromodel, each performance specification of the op amp is modeled separately, by a set of fifteen parameters, independently chosen each other. A large experimentation was carried out to investigate the validity of the proposed approach, with reference to the electrical characteristics of several integrated MOS op amp, available in the literature [54].

- On the small-signal behaviour of the MOS transistor in quasistatic operation

In the context of MOS analog ICs, the use of devices with aspect ratio (gate length to gate width) as large as 500–100 was often necessary to meet the performance required. In these devices the intrinsic capacitance effects can dominate the device behaviour in the frequency domain, thus requiring accurate small signal modeling to predict AC behaviour of analog circuits [43, 46, 66, 67]. However very inaccurate models were available to the designers, so that they tend to yield very conservative designs. For example, amplifiers designed with excessive stability margins, or working well above threshold (with excessive power consumption), due to the poor knowledge of capacitance effects.

The contribution of the paper by C. Turchetti, G. Masetti and Y. Tsividis [62] to this problem was twofold:

(i) it proposed a complete small-signal topology for the MOS transistor;
(ii) the small-signal capacitances and conductances in the above model were derived using a general formulation based on quasistatic assumption.

- A CAD-oriented analytical MOSFET model for high-accuracy applications
In the design of low power low voltage analog ICs there was a continuous demand for very precise and CAD-oriented MOSFET models. Although analytically models which avoid previous integral formulation [49] and able to correctly describe all the operating regimes of the device were reported [67], they were not explicitly expressed in an analytical form, thus requiring the solution of an implicit equation. The iterative procedure required for solving such an implicit equation, was the main obstacle for the implementation of those models in CAD programs.

In the paper by C. Turchetti and G. Masetti [58], an explicit formulation for the surface potential along the channel of a long-channel MOS transistor was derived, that overcomes the limitations of the previous models. On the basis of this formulation a model for the drain current which is (i) a continuous function of all the voltages applied to the device; (ii) valid in all the operating regimes of the device (weak inversion, moderate inversion and strong inversion) was established.

- Influence of diffusion current on the DC channel and AC characteristics for the Junction Field-Effect Transistor (JFET)
An advancement of analytical theory for the JFET, that usually takes into account only the drift component of the drain current, is reported in the paper by C. Turchetti and G. Masetti [60]. In this paper a precise analytical model for the JFET that includes both diffusion and drift currents, giving a natural saturation of the output characteristics, was presented. The model gives analytically an expression of the DC characteristic of a long-channel JFET valid in all the regimes of the device: linear region, pinchoff, sub-pinchoff.

- Analysis of the depletion-mode MOSFET including diffusion and drift currents
Before the development of CMOS technology, one of the main problem in obtaining high-performance circuits was the need for transistors with negative threshold. As a consequence the adoption of depletion-mode MOSFETs (DMOSFETs) in the realization of the MOS ICs was considered. However, although for the enhancement MOSFET some good physical models [56, 58, 67], valid within the framework of the gradual channel approximation scheme, were developed, for the depletion mode MOSFET the analytical models proposed until then were based on too simplified assumptions, thus leading unrealistic results [30].

The purpose of the work by C. Turchetti and G. Masetti [59] was to present an analysis of a long-channel depletion-mode MOSFET which, taking into account to both the diffusion and the drift components of the current, was able to predict the DC characteristic of the device in the linear, saturation and sub-pinchoff regimes of operation.

- A charge-sheet analysis of short-channel enhancement-mode MOSFET's
With the continuous demand for higher density ICs, a corresponding scaling of device sizes was required, thus giving rise to the so-called short-channel MOSFET devices. A detailed knowledge of the physical behaviour to determine the electrical characteristics of such devices, whose dimensions was under the micron, required

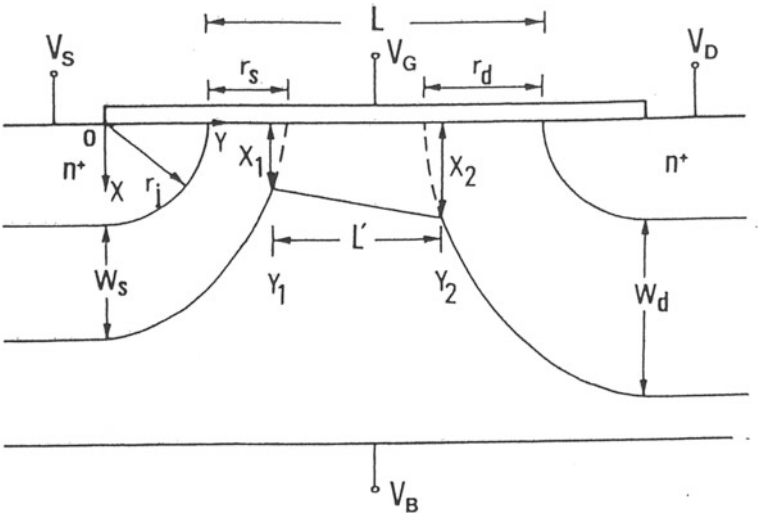

Fig. 5 Schematic cross section of a short-channel MOSFET [61] ©[1986] IEEE

the solution of two- or three- dimensional device equations, that is impractical for CAD using. This requirement was the motivation for the development of analytical and pseudo analytical short channel MOSFET models.

The purpose of paper by C. Turchetti and G. Masetti [61] was to derive a charge-sheet approach for the short channel MOSFET model, which was able to describe the device characteristics in all the operating regimes, i.e., strong inversion, weak inversion and saturation, without introducing discontinuities in the drain current and it derivatives with respect to bias voltages. With reference to the cross section of a short *n*-channel MOSFET shown in Fig. 5, the model was developed by coupling and solving the Poisson's equation and the continuity equation, under the charge-sheet approximation, that is assuming the free charge in the channel is concentrated in a small region close to the silicon surface [60, 67].

- A Meyer-like approach for the transient analysis of digital MOS ICs

Transient analysis of digital MOS ICs performed by simulation program such as SPICE, requires accurate modeling of intrinsic charges in a MOSFET. However one of the most widely adopted model, the so-called Meyer's model [43], did not guarantee the charge conservation in a MOSFET during transient analysis. To solve this problem the Ward's charge based model [66], that did not have this drawback, was developed. However, Ward's complete model was somewhat complex to be currently used as a standard model for the design of all MOS circuits. Besides both the Meyer and Ward models were developed under quasistatic operation, that is inadequate assumption for circuits operating at relative high speed.

The above considerations were the basic motivations for the development of a simple "Meyer-like" model presented in the paper by C. Turchetti et al. [63]. Start-

ing from the integral relationship for the gate current, after a numerical integration approach, an expression for the discretized gate current that satisfy charge conservation requirement, was derived.

- A non-quasi-static analysis of the transient behaviour of the long-channel MOS valid in all regions of operations
With the appearance of many digital, analog, and mixed digital/analog MOS ICs operating at relatively high speed, the accurate modeling of transient behaviour in MOSFET devices, became of paramount importance in the design of such circuits. In particular, the inertia in the charge transport of the carriers from source to drain and in the charge readjustment when fast turn-off or turn-on transient voltages are applied to the device terminals, were the main effects to model in such devices [46].

The purpose of the paper by P. Mancini, C. Turchetti and G. Masetti [38], was to present an analysis of the non-quasi-static behaviour of the intrinsic long-channel MOS transistor, when arbitrary voltage steps are applied to the four device terminals. The analysis was developed for a long-channel MOSFET assuming a charge-sheet formulation, thus yielding a model valid in all operating regimes of the device, i.e., strong inversion, moderate inversion, weak inversion and saturation.

3 Statistical IC Design

In the last decades, the advances in IC fabrication technology to obtain faster and more complex chips have determined a continuous reduction in the feature size of CMOS devices. As a consequence, at the decananometer geometries used in VLSI technologies, accurate modeling of statistical behavior of integrated devices has becomed essential in the design of ICs, for several reasons.

Local and global statistical fluctuations of the electrical parameters of the devices in submicron ICs severely limit the performance obtainable from both analog and digital circuits. In the design flow of high-performance ICs it is therefore of increasing importance to define statistical models that are able to predict such random variations. Thus, the research has addressed the following issues:

- Definition of a statistical MOS transistor model that links the variance and correlation of critical model parameters (BSIM3, MOS Level9) to the covariance of the process parameters affected by random variations. This model is able to predict the mismatch between devices as a function of length, width, area, orientation, and distance between devices on a chip [13].
- Definition of a methodology for estimating the statistical model parameters.
- Definition and design of test structures for evaluating both *intra-die* and *inter-die* process variations in order to (i) accurately assess the device mismatch (indispensable for the estimation of performance of more complex circuits such as digital-to-analog (D/A) converters) and take into account the effects of the geometry and the distance between the devices [17], and (ii) easily monitor the mismatch

during the production cycle with test patterns in the spaces between the dice (scribe lines) [20].
- Layout based improvement of the mismatch model in order to take into account the partitioning of the devices and their mutual positions on the chip [9, 19].
- Development and characterization of a versatile statistical model for submicron MOS transistors that allows to evaluate the effects of technological variations on circuit performance without using complex Monte Carlo simulations [25].

- *Statistical IC modeling for parametric yield maximization*

In order to estimate how the statistical variations of process parameters affect the circuit performance and to design ICs in such a way as to maximize the yield, the statistical analysis of electronic circuits has been studied. A methodology for carrying out the sensitivity analysis of circuit performance to the variations of device model empirical parameters has been proposed. The methodology it is based on an accurate statistical MOSFET model that takes into account the correlations between the devices as functions of device sizes and mutual distances [12, 16]. The validity of this technique has been demonstrated by implementing the mismatch model in a statistical CAD tool [18, 21]. Additionally, by modeling the mismatch of the drain current of MOSFETs, a methodology of statistical design of high performance CMOS D/A converters has been developed. The technique allows to explore different circuit architectures and to assess the effects of the layout on the performance without using standard Monte Carlo simulations [24, 26].

Finally, a technique for statistical simulation of non-linear ICs affected by device mismatch has also proposed. This simulation technique is aimed at helping designers maximize yield, since it can be orders of magnitude faster than other readily available methods, e.g. Monte Carlo. Statistical analysis is performed by modeling the electrical effects of tolerances by means of stochastic current and/or voltage sources, which depend on both device geometry and position across the die. They alter the behavior of both linear and non-linear components according to stochastic device models, which reflect the statistical properties of circuit devices up to the second order (i.e. covariance functions). DC, AC, and transient analyses are performed by means of the stochastic modified nodal analysis, using a piecewise linear stochastic technique [4, 5].

- *Statistical circuit simulation*

A fundamental aspect that cannot be neglected, especially in analog circuit design, is that of fabrication tolerances, that translate to parametric uncertainties in the resulting transistors. These uncertainties are usually bigger between chips produced in different fabrication lots, decrease significantly within the same lot and within the same wafer, and should be minimal for very closely spaced transistors in the same IC. Unfortunately, taking care of such uncertainties at design stage is not easy. CAD tools usually only offered a Monte Carlo simulation option, that just randomly choses the transistor model parameters within the specified tolerance range and performs a whole, and usually long, simulation for each random draw.

- SiSMA—A Tool for efficient analysis of analog CMOS integrated circuits affected by device mismatch
For many analog circuits, the dependence of the output from model parameters is not usually very strong. After all, they should be designed to be as immune as possible to these variations! With this consideration the idea of trying to linearize this dependence around the nominal solution was born. Performing a linearized simulation is much faster than performing a full nonlinear circuit simulation, and so the tool SiSMA was developed. It contains a circuit simulation engine similar to that used in SPICE for linearized simulations, but instead of sweeping the frequency of an AC source, it propagates variances from the sources of uncertainties to the circuit outputs. As shown in [1, 3], it can achieve simulation speeds orders of magnitude faster than a conventional Monte Carlo simulator.

- Piecewise linear second moment statistical simulation of ICs affected by non-linear statistical effects
Of course, most digital circuits and some analog circuits exhibit a strongly nonlinear behaviour that cannot be linearized without incurring into severe approximation errors. Yet, oftentimes a piecewise linear model can be used to better the results of a simple linear model. The tool SiSMA was hence augmented to support this additional operational mode, whereby linearization is performed across a multitude of operation points, carefully selected to allow reconstruction of the required output variances. In [5] the approach is described, and successfully applied to the simulation of the effect of the tolerances on performance indices such as propagation delay in a digital adder or harmonic distortion in an analog multiplier.

4 System Level and Circuit Design

Due to steady downscaling in CMOS device dimensions, from 2005 extremely complex systems called System-on-Chip (SoC) have been implemented. A fundamental issue has been represented by the design productivity gap: the number of available transistors grows faster than the ability to design them meaningfully and efficiently, guaranteeing a feasible time-to-market. The escalating gate count, desired system heterogeneity and trend towards increased productivity for complex SoC devices did not allowed anymore the use of traditional RTL-to-gates design methodology that was based on VHDL or VERILOG simulation. Thus, electronic system level (ESL) design methodologies have been developed on understanding the functionality of the system components, separating system design from implementation. Thus, industry has addressed SoC design by exploring the extension of an existing specification/design language, such as C/C++ or Java with hardware-oriented (memory, control, communication and synchronization) data structures.

In order to bridge the gap between technology capabilities for the implementation of SoC and electronic design automation (EDA) limitations, an environment integrating new concepts within new languages and methodologies, as well as within

a corresponding set of system-oriented EDA tools was needed. In particular these requirements had to be met:

- high degree of reuse of IP blocks, beyond the borders of intra-company reuse;
- optimal hardware and software partitioning based on a system abstraction;
- interoperability between tools from various domains, such as analog, digital, micro-electro-mechanical (MEMS) devices to support heterogeneous design;
- hardware/software co-design.

Some relevant aspects of system level design has been faced by the he research group of electronics of the Università Politecnica delle Marche aspects in the last 20 years: system level power estimation, transaction level modeling and system level modeling of heterogeneous systems.

- System level power estimation

System-level design and IP modeling is the key to fast SoC innovation with the capability to quickly try out different design alternatives, to confirm the best possible architecture, including the power consumption issue, early in the design process. At this high level of abstraction the power estimation allows:

- the evaluation of different system architectures: in this case there is not always the need for a very accurate estimation; power can be evaluated quickly if it is possible to know the design complexity and the signals activity derived by a fast functional simulation;
- the precise evaluation of the power consumption of a particular block in the system, in order to carry out accurate power values for IP qualification: in this case a low-level model of the system should be provided, often obtained through synthesis or hardware inferencing.

From 2001 the research group developed a system-level approach power estimation approach and a methodology to integrate a power model into an existing executable specification. In particular we have developed two libraries, called PKtool (Power Kernel tool) [6, 64, 65] and PowerSim [31, 32] based on SystemC 2.0, that the designer can use to efficiently create a hierarchical power model of the system under development. Particular attention has been dedicated to the definition of the user interface, the set of methods that can be used to access power functionalities; the designer only has to perform a small set of steps to integrate the power model in the system-level specification, with a very small impact on the code already written.

- Transaction level modeling

The design of complex Systems-on-Chip and multi-core systems requires the exploration of a large solution space. Multi-core system design methodologies perform architecture exploration at high level, taking into account constraints at this high level.

Transaction level modelling (TLM) has been widely used to explore the space solution at system level in a fast and efficient way. TLM enables architectural exploration, performance analysis and functional verification in the early stages of the

design with fast, data-accurate simulations using abstracted transactions between modules. The SystemC/TLM modeling methodology has been adopted for the design of the memory controller in [23] and for power estimation in [64] and in modeling of a Bluetooth standard in order to evaluate its performances in [7] and in the in modeling of the AMBA bus in [22].

- System level modeling of heterogeneous systems
The integration of heterogeneous systems in the same chip, such as digital, analog, biological and micromechanical parts brought to the necessity of their co-design and co-simulation. The necessity of simulating a continuous-time analog part can arise, for example, in the area of power switching control as in the automotive or RF domains. To this aim, it has been proposed to constitute an Open SystemC Initiative (OSCI) Working Group devoted to the development of an extension of SystemC to mixed-signal simulation: SystemC-AMS. Furthermore, SystemC must also extend to heterogeneous domains of application (i.e. electrical, mechanical, fluidic). Currently, the SystemC-AMS implementation is structured into different layers. The solver layer provides simple but efficient solvers for linear differential equations and for explicit-form transfer functions. The synchronization layer provides a simple and fast synchronization scheme that executes analog solvers before the first delta cycle of each time step, scheduling them using static data-flow. We developed an analogue mixed-signal extension to SystemC [47, 48] for the modelling and simulation of heterogeneous systems based on wave exchanges. This extension, named SystemC-wave mixed signal (WMS), allows the analogue part of the system to be modelled by a set of analogue modules, which communicate by exchanging energy waves. The approach based on wave quantities permits a total freedom of interconnection and therefore facilitates the development of reusable libraries of analogue modules. Moreover it is also better suited than SDF for analogue modelling, since it includes load effects naturally and provides more abstraction flexibility with respect to a circuit-level description.

- ICs for artificial neural networks, nonlinear dynamic fuzzy systems and RF applications
With the continuing improvement in the quality of the device models, and hence in the accuracy of computer simulation of integrated circuits, development of complex, mixed-signal analog/digital CMOS ICs has become possible and affordable. Analog processing paradigms, such as neural networks and fuzzy-logic, lend themselves to analog implementation quite easily. The activity of ICs design involved the analog implementation of approximate identities neural networks (AINNs) in 1.2 μm standard technology. Here a new stochastic learning algorithm whose parameters are stored by a multi stable circuit has been designed [10]. The architecture of a analog fuzzy control device for home appliance industry applications, has been developed. In particular, a prototype of the analog part of this device has been designed and implemented on silicon using a standard 0.8 μm CMOS technology, and for the membership functions a current-mode programmable translinear circuit has been designed [8]. Still, one major problem that was not easily solved in the analog domain

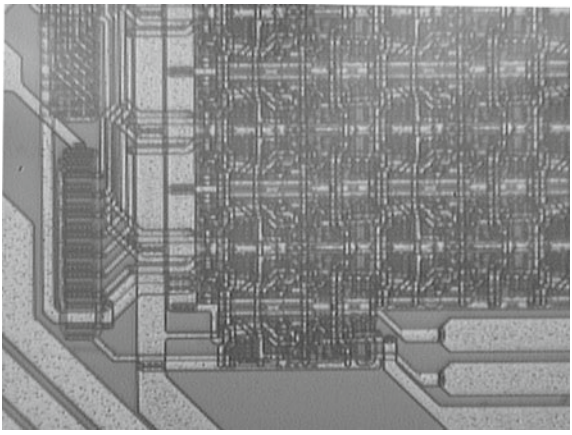

Fig. 6 Microphotography of a portion of 1998-era 800-nm CMOS IC for analog-domain storage of information. Individual transistors can be spotted to the left, while the upper-right image is a portion of a 7×5 matrix of storage elements

was that of (analog) parameter storage. The section dedicated to the storage of the fuzzy model parameters was thus designed, built, and tested in a standard 0.8 μm CMOS technology [14]. The purpose of the paper [2] was to further analyze the feasibility of a fully analog solution to create a multi-level memory for such storage, and evaluate the performance of such an implementation, based on nonlinear feedback circuits to create multiple attraction points and/or hysteresis. Figure 6 shows a microphotography of one of the chip built for this purpose in the late '90s. At the left side individual transistors, with a minimum gate length of 800 nm, can be spotted.

Subsequently, a new architecture has been proposed that implements the fuzzy model known as "fuzzy partition" [11, 15] and whose circuit has been designed and implemented in a standard 0.35 μm CMOS technology.

Besides, the design activity of radio frequency (RF) ICs involved the design and simulation of some circuits in C-band, in particular low-noise amplifiers (LNAs) [27, 28] and switching circuits with low losses such as the single-pole double throw (SPDT) switches [29] in order to test the cutting-edge 0.25 μm SiGe BiCMOS technology. The acquired skills have been exploited to the design of a multi-band LNA for WLAN home automation in 0.35 μm BiCMOS technology.

5 Graphene Based Field-Effect Transistors and Modelling Perspectives

The continued miniaturisation of device dimensions in ICs means that innovative solutions are demanded to overcome critical challenges in performance and reliability of future-generation electronics approaching fundamental limits due to aggressive down-scaling. Real prospects towards realization of the next-generation transistor technology are associated with high-performance devices and interconnects, that may be achieved by addressing key issues associated with applications in the areas of graphene/nanotube transistors and graphene/nanotube-based interconnects. Such

solutions promise to extend the life of digital electronics beyond the limits achievable with current silicon technology. The main hurdle preventing development in the area of graphene transistors is the absence of a band gap in graphene. Graphene only displays a quasi-band gap (vanishing of density of states), which translates into quasi-saturation, low gain and low I_{ON}/I_{OFF} for graphene transistors. Without a band gap, graphene transistors dissipate too much energy, exhibit large leakage currents and the current flow in graphene cannot be stopped to enable effective transistor switching action. In fact, the best current modulation reported to date has been about 30, measured at cryogenic temperatures. In addition, due to oxide charges and metal doping, zero band gap graphene has a finite minimum charge density despite the absence of any applied gate voltage. For that reason, as mentioned, finite current is usually measured in undoped graphene, with strong limitations in the use of as future CMOS-type logic circuits. Among the positive features of graphene-based transistor devices, we may mention (i) high mobility (up to 100 K cm^2 V^{-1} s^{-1}), (ii) low dimensional systems, few defects, (iii) high supported current ($> \mu$A/nm), (iv) planar profile. Conversely, possible limitations reside in: (i) absence of band gap, (ii) ambipolar behavior, (iii) mobility reduced by substrate effect, (iv) no saturation, (v) relatively high contact resistance.

Graphene-based materials could also play a specific role as planar interconnects, due to an intrinsically high thermal conductivity. Apart from challenges associated with scaling at the device level, interconnect systems continue to be an ever-growing challenge and are becoming one of the key components to decide IC performance due to the delay they add to critical paths, the power they dissipate and their susceptibility to electromigration that comes with progressive scaling.

Even with the limitations reported above, graphene FET (GFET) transistors have been successfully fabricated. In terms of operating speed, GFETs have already achieved a current cut-off frequency f_T above 300 GHz using conventional semiconductor manufacturing method (Table 1). Comparing graphene transistor operating speed with existing technologies (such as Si, III-V HEMTs, SiC, GaN etc.) [53] shows that graphene based devices are already comparable to conventional technology state-of-the-art. Moreover, graphene-based technologies will avoid production costs, toxicity issues and poor integrability associated with III/V materials. Differently from infinite graphene, one-dimensional carbon ribbons are theoretically expected to exhibit a band gap due to reduced dimensions electron confinement. The reduced dimensions of single-layer graphene nanoribbons (GNR), as low as 5 nm, could be exploited in transistor-like applications, whereas the performance of multi-layer and single-layer GNR with larger lateral sizes could be considered, in perspective, for on-chip interconnect applications. The expected bandgap for nanoribbons as narrow as 15 nm is 200 meV, and increases with decreasing size of the ribbon up to 0.8 eV for 5 nm wide GNR.

- Quantum transport analysis

Numerical simulation tools for the design of GFETs and interconnect applications are developed by self-consistent analysis. In general, the analysis of 2D nanodevices and nano-layered structures can be carried out by ab initio and first principles

Table 1 Comparison of graphene-FET performance with Si and III-V technologies

Technology	f_T (GHz)	f_{max} (GHz)	g_M (mS/μm)	L_g (nm)	μ ($cm^2V^{-1}s^{-1}$)	I_{DS} (mA·μm^{-1})
Exfol. graphene	300		1.27	140		3.32
CVD graphene on DLC substrate	300	42		40 and 140	3000	
Epitaxial Graphene on SiC	110	70	0.25	100	8700	>2.5
CVD graphene	23	10	0.5	110-170		1.3
Si	485		1.3	29	1400	
InP	385	1100	1.2	<50	15000	
InAs	628	331	1.62	30	13200	
GaN	225	300	0.53	30	2000	1.2

approaches, like DFT, that provide accurate calculations of the electronic structure. Other methods, based on more semi-phenomenological arguments, are commonly used to monitor the behaviour of extended systems made of a large number of atoms, which are computationally unaffordable by DFT: tight binding (TB) with DFT parametrization, and continuous models, like effective mass and $k \cdot p$ perturbation theory. A multimode scattering matrix (SM) method can be applied to model, at the electronic level, the charge transport [40–42]: this is formally equivalent to the non equilibrium Green's function (NEGF) approach, and allows easy simulation of very large structures, despite the possibly high number of electronic channels involved. It makes use of an explicit scattering matrix formalism, provided that the system under consideration is connected to the exterior world by "wave-ports", that are the terminations of semi-infinite periodic electronic waveguides. Such an analysis is applied to low dimensional systems, in their use as interconnects and channels for transistors and mixers. In addition, full-wave numerical techniques, both in frequency and time domains [51] can be applied to graphene and GNR.

Typical numerical results for the current-voltage characteristics of graphene transistor, with 600 nm channel and 200 nm gate electrode, are reported in Fig. 7. In the figure, we assume a Fermi level possibly shifted with respect to the Dirac point, mimicking a natural "doping" level for graphene, due to charge exchange with metal or substrate contacts. More refined simulations are currently under development, in order to take into account for global effects such as finite scattering length of charges, boundary effects, electrode and substrate effects.

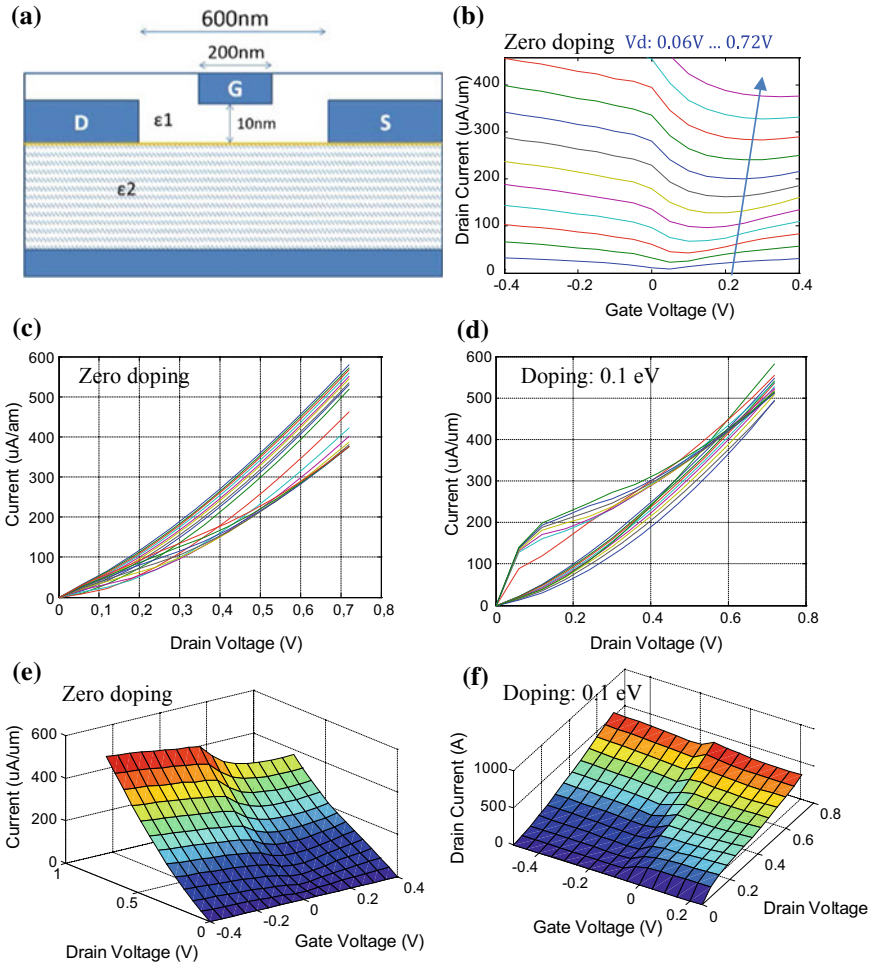

Fig. 7 Numerical simulation of current-voltage curves of graphene FET (geometry in a), showing typical poor saturation behaviour and quasi-linear slope ($b - e$). An oxide dielectric constant $\sigma_1 = 25$ is assumed, with $\sigma_2 = 4$ for the substrate. The "doping" is referred to a possible shift of the Fermi level with respect to the Dirac point [40] ©[2016] IEEE

- Computational platform

Charge-transport and electromagnetic problems are inherently multi-physics, in both usual meanings: (i) they apply the same physical model to different length and times scales, as those of quantum and electromagnetic phenomena, (ii) they link models with different underlying physics. The ambition of our activity is to deal with the above complexity at the circuit level, by developing GNR interconnects, transistor prototypes, and dedicated numerical tools. The proposed computational platform defines, on the one side, general modelling and simulation routes at both device and

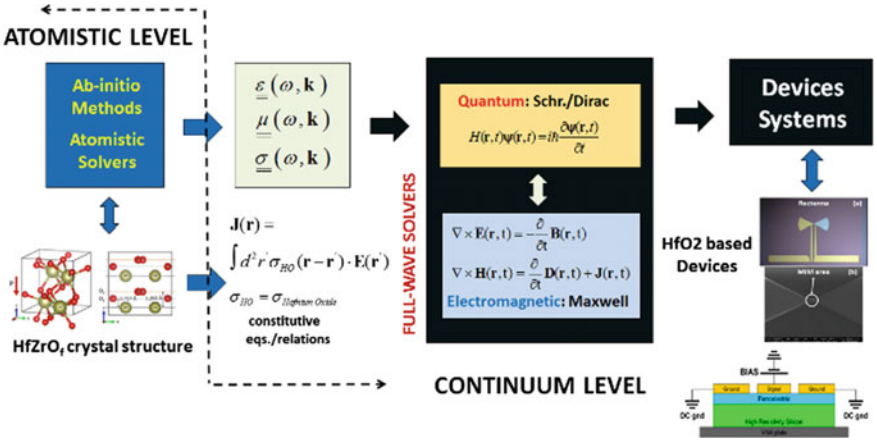

Fig. 8 Schematics of the numerical platform. *Ab-initio* simulations performed at *atomistic* level transfer/integrate the results into/with the larger scale models by constitutive equations/relations, in order to incorporate all necessary physics towards *full-wave* simulation, performed at *continuum* level. At the *continuum (device)* level, we have the simulation of the real devices/sub-modules based on nano-structured materials. At this level, the electromagnetic phenomena can be also coupled to quantum transport phenomena, described by Schrödinger/Dirac equations

sub-module level; on the other side, it provides and optimizes programs and simulations for specific issues and challenges. Particular challenges rely in dealing with the low-dimensionality of the materials and coexistence of multiphysics phenomena, e.g. electromagnetic (EM), charge propagation and quantum transport. Specifically, inherently quantum phenomena like ballistic transport, tunneling, many-body correlations, carrier confinement, and interface effects, overlap with classical physical effects. Such overlap makes traditional circuit design unsuitable to nanoelectronics. In order to overcome the above issues, we developed appropriated models based on the solution of coupled systems of equations dealing with combined electromagnetic-transport phenomena i.e. Schrödinger/Dirac, Maxwell-Boltzmann, etc. The above platform aims at accounting for the different aspect-ratio between nano-structured materials and device environment (see Fig. 8), bridging from the atomistic to the continuum scale (extreme multi-scale analysis). The key-issue is the coupling of quantum models and electromagnetic models, that acts at discrete level, but, in some case, as for ballistic regime, also at continuum level. Other physics can also be included, e.g. coupling to phonons (thermal effects).

Exploiting constitutive parameters extraction from nanoscale models may lead to a compact representation, like the one provided a by complex, temporally and spatially dispersive: (i) electric permittivity/conductivity; (ii) magnetic permeability, also in tensorial form, depending on the kind of example under analysis. These constitutive equations, that should be consistent with the Kramers-Kronig relation according to causality, are then incorporated into the full-wave simulation platform that, in turn, could consists of coupled systems of partial differential equations (PDE),

dealing with combined multi-physics phenomena, in particular: (i) electrodynamics (Maxwell); (ii) ballistic quantum transport (Schrödinger/Dirac) [51, 52]; (iii) thermal effect (acoustic wave equation, continuum mechanics). Concerning the full-wave numerical methods, it is crucial to avail both (i) frequency-domain techniques, as finite-elements/finite-difference methods (FEM, FDFD), and (ii) time-domain techniques, as finite-differences in time-domain (FDTD), and transmission line matrix (TLM) method. It is remarkable to note that the use of TLM permits, in conjunction with the implementation of system identification methods and Krylov subspace reduced order techniques: (i) to calculate the impulse response of the circuits (numerical Green's function), and (ii) to derive global (device) equivalent circuits. Standard solvers usually can simulate either quantum transport or full-wave electromagnetics, but a simultaneous solution is very hard to be achieved at a large scale. That is the reason why remark the need to link the atomistic scale up to the continuous world: separation of the micro-, meso- and macro- (bulk) scales [36] can be achieved by means of a holistic modelling framework incorporating the full-wave description at all scales, but allowing the homogenization as a subset of the of multiscale numerical procedure. Such multi-resolution approach is a representation of the underlying numerical formulation of Maxwell boundary-value problem [37, 39].

6 Conclusion

It is almost sixty years since the invention of the silicon integrated circuit and over fifty years since Gordon Moore observed that the number of components on a single chip of silicon had doubled every year since its invention [44]. However, the atomic structure of silicon will someday set limits to the further evolution of silicon technology. Nanotechnologies offer alternative materials and devices which may circumvent the limits such as resonant tunneling or single electron devices, carbon nanotubes as interconnects or transistors, and eventually complex organic molecules as memory and logic units, to name just a few. In this paper some key aspects that determined the rapid advancement of microelectronics have been reported and several recently discovered nanomaterials have been discussed.

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Birth and Development of the "Electromagnetic Fields" Group

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Abstract It is a popular opinion that the electromagnetic fields are only related to telecommunication systems as a carrier of the information. This is certainly true, but it is also in some way misleading because it excludes a lot of applications of paramount interest both from a research and a technological point of view. In this sense the research activity of the "Electromagnetic fields" group is exemplary. In fact, without disowning telecommunication applications, the research has been increasingly oriented towards new and original aspects, not strictly related to ICT. This new point of view led to deepening more and more topics related to physical aspects of the interaction between the electromagnetic fields and matter. As a consequence, models describing the behaviour of the electromagnetic fields in non-conventional environments were developed. For example, models combining Maxwell and Boltzmann equations to treat the non-linear effect of the plasma ignition were introduced; by the same token a multi-physical approach Maxwell-Schrödinger/Dirac to characterize the problem of the quantistic transport in nano-structured materials was developed. In the paper the most important research topics, their developments, applications and their evolution will be presented.

1 Early Development

The activity of the "Electromagnetic Fields" research team (simply 'group' hereinafter) started at the beginning of the 80s of the last century, when Prof. Roberto De Leo, full professor of "Electromagnetic Fields", moved from Università di Bari to Università di Ancona. He immediately was aware of the development possibility offered by a new university and contacted Prof. Tullio Rozzi, full professor of "Microwaves" at the University of Bath (UK), who soon thereafter moved from England to Ancona. So, the development of the two main research lines that have always characterized the activity of the group can be dated back at the first half of the 80s.

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One of the most important research topic investigated by Prof. De Leo group was the study of the environmental impact of the electromagnetic fields, a subject that allowed the Ancona research unit to become one of the most relevant at national level in this field, anticipating problems who would have gained the attention of the scientific community and common people many years later.

In the very general context of the environmental impact, we consider both the interaction between electromagnetic fields and human body, and the coexistence of electronic devices and equipments in the same space. The first topic concerns the safety aspects of the electromagnetic fields, the second electromagnetic compatibility (EMC) problems.

The dosimetry studies aimed to evaluate the power deposition into human tissues when exposed to electromagnetic fields allowed to develop original models and experimental techniques, that were progressively applied to investigate the problem of the therapeutic use of the electromagnetic fields. In particular, hyperthermia treatments, that is the possibility to nurse tumoral tissues with temperature enhancement through electromagnetic radiation, were intensively investigated. The key point was the design of the applicator, the antenna to be placed on the patient skin to radiate the cancer region. The challenging aspects were the design of the radiating structure in the very near field of the antenna, especially for the problem of the matching conditions varying from a patient to another, and the capability to focus radiation into the tumor, avoiding temperature increase of the healthy tissues. These studies led to cooperate with other academic institutions and with industrial partners: in the first case cooperation resulted in an European Project, and in the second one it gave rise to the realization of a device for hyperthermia treatment successfully tested in hospitals [1–7].

In the same time the group investigated the problem of the brain cortex stimulation with pulsed magnetic fields, showing a capability to anticipate forthcoming scenarios, because this technique is currently investigated as possible treatment of some neurological disorders as depression and Parkinson. In Ancona the research was essentially addressed to study the possibility of replacing the electrical brain stimulation, painful and uncomfortable for the patient, with the magnetic stimulation, without any inconvenience for the patient, aimed to check damages of the motor area of the brain cortex. Also in this case the research activity, in cooperation with some neurologists of the regional hospital, was at first directed to develop a realistic model to evaluate the interaction between a magnetic pulse and a human brain, in particular the current density distribution into the brain, and then to the design of applicators able to focus the currents in specific regions [8–10].

Ancona was also one of the first Italian university to deeply take care of the EMC aspects, both as a research topic and as an educational matter. In fact the University of Ancona was the first in Italy to insert a class of ‘Electromagnetic Compatibility’ in the degree course of ‘Electronic Engineering’, so fostering the change of philosophy in modern engineering design, in the sense that EMC should not be considered an accidental trouble, but an important aspect of the design constraints, because EMC phenomena have a rigorous electromagnetic support and can be accurately modelled. In the early 90s, on behalf of the Italian branch office of Hewlett Packard,

the group gave many lectures in different Italian locations to engineers coming from Italian industries. From a research point of view the group investigated aspects concerning both external and internal compatibility. In the first case the focus was the shielding effectiveness of enclosures with particular concern to apertures and resonance effects, whereas, in second case, crosstalk effects among traces of PCBs were theoretically and experimentally characterized [11–15]. However the topic that had not been deeply studied yet in the literature, and that gave the group the maximum international visibility was the systematic approach to the study of fast and intense transient fields, mainly due to ESDs events or generated during EFT tests. Accurate models, experimentally validated, in the time and frequency domain, for linear and non-linear devices were developed, and allowed to show direct and indirect effects, excitation of dangerous resonances [16–20].

In early 90's group headed by Prof. Rozzi started works on advanced electromagnetic models of several kind of waveguides, in particular planar structures. The research was aimed to obtain numerically efficient and accurate models of, e.g., microstrip and coplanar waveguide accounting for actual thickness and losses of conductors, in contrast to what available at the time, where finite thickness and losses were addressed by approximate perturbative approaches. This way a new technique was discovered, the so called "Generalized Transverse Diffraction Resonance" (GTRD) approach. At the end of 90's this was applied not only passive waveguides but also to active devices, such as Field Effect Transistors, in order to model a new class of distributed amplifiers (Travelling Wave FET), and principles were discussed in-depth in a book [35] edited by the IEE (currently IET), London. While the approach was conceived for 2D, namely waveguide, in so called eigenvalue problems, there were initial ideas to extend it to a fully arbitrary 3D circuit (deterministic problem). As matter of fact this process was later accomplished between the end of 90's and early years of the new millennium, and a software, called Electromagnetic 3D Simulation (EM3DS) was developed as result of such theories. EM3DS was among the very few general purpose simulation software available at that time—likely one out of 10 or slightly more- and gained popularity being used by many relevant institution and companies (e.g. NASA,[1] Intel,[2] L3 comm[3] etc.), and integrated in commercial software by Intellisense[4] (Corning) and Coventor,[5] while being able to work seamlessly with software like Microwave Office (AWR,[6] currently National Instruments). Further studies involved coupled acoustic waves and electromagnetic waves for integrated resonators like BAW and TFBAR.

[1] https://www.nasa.gov/centers/glenn/home/index.html.

[2] https://www.intel.com/.

[3] https://www.l3t.com/.

[4] http://www.intellisense.com/.

[5] https://www.coventor.com/.

[6] https://www.awrcorp.com/.

2 From the Old to the New Millennium

We have to consider that in these years an extraordinary growth of the mobile telecommunication systems led to a dramatic increase of the number of base stations in urban areas: as a consequence the problem of the exposition of the population to electromagnetic fields became a matter of discussion on the media, in public meeting, at the central and local parliaments. As a consequence, the study of the electromagnetic environmental impact was the natural evolution of the previous studies concerning the interaction of the fields and the human body. A further motivation to approach the problem came from the continuous requests of many local governments to participate to the writing of the 'antenna planning' for cellular networks. The group decided to face the problem with a very general approach, consisting in an innovative philosophy, where the electromagnetic impact should have been a constraint of the network, as other telecommunication requests. More specifically, the problem concerns the choice of the RBS positions, antenna tilts and heights, and radiated powers for a specified number of RBSs serving the interested area. The proposed solution is based on an optimization procedure that carries out the following principal requirements: (1) minimization of the radiated electromagnetic field, (2) maximization of the C/I ratio, (3) minimization of the distance between RBSs and the area with more traffic, (4) maximization of the coverage percentage, and (5) maximization of the efficiency of the base station system. Original techniques based on artificial neural networks were developed to efficiently evaluate the path loss of the electromagnetic waves in urban environment, and, in the framework of a project of the national agency for environmental protection, a method was proposed to compare the environmental impact of different base stations [21–24].

In the EMC research domain, new topics specifically related to measurements were developed. In particular the characterization of field sensors in a wide frequency range allowed to perform measurements of fields generated by fast transient currents, and the study of the reverberating chambers allowed to characterize this particular measurement test site. In these years the group developed a new idea to stir the field inside the chamber, called source stirring, whose advantage with respect the more common mechanical stirring is the lack of heavy and bulky mechanical paddles. The technique and the array to perform the electronic stirring were patented [25–31]. It worth noting that in these years the plasma antenna was also theoretically studied [32] and experimentally characterized: this was the first self-consistent model of this kind of device, based on a multi-physic approach consisting in a mathematical system formed by the Maxwell and Boltzmann equations: the model allows to accurately describe the non-linear effects of the plasma ignition through an external field, describing all the transient behaviour of the physical quantities till steady state condition [33–35].

In the new millennium most of Rozzi's group shifted toward nanotechnology, in both theoretical and experimental studies. Nanotechnology is a technological field covering all aspects of nanoscale science and technology from a multidisciplinary perspective. It characterizes the understanding and control of matter at nanoscale

dimensions, that is from few hundreds nm down to atomic dimensions. Nanotechnology not only yields miniaturization of devices and enhancement of integration density, but also features unusual physical, chemical, and biological device properties. Since many nano-structured materials exhibit their most interesting properties in a wide spectrum, from the microwave up into the optical frequency range, the concept and realization of nanoelectronic devices is a challenge also for the microwave/RF engineering community. At the nanoscale, both the charged particles and electromagnetic fields must obey the laws of quantum mechanics, which leads to quantum electrodynamics. Therefore, by the theoretical point of view, intense work was devoted to exploit the machinery developed to solve Maxwell's equations into the framework of quantum mechanics, and later using relativistic quantum mechanical equations (Dirac formulation) to express alternatively Maxwell's equations [36, 37]. Starting from well-known numerical techniques (e.g. TLM, FEM, Scattering Matrix Method), full-wave solvers for the multiphysics modeling of the combined Maxwell-Schrödinger/Dirac problem have been developed [38, 39]. A core concept relies in the fact that the electromagnetic field provides source terms for the quantum transport equations, that, in turn, provide charges and currents for the electromagnetic field. The main research topics can be summarized as: (i) the modeling of nano-structures/devices/systems based on low-dimensional materials, e.g. carbon-nanotubes (CNT), graphene, 2D materials beyond graphene, nanoparticles; (ii) the analysis of complex systems, ranging from nano- to meso-scale, and including quantum transport, electromagnetics, opto-mechanics, thermal effects, opto-mechanics, opto-electronics.

On the experimental side, the group pioneered a new approach into the framework of Scanning Probe Microscopes (SPM), namely the Scanning Microwave Microscopy (SMM) [40]. In this approach a probe is brought in close proximity to the surface of a sample, and current scanning probe microscope are able to image single molecules; in SMM a microwave signal is injected in the probe, and scanned while detecting changes in the reflected microwave signal. Imaging resolution can be sub-nanometric or even atomic, in spite of centimetric wavelength, due to the behaviour of evanescent waves produced by the sharp tip. This way a map of differences in local electromagnetic properties (e.g. dielectric constant, conductivity) can be obtained; a set of calibration techniques was developed [41] enabling local quantitative measurements. SMM, with respect to other techniques, allows to obtain quantitative data (electromagnetic properties) and at the same time to probe below surfaces also samples that are optically opaque. At the same time it was discovered that some principle of Time Domain Reflectometry could be exploited to improve the quality of images [42] and to obtain further calibration approaches [43]. Incidentally, during a set of experiments on semiconductor polymers, a new phenomenon was discovered [44], that could lead to a new generation of mass storing devices, where the interaction between a probe and a semiconductor could permanently lower locally the polymer conductivity, by changing the degree of disorder at molecular scale (Fig. 1). Microwave microscopy could be also a new device to investigate non-invasively, without the need of labelling, biological samples, and as matter of fact the group is focusing in performing measurements on cells, mitochondria and small

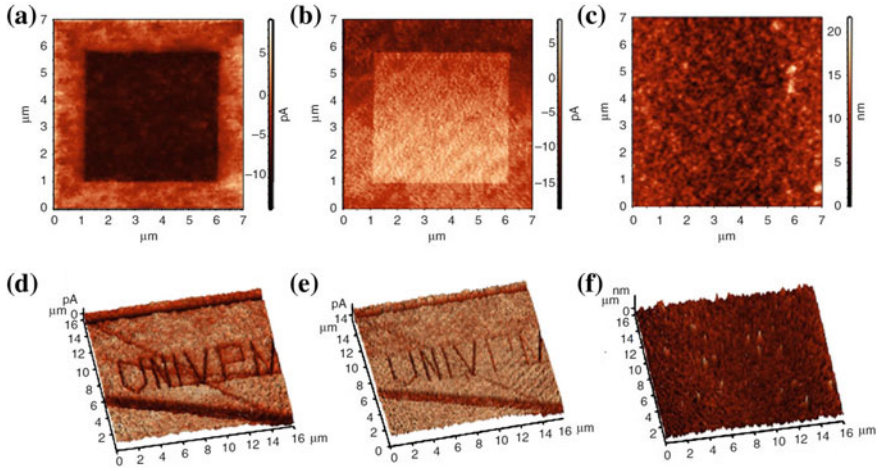

Fig. 1 Comparison between current maps, lateral force and topographic images in scanning probe microscopy (conductive Atomic Force Microscopy). A square, 5 µm of side, was written; reading is performed in an area 7 µm × 7 µm in P3HT: [70] PCBM (1:1) annealed at 100 °C for 15 min. **a** Current map (0.5 V) **b** lateral force image: the written square appears as a region with increased molecular disorder **c** topography: no topographic change is visible. The above images were obtained simultaneously. Also, the acronym "UNIVPM" is written and represented in 3D: **d** current map, **e** Lateral force (inverted for clarity) and **f** topography (Reprinted from [44])

nanometric vesicles, called exosomes, that could be the mean by which some chemical signal spreads among cells; recent theories also suggest a role of exosomes in spreading of metastases in cancer. Mitochondria are on the other hand implied in a process, called apoptosis (cell suicide), whose role is being investigated for cancer, while being at the basis of cell metabolism and, consequently, potentially underlying degenerative diseases. Microwave microscopy could become a tool to compare electrical properties of organelles in both healthy and disrupted or ageing cells [45].

Following the same concepts introduced in SMM, novel imaging techniques, based on scanning probe microscopy, were implemented in the range of optical frequencies by merging together in a lens-free system different methods, such as: Contrast-Phase Microscopy [46], Optical Tomography [47] and Synthetic Holography [48]. These systems exploit the principle of low temporal coherence combined with the high spatial coherence propriety of light confined inside a scanning optical micro-cavity. These approaches are well suitable to work in liquid environment, for biological applications, and integrable with the actual SPM systems to achieve nanometric resolution.

In the last years, some properties of the scattering matrix for non-uniform radial waveguides were analysed in order to simplify the evaluation of the e.m. fields in such structures [49]. The results were applied not only to e.m fields but also to acoustic applications. The analysis of the properties of the scattering matrix were used to define a new kind of equivalent circuit, able to represent N-ports microwave devices, in presence of guided and/or evanescent modes [50, 51]. The new circuit is

based on a polygon with N sides, as the number of ports, and N(N − 3)/2 diagonals. Moreover, N transmission lines are connected to the N sides. Each side and diagonal are loaded with susceptances that represent the "kernel" of the microwave device. The circuital properties of the device (filter, coupler, multiplexer, …) are contained in the "kernel" of the circuit. The polygon equivalent network can be used for example in the measurement of N-port device [52] and in the synthesis of hybrid coupler [53].

3 Nowadays and Beyond

3.1 Reverberation Chamber

Reverberation chamber (RC) theory and applications remain hot topics in the current and future activity planning of the EMC group. This research activity led to international cooperation with other Universities as the University of Nottingham (UK), the College Park (USA), the Queen Mary of London (UK) [54]. From an industrial point of view, the RC finds application in traditional electromagnetic compatibility tests (immunity and emissions) and power electromagnetic applications, like the microwave heating processes. In all these fields of application, the Ancona activity was characterized by a strong interaction with industries (ELASIS-FIAT, Emitech, Tornati Forni, Unibind). The future trend in theoretical aspects will be focused on the necessity to properly combine deterministic and stochastic electromagnetic methods of analysis [55–58]. The necessity of stochastic methods becomes more evident when the RC is transformed into a chaotic environment [59, 60]. Another interesting RC application is the characterization of shielding materials in aerospace and building construction applications [61–64]. The advantage is the random field excitation of the material more adherent to real life situations, w.r.t traditional deterministic methods [65]. Recently, the application of RCs has been extended to the testing of wireless devices and systems [66]. In fact, the RC is able to provide a rich multipath propagation environment, very similar to real life situations where these devices (access points, smartphones, IoT devices, etc.) may operate in presence of strong reflections having random behavior. This last activity opened other research topics and led to the built-up of a joint laboratory TIM[7]-UNIVPM for testing real live LTE base stations in 4G technology provided by NOKIA[8] [67–70]. Strong research and application activities are expected in the future for the extension to the emerging 5G technology.

[7] https://www.telecomitalia.com/tit/it.html.

[8] https://www.nokia.com/it_it/.

3.2 Electromagnetic Sensors

European and national research policies have, among their priorities, initiatives that will contribute to build a healthy and active population for the future, as well to enhance inclusion of people with disabilities. In line with this topics, the research group also focused on the development of sensors to monitor vital parameters (breathing and heart rate) that can be used in domestic environments, as well as sensors that can be used by blind or visually impaired people both in everyday life (sensors for mobility) and in sport.

The monitoring of vital parameters through electromagnetic sensors developed by the team is non-contact and allows the subject to remain dressed and covered if the monitoring takes place during sleep [71]. This reduces the invasiveness of the system and increases its acceptance and ease of use.

This application activity has led the research team to work alongside companies that belong to the Marche territory with strong attitude to innovation. This collaboration leads to an exchange of know-how between companies and university that has allowed to address problems of implementation and design not common in daily academic activity. The realization of demonstration prototypes was the result of this synergy [72].

The activity on electronic travel aids for the autonomous walking of visually impaired person has turned to the planning and realization of a system based on a obstacle detection radar [73, 74]. The system has been miniaturized to allow the placement of the antenna on the white stick [75]. In parallel to this activity, two prototypes of systems have been designed and built to assist blind people in running: one to be inserted into an athletics track [76, 77], and another for road training [78], again for running. For these projects the group collaborated with a Paralympic champion who resides in our Region: Andrea Cionna, who offered his advice on the implementation of the systems, as well as tested them. Some short videos of the systems realized are available on [79].

3.3 Electromagnetics at Nanoscale

Nowadays, nanotechnology is one of the core research area of the group. The development of modern devices based on nanostructured materials and nanotechnologies, for a wide area of applications ranging from microwave to photonics, relies on an electromagnetic computational platform defined by new general modelling and simulation routes. Accordingly, programs and simulations are developed and optimized for specific issues and challenges. The latter are related to the low-dimensionality of novel materials and to the possible coexistence of multiphysics phenomena, e.g. electromagnetic (EM), charge propagation and quantum transport [80–87], In particular, quantum phenomena like ballistic transport, tunneling, many-body correlations, carrier confinement and interface effects overlap with classical physical effects, which make traditional circuit design unsuitable to nanoelectronics. To this purpose, we

developed appropriated models based on the solution of coupled systems of equations dealing with combined electromagnetic-transport phenomena i.e. Schrödinger/Dirac, Maxwell-Boltzmann, etc. The above e.m. platform takes into account the different aspect-ratio between nano-structured materials and device environment, bridging from the atomistic to the continuum scale (extreme multi-scale analysis). The key-issue is the coupling of quantum models and electromagnetic models, that acts at discrete level, but, in some case, as for ballistic regime, also at continuum level [80]. Other physics can also include, e.g. coupling to phonons (thermal effects), in opto-mechanical cavities, [87, 88]. In order to support semiclassical modelling, ab initio methods for high-frequency simulations of atomic-thick materials/surfaces need to be considered, as the Density Functional Theory (DFT). A key development is that the aforementioned discrete, ab initio methods (atomistic level) transfer/integrate the results into/with the larger scale models by constitutive equations/relations [80], in order to incorporate all necessary physics towards the continuum, full-wave method (device/sub-module level).

Constitutive equations must result in constitutive relations, eventually in integral form, which are usually numerically easier to handle. Exploiting constitutive parameters extraction from models may also lead to a compact representation, like the one provided a by complex, dispersive: (i) electric permittivity/conductivity; (ii) magnetic permeability, possibly in tensorial form. Standard solvers usually can simulate either quantum transport or full-wave electromagnetics, but a simultaneous solution is very hard to be achieved at a large scale. There is therefore a strong need to link the atomistic scale up to the continuous world, in order to characterize practical macroscopic elements, like micro-antennas, terahertz and plasmonic devices, periodic and aperiodic metamaterials. The combined solution of quantum transport and electromagnetic wave propagation features: different partial differential equation systems (PDE-S); different propagation/diffusive nature of the PDE-S; non-linear coupling; large geometrical/electrical aspect ratios.

Nano-structured materials and electromagnetic (EM) smart surfaces are also the target for innovative industrial products for antenna, radar and sensing application at microwave frequencies and in photonics. These are micro- to nano- structured artificial surface materials (2D or 2.5D), where: (a) the working principles exploit extreme sub- wavelength features already for passive (linear) operation; (b) the material need to encompass an overall size of hundreds of wavelengths; (c) localized or distributed active non-linear micro- to nano-scale inclusions are deployed densely in the underlying textured surface. The latter include constructs comprising carbon nanotubes (CNT), metal nanowires and nanoparticles, graphene, or more conventional semiconductor-based devices.

The activities described above are now at a final stage, but new ideas and potential applications have arisen from them. Nowadays, studies are already underway to verify the feasibility of using the monitoring system of vital parameters to monitor the energy expenditure of a person at home, even in this case without the use of bulky and annoying electrodes connected to the person. At the same time, the experience of autonomous mobility of blind people could be borrowed for applications in the field of civil protection where there is a need to use drones with autonomous driving.

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Digital Signal Processing for Audio Applications: Then, Now and the Future

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Abstract In the last fifty years, the development of new technologies has enabled machines to sustain the ever increasing computational load, thus providing the implementation capability requested by real time applications. In this context, digital signal processing played an important role especially with relation to audio systems. Several approaches have been proposed to solve the main issues of the audio field in complex scenarios, including advanced audio rendering applications and acoustic monitoring systems exploiting multirate adaptive algorithms, machine learning techniques and deep neural circuits. Following this trend and based on our experience, the future will witness the joint use of these techniques to design applications able to improve quality and comfort of people's daily life. Among them, in this contribution we want to focus on the employment of advanced audio augmented reality solutions, involving both virtual audio sensors and transducers, to design enhanced spatial hearing experiences in diverse application contexts, spanning from entertainment to safety.

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1 Introduction

In the last fifty years, the development of new technologies has enabled machines to sustain the ever increasing computational load, thus providing the implementation capability requested by real time applications. In this context, digital signal processing played an important role especially with relation to audio systems that are present in different applications and scenarios of the daily life. In particular, the growing presence and adoption of electronic equipment in the everyday life, has led to the need of audio processing procedures to make the ambient intelligent, such as the automatic recognition of commands and activities performed by subjects in their living environment, to help and support them. Furthermore, the pervasiveness of technology has raised a great attention on the aspects related to a comfortable living, including also the acoustic comfort. In this context, several audio processing algorithms can be used to enhance the audio reproduction systems, exploiting audio equalization and analyzing the non-linear behaviour of audio devices. All these applications can be implemented introducing multirate adaptive algorithms and machine learning techniques. Multirate adaptive algorithms are based on the use of adaptive filtering with subband structure allowing a real time identification of the analyzed system with fast convergence and low computational complexity. Machine learning techniques, including deep neural circuits which have recently encountered a remarkable success, are aimed at extracting useful representation knowledge from acquired audio signals, to pilot the execution of automatized services. Taking a look at the future, the use of these techniques will increase since they guarantee good results in terms of computational complexity, achieved quality and easy adoption in those applications that address people's comfort in their daily life.

In Sect. 2, a brief overview of our contributions is reported. In particular, Sect. 2.1 describes our contribution on the use of audio signals for ambient intelligence while Sect. 2.2 reports our contribution on the use of audio algorithms for the improvement of the audio reproduction. New trends and future research directions are presented in Sect. 3, where the employment of advanced audio augmented reality solutions, involving both virtual audio sensors and transducers, is introduced to design enhanced spatial hearing experiences in diverse application contexts.

2 Our Contribution in the Audio Field

2.1 Audio-Based System for Ambient Intelligence

Systems and solutions based on audio processing are of great interest for Ambient Intelligence, to allow the automatic recognition of commands, the identification of either so-called Activities of Daily Living (ADLs) as well as anomalous events or potentially dangerous situations, like human falls. Several research studies addressed

the possibility to exploit the audio signals acquired by means of suitable microphones deployed in the monitored living environment [2, 17].

In this context, the Audio-based System for Ambient Intelligence [5, 51, 52] has been recently developed by some of the authors at UnivPM. It addresses the automatic detection of emergencies and the recognition of commands in home automation contexts. An emergency here is represented by a situation of distress for the user, where he/she intentionally asks for help, or by an abnormal acoustic event. Recalling the classification proposed in [1] the application scenario is thus monitoring for emergency detection and ambient assisted living. The system operates in two modalities that are chosen by the user to monitor different situations.

The first modality, speech monitoring, is enabled when the user is inside the home and consists in recognizing home automation commands and distress calls. Commands are automatically interpreted to control the appliances and the devices connected to the home automation system. Distress calls are employed to provide tele-assistance to the users. In particular, a distress call triggers an automatic phone call to a relative or a care center that then can provide assistance to the user. The acoustic environment is constantly monitored to detect speech signals by means of a Voice Activity Detector (VAD), and a speech recognizer based on PocketSphinx [23] captures distress calls and voice commands. Robustness against noise and reverberation is increased by integrating Power Normalized Cepstral Coefficients (PNCC) [26] and Multichannel Histogram Equalization (MHEQ) [57]. In addition, the sounds from a television or a radio are reduced by means of an interference cancellation module. The recognition performance has been assessed on ITAAL [52] a corpus of home automation commands and distress calls in Italian. The experiments have been conducted both with and without the presence of a radio show that represents an interference audio signal that can be present in the everyday use of the system.

The second modality is activated for surveillance purposes, e.g., when the user is outside the house. The system now monitors the acoustic environment to detect events that deviate from normality. As in the case of distress calls, their detection triggers an automatic phone call towards a user-defined phone number. The novelty detector [33, 34, 47] is based on the approach proposed in [39] which consists in extracting a set of features from the audio signal, and in modeling normal sounds by means of a statistical generative model. PNCCs, MFCCs, critical band-based TEO autocorrelation envelope [64], MPEG-7 features [25] and their combinations have been evaluated in order to determine the feature set with the overall best performance/computational cost ratio. In regard to the normality model, Gaussian Mixture Models and Hidden Markov Models have been both considered in order to find the best performing technique for the application scenario. Differently from [39] in the recognition phase, the decision is performed on a chunk-based analysis. The effectiveness of the approach has been assessed on a newly developed corpus for novelty detection, named A3Novelty, which contains more than 56 hours of recordings comprising both normal abnormal sounds.

Summarizing, it can be said that the system combines active and pro-active operation modes for emergency detection, since the user can explicitly ask for assistance by uttering a distress call, or have the system detect an emergency by analyzing

abnormal sounds. Moreover, the latter mode is performed by means of a novelty detector algorithm that does not require the explicit modeling of abnormal sounds representing an emergency. In regard to the sensors employed, the use of microphone does not require the user to wear a specific device for emergency detection and allows a simple integration of a voice user interface. Finally, the proposed system comprises both the algorithms for emergency detection, and the ones for its management, i.e., for enabling the communication between the person asking for assistance and the relative or care center. The algorithms have been implemented on a low-consuming embedded platform, i.e., the BeagleBoard-xM, while state-of-the art alternatives are based on more costly and energy consuming PC hardware [46].

A specific subsystem for fall detection based on an innovative floor acoustic sensor, as described in [50], has been also developed and included in the overall audio-based system for Ambient Intelligence. The sensor is composed of a microphone embedded in a resonant enclosure whose bottom surface is in direct contact with the floor. In this way, the microphone captures the acoustic waves transmitted through the floor and it mainly captures the sound of falling objects, resulting in a minor sensitivity to the environmental noise. In addition, it is able to capture the subtle signal components transmitted through the floor, which are absent in the signal transmitted through the air. The fall signals are then processed to recognize from which kind of fall they are produced: for this purpose, a multiclass classifier is implemented. The algorithm is based on Mel-Frequency Cepstral Coefficients as low-level acoustic features and Gaussian means supervectors as features for a Support Vector Machine classifier. More in details, a background model is created from a large set of audio events signals, and for each audio event class taken into consideration, a set of supervectors is calculated by adapting the background model with the Maximum a Posteriori algorithm and extracting the means of the Gaussians. The supervectors are then employed for training the Support Vector Machine classifier. The performance of the system has been assessed by creating a corpus of fall events acquired using the audio sensor in a realistic scenario. The obtained results showed that the proposed approach is able to discriminate persons' falls with values of recall and precision higher than 98%. A recent update of the subsystem includes a semi-supervised approach, relying on advanced template-matching solutions, for automatic human fall detection [15].

It must be observed that falls of persons have been widely addressed by the scientific community, since they represent the primary cause of injury-related death for the elders [37]. Approaches to the problem are based either on wearable sensors (e.g., accelerometers) or on ambient sensors (e.g., microphones, cameras, floor vibration sensors). The first ones exploit the information of the falling body acceleration [14], from which a fall event is detected when the value exceeded the typical normal level. Instead, the ambient sensors reveal the falling activity from the observation of the environment in which they are positioned: those could be used individually [55, 65] or combining the information coming from heterogeneous sensors [63, 66] for improving the reliability. In the case of floor vibration sensors, the detection is performed by analysing the signal resulting from the fall event, which produces a characteristic vibration, while in systems based on videocameras, the detection is based on the deformation of the human shape. Recently, several approaches appeared

in the literature that are based exclusively on audio signals [31, 32]. The motivation is that microphones are perceived as less invasive compared to wearable sensors and cameras and they do not suffer from occlusions. A common approach is to install several microphones in the house, usually on the ceiling or near the walls. The problem with these approaches is their sensitivity to environmental noise, that usually requires the adoption of beamforming techniques to enhance the signal quality and thus achieve a sufficient detection accuracy [31]. The floor acoustic sensor is immune to this kind of limitations.

Concluding, it is interesting to underline that, besides a specific deployment of acoustic sensors in the environment to be monitored, also microphones mounted on mobile devices, like smartphones, can be effectively used to collect audio data, and integrated into ADL identification modules, in order to facilitate the correct classification of the ADL by sensor-fusion approaches. As shown in the recent review by Pires et al. [49], most of the studies exploiting microphones on-board smartphones apply audio fingerprinting techniques, aiming to find a match between the signal collected by the microphone during ADL execution, and a database of well-known audio fingerprints. Being the published methods very diverse, and having been tested over different data sets and different feature extraction techniques, it is quite difficult to provide a final evaluation about the best audio fingerprinting technique to be used for the aim of ADL identification. Different approaches exist, that avoid the need to collect big amounts of fingerprints, despite being anyway able to identify different acoustic events. This aspect will be faced in the next future and suitable algorithms need to be developed for integration within the current Audio-based Systems of Ambient Intelligence.

2.2 Advanced Systems for Audio Reproduction Enhancement

When sound is reproduced by one or more loudspeakers in a real scenario, the acoustic perception is modified by the characteristics of the listening environment such as a room or a car cockpit. A small quantity of reverberation is required since it adds spaciousness and depth to the sound, however excessive reflections or resonances may result in an undesired alteration of the auditory illusion, adding some artifacts (e.g., frequency band extension, nonlinearities) to the original sound. In this context, an audio equalization algorithm is required to contrast the detrimental effects of the room environment and of the reproduction system [13]. Equalization is realized taking into consideration the transfer function that represents the path from the sound reproduction system to the listener and then this function is modified with a suitably designed equalizer that can be realized in several manners. The basic idea is to measure the impulse response of the environment using a microphone, and then obtain the equalizer through its inversion. However, several issues influence this method, and thus a wide variety of techniques have been developed over the last 40 years to counteract them [13]. Approaches to the design of the equalizer can be divided in single-point and multi-point ones. A single position equalizer estimates

the equalization filter on the basis of the measurement of the impulse response in a single location [38]. This way, the filter is effective only on a reduced zone around the measurement point, the extension of which is proportional to a fraction of the acoustic wavelength. However, the impulse response varies significantly with the position of the microphones in the room or car environment [29, 35] and with time [22] as these environments can be considered as "weakly non-stationary" systems [36]. To enlarge the equalized zone and to contrast the room and car response variations, multi-point equalizers have been proposed [4, 7, 11]. A multi-point equalizer uses multiple measurements of the impulse responses at different locations in order to design the equalizer. These approaches can be used for fixed and adaptive equalization [12]. The former is based on measurements obtained with a microphone positioned in a fixed place, the latter is capable of tracking and adapting to environment variations that can occur due to the modifications of temperature, pressure, and movement of people or other obstacles within the enclosure. Different pre-processing techniques can be applied to contrast the audible distortions caused by equalization errors due to these environment variations [11], and different equalizer design techniques can also be adopted, taking into consideration minimum-phase or mixed-phase approaches.

In the context of audio reproduction enhancement, an important role is relative to the audio devices identification. The non-linear behaviour of some devices could be considered beneficial in some cases, such as guitar amplifier reproduction, or not beneficial in the case of impulse response measurement, where the amplifier can introduce its own non-linear behaviour. Several methods can be found in the literature about non-linear system identification.

Volterra series is a linear-in-the-parameters (LIP) [8] nonlinear filter used for non-linear signal processing and non-linear system identification. It was actively used in the audio field from audio effect emulation [59, 60], to nonlinear acoustic echo cancellation [3, 6] or nonlinear active noise control [18, 58]. The identification of Volterra series can be carried out by searching the minimum of the mean square error (MMSE) between the outputs of the series and the target system. If the input is taken from an independent identically distributed (i.i.d.) sequence, it is well known that the cross-correlation method due to Lee–Schetzen [56] gives the optimal solution in the MMSE sense. This method needs the output to be expressed as a sum of orthogonal functional as those proposed by Wiener [62], since Volterra functional are not orthogonal to each other.

The Lee–Schetzen method undergoes many drawbacks: the central moments of a Gaussian input deviate from ideal values as the moment order increases [43]; the input non-idealities affect particularly the estimation of the kernels diagonal points [43, 44]; and the problem is worsened by the errors caused by a model order under-determination [40].

Effective solutions that overcome the problem of diagonal points identification have been proposed in the literature, for series up to the third order in [19], and for a generic order in [48], where a comparison between the two methods is also provided. While in analytical power series (infinite sum of elements), the identification with cross-correlation is independent of the input variance, this is no more true with truncated power series, where the approximation error depends on the variance used

in the identification: a Volterra series is optimal only for inputs with variances in a neighborhood of that used for identification, also called the problem of "locality" of solution [40]. An improved cross-correlation method to overcome the problem of the "locality" of solution, based on multiple-variances has been proposed for Wiener-Volterra series and Gaussian noise in [40]: low input variances are used to identify lower-order Wiener kernels, while the input variance is gradually increased for higher-order kernels. This allows a better identification of systems that have high dynamic inputs, like audio systems, and can be applied to amplifiers [41, 45] or loudspeaker systems. In [41] the multiple-variance approach was used for the identification of audio devices with deterministic periodic signals, called perfect periodic sequence (PPS), that guarantee the orthogonality of the basis functions on a finite period. In [45] the multiple-variance approach for the identification of tube audio devices was completed with a method that drastically reduces the curse of Volterra series dimensionality, i.e. the exponential relashionship between the coefficient of the series and the order and memory of the system to be identified.

It is possible to make easier the nonlinear system identification with the use of Wiener nonlinear (WN) filters, which derive directly from the double truncation of the Wiener series. The WN filter is a first example of nonlinear filters with orthogonal basis functions, in particular, orthogonal for a white Gaussian input signal. The orthogonality of the basis functions allows the efficient identification of the filter coefficients with the cross-correlation method, as in [30]. PPS can also be developed for WN filters. Expressing the WN filter as a linear combination of basis functions and using a PPS input signal, problems in the estimation of the kernel diagonal points can be avoided [9, 10]. Also the multiple-variances method, that avoid the locality of the solution, can be applied to WN filters [42] with some advantages with respect to the use of a white Gaussian input, as originally proposed in [40].

All experiments have been realized taking advantage of the semianechoic chamber realized at the Department of Information Engineering, and shown in Fig. 1, that allows to perform several tests in a controlled environment.

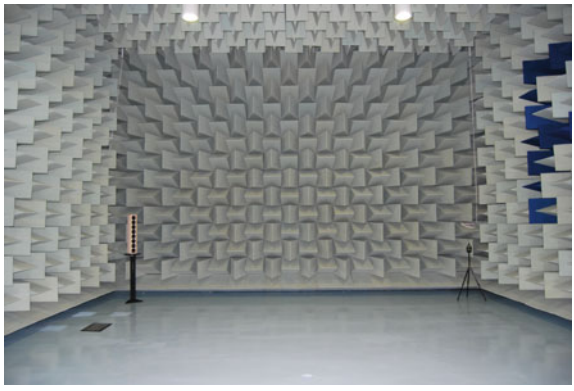

Fig. 1 Semianechoic chamber at the department of information engineering used for audio experiments

3 A Knowledgeable Vision on Digital Audio Applications

3.1 Vision

The overall future vision on Digital Audio applications sees the synergistic combination of methodologies for spatial audio processing aimed at augmented and virtual reality on headsets, and techniques of machine audition in the context of safety monitoring (Fig. 2). By analyzing and defining the acoustic scene through the use of microphones, the correct spatial information can be reproduced by means of headphones.

Audio augmented reality (AAR) combines virtual sound sources with the real sonic environment of the user [21]. It can be realized by means of a device that a user could be wearing at all times, such as a headset [53]. This way, the user can at the same time, hear and interact with the real acoustic environment in a natural way, allowing ordinary speech communication with other people and permitting all those operations for which acoustic feedback is important [16, 61]. To generate and render

Fig. 2 Future vision on digital audio applications where augmented and virtual reality will be applied on headsets for spatial audio processing

virtual auditory events, it is necessary to consider the properties of a real auditory event and its perception by the human ears. The human perception is spatial and it is bounded to localization cues and to the brain capability of interpreting them. Therefore, it is possible to develop a spatial rendering system through the use of auralisation, i.e., the reproduction of virtual sound considering the human perception capability in such a way that it evokes the same listening experience of a real sound source at a specific point in the space [27]. This aspect is realized considering binaural audio approaches that recreate this sensation exploiting the Head Related Transfer Functions (HRTFs) [20]. HRTFs are unique to each person since they are related to the human head physiology, however several approaches capable of overcoming HRTF individualization can be found in the literature [20]. In this context, several approaches for the enhancement of spatialized sound reproduction can be developed. Adaptive equalization is another key point to be implemented since it is necessary to make headphones acoustically transparent allowing a real perception of the ambient sounds [53]. In [54], a natural augmented reality headset with two pairs of binaural microphones to achieve natural listening experience using online adaptive filtering was presented. If the ambient is extremely noisy, an Active Noise Cancellation (ANC) system can be developed for the headset. Active noise controllers (or cancellers) cancel the noise in a certain location by destructive interference with an anti-noise signal [28]. In this particular case of AAR, selective ANC is considered since just specific disturbances have to be cancelled, preserving other sound sources that are important for a pleasant fruition of the audio scene [24], or for the audio security of the user.

In the perspective of the future research activities, two relevant application scenarios are of interest: indoor (applicable to workers in a noisy factory) and outdoor (targeting pedestrians listening to music). In both scenarios, the computational time required by the overall processing chain (source localization and enhancement, acoustic scene understanding, and synthesis of the audio stream) must be kept at bay in order to give the user the proper time to react. At the authors' best knowledge, the idea of synergistic cooperating tools coming from machine audition and augmented reality on headset, featuring a low latency in order to increase the sense of presence in real environments, is innovative and not addressed before. This goal poses several challenges, which compel researchers to develop solutions that go beyond the state of the art. In order to keep under control the reaction of the system, it is important to consider the different nature of the scenarios of interest, especially for what concerns the interfering noises and the reverberation.

The overarching goal of the envisioned research is pursued into three main objectives, all of them pertaining to areas that are individually very active.

Audio Quality Enhancement. This objective aims for the enhancement of the sound field acquired by one or more microphone arrays, to obtain specific signals for the subsequent analysis of the acoustic scene. This is a very active area in the audio community, and many applications in the last years have gained commercial interest. The scenarios of interest mentioned above, however, require to develop functionalities with capabilities that go far beyond the state of the art. In particular, innovative algo-

rithms for source enhancement that can work in the presence of strong reverberations, multiple moving sources and interferers will be investigated and developed.

Acoustic scene analysis and understanding. Research on this topic has been receiving much interest within the audio research community. In this context, the problems of localizing sources and understanding their nature will be tackled by exploiting innovative techniques, such as plenacoustic methods, which are able to accommodate reverberant environments and multiple sources. In particular, advanced deep learning techniques and neural network architectures will be considered to overcome the main problems of the aforementioned scenarios.

Audio augmented and virtual reality. In this objective, an artificial sound spatialization system exploiting personal spatial audio technologies will be proposed. Starting from the study of the state of the art, innovative solutions based on HRTF will be presented, exploiting the possibility of using alternate and less expensive solutions for spatial audio rendering, based on spatial cues such as Interaural Time Difference (ITD) and Interaural Level Difference (ILD). Furthermore, some techniques capable of improving the sound perception will also be investigated, such as adaptive equalization and selective ANC.

3.2 Proposed Methodology

The intended research direction envisioned for the future is both innovative and challenging, being based on the effective combination and fusion of different powerful methodologies. In particular, it mainly draws on the digital signal processing and machine learning theories applied to audio and acoustic data. The proposed methodology aims at providing effective solutions to the tasks identified, while meeting some constraints posed by a specific application scenario and by the quality requirements desired by a user. Among such constraints, a particular attention in the algorithmic design and development will be given to the available computational resources. Indeed, the available hardware is subject to the scenario considered. For instance, in indoor scenarios distributed hardware architectures may be used, whereas more limited computational resources will be available in outdoor scenarios (e.g., portable devices). In that sense, the methodology aimed at will be compatible and adaptable to the different application contexts that will be considered and the proposed algorithms will be designed to be efficient also from a computational point of view. The proposed methodology will show a significant degree of novelty, mainly due to the novelty of the proposed application scenarios, to the design of algorithms that must be able to satisfy the imposed constraints (e.g., quality, hardware), to the development of algorithms deriving from the joint use of machine learning and signal processing methods. Taking into account all the aspects mentioned above, the envisioned methodology includes diverse sets of algorithms, as described below.

A first set of methods is devoted to the quality enhancement of the audio captured by microphones. To this end, the geometric arrangement of microphones with

respect to the sound sources requires an accurate study that depends on the specific application. In stationary and controlled environments, arrays can be easily placed on fixed and even bulky supports and their dimensions are not an issue. In contrast, the array size may be required to be spatially limited e.g., when microphones are integrated in a portable device. However, regardless of the specific application, the arrangement and correct calibration of the microphones significantly affect the qualitative improvement of the audio signal. Methodologies to accomplish this task include: spatial filtering design for defining the optimal geometries of microphone arrays in well-defined environments; optimization algorithms for the selection of a subset of microphones for a fixed geometry; deep learning techniques for relaxing the geometrical constraints and the necessity of microphones calibration, and super-resolution techniques that use a priori information to increase the signal resolution.

Different natural and artificial artifacts usually affect the quality of the captured audio, including background noise, reverberation and interfering sounds. A first significant enhancement of the audio quality is provided by beamforming techniques, which aim at reducing the noise sounds coming from outside the sound field of interest where a desired sound source is located. Advanced space-time processing methods can be developed according to some general characteristics of the microphones employed (e.g., single microphone, distributed sensors, coincident microphone arrays). In a second stage, the residual noise can be further reduced by implementing signal enhancement algorithms to improve the audio intelligibility. Enhancement methods also include the plenacoustic representation, which provides a ray space image of the directional components of the sound field by using small sub-arrays among the employed microphones, machine learning techniques for dereverberation, as well as the separation of mixtures of sound signals.

The identification of the source position is fundamental to correctly recognize the nature of a sound and provide an accurate rendering of the audio signal that can be pleasant to the human listening. To this end, several methodologies will be involved for the sound localization, including binaural techniques based on HRTF, plenacoustic framework for distributed microphones, deep learning techniques for 3D sound localization.

Once signals have been acquired, enhanced and spatially localized, it is important to perform a description of the whole scenario with a high-level detail. An acoustic scene is characterized by particular sounds that can be associated with a specific event. Advanced machine learning algorithms can be developed to detect a well-known sound or even to identify an "anomalous" event that might represent a potential risk for human safety. However, the detection of an anomalous sound event should be followed by an adequately trained classification architecture to correctly evaluate the possible risks. To this end, novel deep learning solutions involving semi-supervised learning, data augmentation, and transfer learning strategies will be taken into account. Sound events can be further analyzed to describe a particular environment by "listening" to the sound rebounding in it. Such analysis, known as "acoustic scene understanding", can be performed by involving data-driven models, providing a scene classification based on the analysis of frames with different temporal depth.

The high-quality audio signal rendering for an enhanced experience is also included within the proposed methodology. In order to provide the user with a spatial perception of the augmented audio, several methods based on the HRTF will be developed. In particular, research efforts will be focused on the spatial audio rendering engine and its personalization, as well as on methods for personalizing HRTF according to the user preferences, by using morphing of data both from publicly available datasets and from real measurements. In order to improve directional cues of warning messages, low-latency solutions will be investigated involving time difference and interaural level difference. The audio rendering for augmented reality also involves adaptive equalization for acoustic transparency in headset reproduction. Indeed, novel equalization algorithms will be developed to make headsets perceptually transparent to specific external sounds, while providing at the same time an optimal reproduction of the infotainment audio message. Moreover, some procedures to automatically select desired sound events will be developed based on spatial filtering and advanced active noise cancellation, besides integrating the information provided by the acoustic scene understanding subsystem.

4 Conclusions

Digital signal processing brought exciting achievements and innovations in the audio domain, during the last fifty years. Among them, this chapter focused on advanced audio augmented reality solutions, involving both virtual audio sensors and transducers, to design enhanced spatial hearing experiences in diverse application contexts, spanning from entertainment to safety. According to the authors' knowledge gained in the field and future perspectives, all these innovative techniques will lead to new applications able to substantially improve quality of experience and comfort in people's daily life.

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Telecommunications in the ICT Age: From Research to Applications

Marco Baldi, Giovanni Cancellieri, Franco Chiaraluce, Adelmo De Santis, Ennio Gambi and Paola Pierleoni

Abstract The human society in the information age deeply relies on digital information processing, communication and storage. Photonic routing and switching is expected to be exploited in future all-optical networks. Channel coding is needed in order to protect information against natural disturbances, and modern coding schemes are able to reach the ultimate limits predicted by Shannon. On the other hand, post-quantum cryptography is necessary for assuring security against cyber attackers, possibly provided with quantum computers. Source coding, especially in video data compression, is recommended for optimizing the bandwidth usage. Spread spectrum systems can solve the problem of radio transmissions over common frequency bands. These technologies are of crucial importance for the evolution of networks and of the whole Internet, allowing people to interact each other and access information in the web. Nowadays, the conventional Internet of people has moved into the pervasive Internet of Things providing innovative services in a variety of application fields. In this respect, domotic systems, based on ambient and wearable sensors, appear of dramatic importance in the design of future assisted living protocols.

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1 Introduction

Digital signal procedures have replaced analog signal procedures in recent years. Such a transformation is clearly evidenced in the scientific production described below. Copper cables have been progressively substituted by optical cables in the transport network. Higher and higher radio frequencies have been employed in mobile telephony and subsequently in smart-phone services. Asymmetric Digital Subscriber Line (ADSL) and Very-high-bit-rate Digital Subscriber Line (VDSL) fixed connections linked users to central offices, up to the advent of a new organization in the access network. It is actually under deployment, being constructed on a completely passive support. This new infrastructure, called Passive Optical Network (PON), will guarantee an access speed up to several Gbit/s, by means of a solution named Fiber-To-The-Home. Since early seventies, relevant contributions to the study of telecommunication service availability in transport and access networks were produced, considering a micro-coaxial cable as a support [17]. Such technology was invented in Italy and gained some success around the world before the advent of optical fibres.

A telecommunication network is supported by a geographic infrastructure over which proper transmission protocols are implemented, according with the Open System Interconnection (OSI) 7-layer model, with particular attention to the first four layers. Any future evolution has to take into account that public services must be guaranteed to all the users with neutral access assurance. On such goals the true concept of Next Generation Network can be developed. This philosophy is a common element in what follows.

Such a digital revolution has implied significant advancements in various topics of the telecommunication world, that will be presented in the following sections. More precisely, the organization of the chapter is as follows. Section 2 deals with the study of optical transmission on multimode and monomode fibers. Optical switching and photon counting techniques are also discussed. Section 3 is devoted to reliable and secure digital transmissions. Channel error correcting codes are employed for assuring reliability and a secure physical layer is modelled against various types of cyber attacks. In particular, post-quantum cryptography based on proper codes is suggested for saving double-key cryptosystems from quantum computer threats. In Sect. 4 advanced systems for monitoring human activities in ambient assisted living are presented. They are based on TV signals, image recognition and data collection from distributed sensors. Section 5 is finally dedicated to interactions in wireless sensor networks, with particular attention to Internet of Things (IoT) applications.

2 Optics and Optical Communications

Research on optics and optical communications starts from an accurate description of the transmission medium and the electro-optical devices acting on it, then accounts for the systems and the networks which can be set up, finally faces the optimization in optical data packet routing and delivery. We can identify three main issues:

- multimode optical fibers and related optical sources with experimental measurements and tests;
- single-mode optical fibers and all-optical switching;
- optical networks and protocols.

All these aspects exploit the particular features which characterize an optical carrier for information transfer, which can be summarized in: high speed, good reliability, strong resilience against possible unauthorized information manipulation.

The study of time dispersion in multimode optical fibers has been exhaustively developed [20], considering also a proper diffusion equation for taking into account mode coupling [29]. Ray optics represents a valid model in order to simplify the description of optical power evolution along the fiber length on the trajectories imposed by a proper refractive index profile, when the propagating modes are in the order of some thousands [21, 24]. A double-α graded index profile has been proposed with the purpose of optimizing time dispersion performance [22]. This design solution is able to relax some construction trade-offs.

2.1 Multimode Optical Fibers and Related Optical Sources

The study of top-emitting Burrus type light-emitting diodes (LEDs) was developed, considering a model based on a circularly symmetric transmission line [30]. This theory is able to explain some well known phenomena regarding a time delay in the excitation of high-order modes in a multimode optical fiber [32]. Such process could induce remarkable performance degradation.

Measurement tests were carried out in cooperation with Centro Studi—Fondazione G. Marconi. They regarded modal differential attenuation, steady state reaching in loss contributions, the role of cables and joints [25], bandwidth evaluation in the frequency domain [26]. Transmission system designs, employing multimode fibers, have been treated when such links were firstly proposed in the transport network [28]. Different combinations of sources (LEDs or lasers) and detectors (PIN or avalanche photodiode (APD)) were compared. An exhaustive analysis of multimode fiber joints and in particular of their non-reciprocal behavior has been presented in those years [27].

2.2 Single-Mode Optical Fibers and All-Optical Switching

Single-mode optical fibers were modelled since 1985, with special attention to polarization mode dispersion [37], and effective cut-off wavelength of the first higher-order mode [31, 38]. Optical coherent transmissions and enhanced birefringence in order to select a single polarization have also been studied [23]. Spread spectrum systems at optical frequencies and photon counting procedures have been proposed [19].

Soliton propagation in single-mode fibers, exploiting the presence of a high peak power ultra-short optical pulse, has been described by means of non-linear temporal Schrödinger equation [33]. Very high speeds in the data flux appeared to be achievable.

Non-linear optics for modelling optical switching has been treated in the period 1985-89 with particular reference to four-wave mixing and optical frequency conversion [34]. Such type of devices has become commercially available products only very recently. All-optical spatial soliton coupling, in order to construct a polarization modulator, has been exploited [36].

2.3 Optical Networks and Protocols

Enhanced protocols were proposed for proper implementation on optical networks [15]. A multi-layered architecture has been introduced for future transport and access optical networks [16]. Graph theory and edge coloring have been exploited for the optimization of wavelength routing algorithms. Optical propagation and fiber communication systems were reviewed in a long invited paper devoted to show the state of the art in this important field of research and applications [35].

3 Reliability and Security of Digital Transmissions

Modern digital transmissions need to be reliable and secure. Reliability is related with the requirement to have a sufficiently low error rate at the receiver, in such a way the transmitted information is correctly interpreted and can be properly used. Security is related with the requirement to protect transmitted data from illicit interception, so preventing the possibility that unauthorized receivers can disclose the data. Reliability, obviously depends on the channel and the operation conditions. However, it can be usually improved by using well-designed error correcting codes. Commonly less known is the possibility to use error correcting codes also to achieve security, which can be done at the physical level, as occurs with the so-called *physical layer security* (PLS), or at higher level, as occurs with the so-called *code-based cryptography*. These issues will be discussed in the next sections.

3.1 Channel Coding

The invention of turbo codes in 1993 [14] has been a real breakthrough for the design and optimization of error correcting codes. By effectively exploiting codes concatenation and soft-decision decoding, turbo codes are able to approach the Shannon limit in several types of different channels. The distinctive feature of turbo codes is to present two distinct behaviors for the region of small signal-to-noise ratios (SNRs) and that of high SNRs. For small SNRs, that over the additive white Gaussian noise (AWGN) channel is typically expressed as the ratio between the energy per bit E_b and the one-side spectral density of thermal noise N_0, the error rate exhibits a waterfall behavior, which means it decreases by orders of magnitude with very small increase of E_b/N_0. For large SNRs, instead, performance is dominated by the code *minimum distance* d_{min} that, in case of linear codes, like turbo codes, is coincident with the minimum Hamming weight of codewords in the code: the larger d_{min} the better the performance. To determine d_{min} for a turbo code is often a a hard task. In [53] an algorithm based on the notion of constrained subcodes is proposed which permits the computation of d_{min} for large codes without set a constraint on the input sequence weight, the latter being a common shortcut to reduce complexity, which however produces only approximate results.

The original turbo code consisted of two recursive systematic convolutional codes, concatenated in parallel and with an interleaver between. But the turbo principle has inspired updating of many other, even classic, coding schemes that, thanks to the new idea have seen a significant improvement of the performance achievable. This is the case, for example, of product codes. In [42] the authors present a thorough analytical evaluation of extended Hamming product code performance in the low error rate regime, and a complete set of techniques covering all possible cases: normal, shortened, and punctured schemes.

Turbo-like codes have been rapidly included in many international standards. Among the first to address the adoption of the new schemes, there is the standard for telemetry (TM) synchronization and channel coding in space missions. Indeed, communication to and from a spacecraft or a probe travelling in the deep space is a privileged benchmark to test the effectiveness of an error correcting scheme. Valuable examples can be found in [18] where all relevant issues, including code rates, frame lengths, modulation formats, performance metrics, complexity, and others, are discussed for TM but also telecommand (TC) signals.

At present, the error correction scene is dominated by another instance of the turbo principle, which are the so-called low-density parity-check (LDPC) codes. These codes are characterized by the fact to have a parity-check matrix with a relatively small number of symbols 1. In this case, it is more proper to speak of belief propagation (BP) as the key algorithm for the decoder to reach a consensus about the estimated value of the received bits. In our research we have investigated several variants of LDPC codes including array convolutional LDPC codes [10], interleaved product LDPC codes [9], and others, up to the most recent spatially coupled LDPC convolutional codes [11] we are currently investigating. We have also proposed inno-

vative procedures to design quasi-cyclic low-density generator-matrix (QC-LDGM) codes [7] that, through the sparsity of the generator matrix, instead of the parity-check matrix, allow to have low complexity but also error floor performance better than that offered by other codes of the same class.

3.2 Physical Layer Security

Transmission security is often implemented at protocol layers higher than the physical one, by exploiting cryptographic techniques based on computation assumptions. Examples will be given in the next section. These schemes rely on the existence of one or more cryptographic keys that must be known by legitimate users and protected from eavesdroppers. On the contrary, when security is implemented at the physical layer, all receivers are perfectly aware of the encoding and transmission procedures, without the need of any shared secret. In this case, security is only based on the differences between the channels experienced by authorized and unauthorized users. On the other hand, exploiting these asymmetries often requires knowledge of the channel, while this assumption is not required in traditional cryptography. Therefore, physical layer security can be viewed as a substrate helping to reduce the complexity of cryptographic techniques at higher layers.

A well-known model to describe a PLS scenario is the so-called *wire-tap* channel, introduced by Wyner [83] in the 70's. According to this model, a transmitter (commonly named Alice), encodes a message vector into a codeword vector before transmitting it. Alice's transmission is received by a legitimate receiver (named Bob) and an eavesdropper (named Eve), and the channel that separates Alice from Bob is generally different from that between Alice and Eve. Therefore, the vector received by Bob is different from that gathered by Eve. Alice can adopt whatever randomization, encoding and modulation scheme, and both Bob and Eve are perfectly aware of the transmission technique she uses. On the other hand, because of the channels difference, the codeword vectors that Bob and Eve obtain after decoding can also be different. PLS is achieved when:

- Bob is able to reconstruct the original message.
- The message recovered by Eve has no significant correlation with the original message.

Over an AWGN channel, this explicitly means that the SNR value over Bob's channels must be sufficiently large to ensure a very small error rate for Bob (reliability constraint), while the SNR value over Eve's channels must be sufficiently small to ensure a very high error rate for Eve (security constraint). The error correcting code used in the system helps satisfying these constraints, but it is also required to reinforce the mechanism through the implementation of suitable supporting actions. A possibility consists in using systematic but punctured codes; in [3] we have shown that better results can be obtained by using instead non-systematic codes resulted by the application of a scrambling matrix.

The study of PLS requires to go beyond the error rate analysis, referring to concepts drawn from information theory. Though conceptually unquestionable, such an approach usually considers asymptotic conditions, that is, codes with infinite length and continuous modulations, which make difficult to evaluate concrete applicability of the proposed solutions. One of the merits of our research on this topic is the fact to have investigated more practical scenarios, by introducing security metrics working in the finite block length and discrete modulation regime. An example is in [5] where, additionally, the previous analyses on the wire-tap channel is extended by considering secret transmissions over parallel channels, under the assumption of knowing Bob's channel and having only a statistical description of the Eve's channel.

3.3 Post-quantum Cryptography

Contrary to PLS, cryptography acts at protocol layers higher than the physical one. The idea, in this case, is to convert ordinary plain text into unintelligible text, storing or transmitting data in a particular form, so that only those for whom they are intended can read and process them. Even if intercepted, encrypted data are useless for an attacker, since he is not able to disclose the information they contain. Obviously, this paradigm implies the availability of strong encryption methods, able to ensure, at least, computational security, that is, to guarantee that the secrets at the basis of the encryption procedures have a negligible probability to be discovered because of the limited (though possibly very large) computational capacity owned by the attackers.

Modern cryptography relies on the adoption of symmetric or asymmetric schemes. Focusing attention on the asymmetric solution, the secret is retained by only one of the parties (e.g., the receiver). From the secret key, another key is derived, which is publicly available (not secret) and from which the secret key cannot be derived. When the sender wishes to provide a message to the receiver he uses the public key. Only the owner of the latter, however, is able to decrypt the ciphered message, thanks to the secret key he knows. The roles of the public and private keys might be interchanged, but the general principle remains the same. Widespread examples of asymmetric systems are RSA (from the names of the inventors, Rivest, Shamir and Adleman) or the system based on discrete logarithms. Focusing attention on RSA, in short its security is based on the difficulty of finding the constituent factors in the product of two (very) large integer numbers. This problem is known to have a non-polynomial complexity, at least with conventional computational approaches.

RSA is used to secure web traffic, to ensure privacy and authenticity of email, to secure remote login sessions, and it is at the heart of electronic credit card payment systems. This scenario, however, is destined to change in the near future. In fact, recent advancements in the capabilities of quantum computers, while allowing to tackle significant computational problems in operating research and computational chemistry, also open an avenue to break the mathematical trapdoors on which current widely adopted asymmetric cryptography rely. The decoding of an error-affected codeword with a general linear error correcting code occupies a prominent place

among the most promising mathematical trapdoors withstanding an attack with a quantum computer. The use of a trapdoor based on decoding of a general linear code to build a public-key encryption scheme was pioneered in 1978 by Robert McEliece [56]. Such a cryptosystem has withstood around 40 years of cryptanalysis without seeing improvements in the computational effort required to break it beyond asymptotically vanishing terms. However, the large keypair sizes of McEliece's scheme, together with the non-negligible computational requirements still provide a hindrance for its use in tightly constrained embedded environments.

We have extensively worked on the subject and we have proposed variants of the McEliece's cryptosystem based both on classic families of codes, like Reed-Solomon codes [6], and on modern quasi-cyclic low-density parity-check (QC-LDPC) codes [4], obtaining significant reductions in the keypair sizes for a prefixed value of the security level. The most dangerous threat against code-based cryptosystems using QC-LDPC codes comes from reaction attacks. These attacks are able to recover the secret key by exploiting the inherent non-zero decryption failure rate (DFR) they exhibit and receiver's reactions upon decryption failures. In [75] we have proposed a special class of codes, known as monomial codes, which make reaction attacks not applicable, while in [8] we have applied countermeasures against non-profiled power consumption side channel attacks.

4 Signals and Systems

The results of the research activities in the TLC framework may be applied in very different contexts, due to the fact that all modern technologies are based on signals acquisition, elaboration and generation. In this section the research activities in the fields of ambient assisted living (AAL) systems, spread spectrum signals and coding of video signals are shown.

4.1 Unobtrusive Monitoring of Human Activities in Ambient Assisted Living

Population ageing is a growing phenomenon, especially in Europe, so researchers are developing active and assisted living solutions to promote ageing in place of elderly people. The objective of a research on active and assisted life is to develop tools with the aim of helping older people to live independently at home. In particular, human activity recognition algorithms can help to monitor aged people in home environments. One of the most critical issues for elderly people is represented by falls, and the development of fall risk estimation and fall detection tools can increase safety of elderly. The research focused on the developing of fall risk estimation and fall detection tools using data extracted from wearable, vision-based and radar-based

sensors. The interest in radar and RGB-D sensors is related to their capability to enable contactless and non-intrusive monitoring, which is an advantage for practical deployment and users' acceptance and compliance, compared with other sensor technologies, such as video-cameras, or wearables. Furthermore, the possibility of combining and fusing information from heterogeneous types of sensors is expected to improve the overall performance of practical fall detection systems [43, 46, 54], even if problems of synchronization arise [47]. However, the availability of skeleton joints simplifies the process of feature extraction from RGB-D frames, and this feature fostered the development of activity recognition algorithms using skeletons as input data, whose performances are evaluated on a large-scale dataset, through support vector machine (SVM) classification [44, 45]. Along with remote health monitoring, technological solutions remote assistance activities, like those related to chronical diseases, are of interest, and may be satisfied through a remote interaction with the patient, without a direct medical examination. Moving from these considerations, a system architecture is proposed for the provision of remote healthcare to the elderly, based on a blind management of a network of wireless medical devices, and an interactive TV set top box for accessing health related data [76, 81]. The selection of TV as the interface between the user and the system is specifically targeted to older adults. The idea is to create a unique interface towards both a cloud-based remote service for consulting of medical reports, provided by the regional Public Administration, and a personal local service that allows to collect and display data from biomedical devices, and to manage user's reminders for medicines [73]. With the use of enabling technologies, as near field communications, and a smart TV equipment, it is possible to effectively deliver telehealth services also to users who may be less familiar with technological devices, such as elder adults, or people living in rural communities [72]. However, the rapid growth of the IoT increases the interest in the application of this technology also in the domain of the environment assisted living. One major issue to address in this context is the identification of a suitable middleware able to leverage the potentialities offered by the IoT and, at the same time, ensure the necessary support to services and functions related to healthcare and personal assistance [50]. Due to its intrinsic nature, IoT may represent an 'integration platform' for AAL that includes features of home automation (energy management, safety, comfort, etc.) and introduces 'smart objects', to monitor activities of daily living and detect any abnormal behavior that may represent a danger, or highlight symptoms of some incipient disease, so overcoming the interoperability issues related to the interconnection of many different communication systems [74]. As a confirmation of remote monitoring effectiveness and usability, either from a patient's or a medical operator's perspective, an evaluation of a telemedicine approach has been performed by testing three remote health platforms, in a realistic scenario involving elder adults and medical operators (doctors and nurses), with the aim to evaluate the main positive and negative issues related to the system and service design philosophy each solution was built upon [79]. In the framework of an AAL solution, it may be of interest to evaluate if the user is spending too much time in a static condition, since this situation could denote an anomalous trend, possibly related to cognitive or physical conditions worsening. For such a kind of monitoring to be effective, the sensor technology

should be the less intrusive as possible, and should not require any specific action by the user. To this aim, a smart insole equipped with force sensors, that is able to classify different dynamic states (sitting, walking, standing, ...) and transmit related data to a supervising system is proposed in [49]. Preliminary experimental results confirm the effectiveness of the approach, in correctly detecting and classifying the user's activities [48].

4.2 Spread Spectrum Systems

Code division multiple access (CDMA) using direct sequence (DS) spread spectrum modulation provides multiple access capability essentially thanks to the adoption of proper sequences as spreading codes. The ability of a DS-CDMA receiver to detect the desired signal relies to a great extent on the auto-correlation properties of the spreading code associated to each user; on the other hand, multi-user interference rejection depends on the cross-correlation properties of all the spreading codes in the considered set. As a consequence, the analysis of new families of spreading codes to be adopted in DS-CDMA is of great interest. Results are provided about the evaluation of specific full-length binary sequences, the De Bruijn ones, when applied as spreading codes in DS-CDMA schemes, and their performance compared to other families of spreading codes commonly used, such as m-sequences, Gold, orthogonal variable spreading factor (OVSF), and Kasami sequences. While the latter sets of sequences have been specifically designed for application in multi-user communication contexts, De Bruijn sequences come from combinatorial mathematics, and have been applied in completely different scenarios. Considering the similarity of De Bruijn sequences to random sequences, the performance resulting by applying them as spreading codes are investigated. The results presented suggest that binary De Bruijn sequences, when properly selected, may compete with more consolidated options [77, 78, 82].

With the aim to propose new spreading waveforms able to increase the performance of CDMA systems, chaotic communication system and a spread spectrum system with similar features in terms of bandwidth and transceiver structure but based on more conventional Gold sequences are compared in the presence of noise and multipath contributions which degrade the channel quality. It is shown that, because of its more favorable correlation properties, the chaotic scheme exhibits lower error rates, at a parity of the bandwidth expansion factor [41]. A possible application of chaotic signals as an alternative to more conventional spreading schemes in direct-sequence spread spectrum (DS-SS) automotive radars is presented, being the radar a key component for road safety systems. Due to their very good correlation properties, chaotic sequences are potentially able to outperform previous options, like Gold codes, with regard to the detection probability and the number of available sequences. Numerical examples are given, in some typical scenarios and under severe operation conditions, due to the presence of interfering radars [51].

4.3 The Coding of Video Signals

Coding and encryption of video signal, to be used in video-communication systems, have been considered in the framework of a source coding activity. With the task to test the effects of the features implementation introduced by the video coding standard H.264, an extensive performance evaluation of spatial, temporal, and hybrid error concealment techniques was provided [58]. The quality of the recovered image was measured, and the comparison among the various schemes is developed, using the JM7.3 Reference Software, either in subjective or in objective terms [40]. The partial encryption of a bit stream was taken into account, with the aim to make the entire stream somehow useless for anyone that cannot decrypt its ciphered subset. The effects of the partial encryption was evaluated as a function of some H.264/AVC coding parameters, in order to obtain a moderate degradation of the video content, which can be appealing for commercial applications, like pay-per-view systems and others, without strictly focusing on security or cryptanalysis issues [80]. A chaotic algorithm which employed suitably arranged chaotic functions was presented for video encryption. The algorithm was implemented on a code which ensured real time transmissions, at 25 frames/s, of the images coming from a video camera. The efficiency of the algorithm was justified theoretically, and demonstrated through simulation examples. The algorithm permitted achievement of a high level of security with reasonable processing times [39].

5 Internet Evolution and the Internet of Things

The world of telecommunications has changed dramatically over the last 20 years, thanks to the combination of the digitalization of information and the unstoppable development of ICT technologies. The way in which today people communicate, get informed, entertain and interact with each other and with the surrounding environment is much more varied and rich than a few years ago. Communications are possible anywhere, with any device, on any channel, in a synchronized or non-synchronized way; they are traceable, lasting over time, personalized, multimedia and social. Furthermore, the disruptive effects of Internet diffusion has profoundly modified the global communication landscape. The Internet has been in concept in the 70s and its usage exploded about twenty year later when the World Wide Web application became broadly available with the arrival of the first commercial browser and server applications. Since that time, a huge quantity of contents and new applications have enriched the Internet, which has grown to reach more than 3.5 billion people. The Internet we experience every day is a complex combination of many elements such as transport networks, user devices, applications and services, held together by two main protocols: the Internet Protocol (IP) for the transport layer (including its control mechanisms: Transmission Control Protocol (TCP) and User Datagram Protocol (UDP)) and HyperText Transfer Protocol (HTTP) for the application layer. From the

so-called Internet of people, which we have known until today, we are experiencing a new revolution consisting of Smart Objects that become an integral part of the Internet environment to achieve the IoT paradigm. This trend is already underway as sensor networks connect to the Internet together with a large part of billions of mobile phones used worldwide. To this group, a myriad of devices of all kinds integrated into everyday life objects (home, office, portable, fixed and mobile sensors, etc.) will be added. The future of the Internet will be dictated by future applications and services scenarios, but the Internet is vital, continuously evolving, and it is difficult to predict its future. From a user perspective, the Internet has been transformed into a new media platform, as the nature of Internet traffic has changed from static data and text file transfer to streaming interactive media content (which is the main part of total Internet traffic). At the same time, the IoT provides a virtual view, via the IP, to a huge variety of real life Smart Objects, ranging from a car, to a seat, to a building, to trees in a forest. Its appeal is the ubiquitous generalized access to the status and location of any "thing" we may be interested in. To exploit this potential, telecommunications networks and services are taking a further step towards their transformation: from people and things to data connectors and the creation of associations between them through services for smart environments and more.

5.1 Wireless Sensor Networks and Smart Environments

In recent years, Wireless Sensor Networks (WSN) are becoming a very promising research field since they find application in many different areas. Thanks to what has been made possible by micro and nano-electronics, computing and communication technologies, over the next few years, billions of sensors will populate cities, homes, factories, devices and even clothes. Many of these will be integrated into devices with processing and communication capabilities, both wireless and wired, and many will become part of a new network layer, the sensor networks, characterized by the use of short-range, high-reconfigurability technologies, a certain dose of autonomy and very low power consumption. Nowadays, WSN are becoming even more a key element in networking and telecommunications especially with the advent of the IoT paradigm, where each single node of the WSN can obtain a unique IP address and it is potentially reachable from everyone, everything, and everywhere through the Internet. The IoT paradigm identifies a service model that makes possible to transform everyday life objects into Smart Object embedding computational capabilities, sensors, actuators and communication systems to detect and control a physical phenomenon or an event and exchange information about it with a cloud platform. The populations of the cities are already invested by these new phenomena. In fact, thanks to these sensors, the physical spaces of the cities are virtually filled with behavioral and environmental data in real time. In the so-called Smart Environment, a digital fabric overlaps with our physical world and extends to offer even richer experiences using the context of our environment to increase our capabilities. Explosive innovation and widespread adoption of smart and mobile devices, and the availability of rich

data sources are changing the cities in which we live, work and act. Thanks to an increasingly widespread computational capacity, urban spaces will be saturated with both visible and invisible means, which will collect and transmit information [55]. Smart Environment applications can be present in the most varied areas such as energy, ecology, transport, health and wellbeing, education, local government, security of the territory, cultural heritage, and tourism. Contextually, also our research studies about WSN and the IoT were successful applied and tested in a variety of case studies. Starting from the development and performance evaluation of protocols and complete architectures for IoT systems [57], we have demonstrated their potentiality in a series of application sectors such as environmental monitoring and control in the cultural heritage field [64], seismic and structural health monitoring [65], AAL [70], location services [69], e-Health systems [52, 67], and Wireless Body Sensor Network [1, 68]. In fact, the proposed IoT solutions can be used in many application fields with great success in terms of costs and resources optimization, variety of implemented features, level of customization and expandability of each solution.

5.2 Wireless Body Sensor Networks

The previous IoT architectures, based on WSN solutions, can simply allow the use of common web services in order to directly interact with each node belonging to the network, whether it is installed in the monitored environment or worn by a subject. In the field of Wireless Body Sensor Networks, we have developed wearable devices and network solutions useful for a series of real-time monitoring functions depending on the desired application and the placing site of the unit on a subject. We have studied and developed a conceptually simply device containing a 3-axes accelerometer, a 3-axes gyroscope and a 3-axes magnetometer, realizing an attitude heading reference system (AHRS). This AHRS provides the correct 3D orientation referred to the terrestrial axes through a special implemented orientation filter able to furnish the correct magnitudes evaluation starting from the raw data [59]. A typical application making use of a version of the previous device concerns the automatic falls detection in elderly. In fact, on the sensor board it can also be real time executed the automatic fall detection algorithm, handling the orientation data from the AHRS and the acceleration data from the tri-axial accelerometer [62]. Based on the excellent results achieved with the developed AHRS, a wearable sensor able to furnish the right altitude of a subject was subsequently proposed [63]. This device also embeds a barometric unit and implements an optimized data fusion algorithm for an extremely accurate fall detection, including a more effective discrimination of daily life activities from falls and a correct recognition of critical falls such as syncopes [60]. The AHRS has also been used as an aid to clinical diagnosis of Parkinson's disease (PD) [66]. The ability to objectively classify different types of tremor, specific for each patient and the evolutionary stage of the disease, through a simple, fast, low cost, and non-invasive instrumental examination is very useful for the diagnosis of the disease and for the study of its clinical course. The inertial sensors are embedded into a

special bracelet allowing the acquisition of the quantities of interest that, through appropriate algorithms, provide an objective and quantitative assessment of the type and severity of the observed tremor [12, 13]. This system is usable in clinical and diagnostic settings, but it can show its effectiveness also in patients home or hospital h24 monitoring. In fact, it is able to detect and objectively quantify PD events such as tremor and freezing of gait (FoG) and to transmit data of multitude of patients and make them available in the cloud.

So far, the history of the Internet has been incredibly successful in the development of technological innovations and telemedicine solutions are one of many examples in this regard. In such context, we have proposed innovative e-Health services for vital signs sharing based on the Web Real-Time Communication (WebRTC) technology that allows any person in a health emergency to remotely interact with the medical personnel [71]. Now, the challenge is to make the Internet able to provide an increasing quality of experience for the end-user and for those applications that will revolutionize our lives in the near future. The IoT is moving in this direction and it is also providing a valuable contribution to the growth of the tactile Internet. This term is used to refer to a data network with extremely low-latency in analogy to the human tactile system that works at extreme response speeds. In this regard, others experimental solutions have been proposed [2, 61] but the real challenge will be to develop data network able to deliver data within one millisecond latency. Such technology would enable previously unimaginable scenarios in automation and remote assistance and countless potential applications such as remote surgery, industrial control, high-precision agriculture, robotics, etc.

6 Conclusions

The transformation of research into practical applications is not always easy, and often requires several years. In this chapter, we have provided a survey for some of the most relevant challenges in this direction, in the field of telecommunications, clarifying the relationships between theory and applications. The main issues faced are summarized below. In communication technologies, information theory and channel coding, principles have to be implemented on proper electronic devices, whose cost does not prevent commercial success of the supported services. Similarly, the prediction of all-optical switches and spatial soliton behavior preceded their practical use by far. On the other hand, transmission security at physical level is a basic need for modern communications and the tools for assuring it are to be practically tested with proper attack simulation. Source coding, especially in video signals, and spread spectrum systems can make digital signals particularly efficient either in bandwidth saving or in interference managing. Monitoring of human activities is an enabling technology for ensuring population ageing preserving health and wellness. Practical solutions have been investigated attempting to insert them in suitable cloud-based protocols and interfaces. Internet evolution, up to the paradigm represented by Internet of Things, expresses a challenge in finding solutions which are reliable, scalable,

and low-cost. In particular, wireless sensor networks offer a great variety of opportunities for such evolution. Body sensors can reveal disease or accidents, especially for elder people, allowing accurate home control with acceptable cost and remarkable reliability. We have shown that all these topics have been properly addressed by the telecommunication group at the Polytechnic University of Marche.

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From the Control Systems Theory to Intelligent Manufacturing and Services: Challenges and Future Perspectives

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Abstract Control Science has played over time and still continues to have a key role for the development of human society such that, in the XX century, it has been recognized as an independent discipline. During the '50's, one of the first international scientific congress to address the area of control theory, namely, the "Convegno Internazionale sui Problemi dell'Automatismo", was held in Italy, at the Museum of Science and Technology in Milan, Italy. In this context, ten years later, the Automatic Control group of the Università di Ancona was born. In this chapter, we want to revisit the main results achieved in the last 50 years by the Automatic Control group of Ancona focusing, in particular, on the recent achievements about linear and nonlinear control; robust, stochastic, adaptive and optimal control; model predictive control; fault diagnosis and fault tolerant control; aerial, terrestrial and underwater unmanned vehicles control; automotive control; switching systems analysis and con-

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trol; underwater robotics; intelligent manufacturing and cyber-physical production systems. The contribution aims to provide the main challenges on these topics and their future perspectives.

1 Introduction

Control Science has played over time and still continues to have a key role for the development of human society such that, in the XX century, it has been recognized as an independent discipline. During the '50's, one of the first international scientific congress to address the area of control theory, namely, the "*Convegno Internazionale sui Problemi dell'Automatismo*", was held in Italy, at the Museum of Science and Technology in Milan and, in 1969, Università di Ancona was born.

During the last 40 years of its history, the Università Politecnica delle Marche (formerly Università di Ancona) has seen the group of automation and control engineering growing first as a branch of the school of Antonio Ruberti, one of the founding fathers of Italian Automation and Control disciplines, and successively receiving contributions from other cultural areas. During the first years after the establishment of the Faculty of Engineering, research focused on the one hand on systems theory and on the other hand on the application field of motion analysis. The activity in both fields, fostered and coordinated at the beginning by Tommaso Leo [1, 79, 80, 82, 113] and, respectively, Osvaldo Maria Grasselli [88–91], ultimately developed, with the contribution of other scholars, in the main scientific areas of control and automation engineering. As a result, this gave birth to several research laboratories, namely the Motion Analysis Laboratory, the Automation Laboratory, the Robotics Laboratory, the Advanced Robotics Laboratory, the Interconnected Systems Supervision and Automation Laboratory, the Laboratory of Modelling Analysis and Control of Dynamical Systems and the Domotic Laboratory.

In these years, the research group has expanded its research interests, by developing them towards significant applications in the various production and service

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sectors, with the general objective to make these sectors, with which the University is connected, grow stronger. As a consequence, several research areas added during time to that of systems theory, such as fault tolerant control, robotics, industrial automation and intelligent manufacturing. This evolution lead the research group to collaborate with various national and international groups, and to develop significant partnerships with important companies, thus becoming a reference in the regional and national development policies of what is now commonly called "Industry 4.0".

This chapter provides a quick overview of the main results achieved in the topics related to automation and control engineering, starting from the control systems theory up to the intelligent manufacturing systems, including the main areas of fault diagnosis and fault tolerant control, industrial automation and robotics.

2 Control Systems Theory

2.1 Time-Varying and Periodic Systems

The control system theory for linear time-invariant systems has been widely studied in the past and, thanks to the previous results, many researchers have made constant efforts to extend the theory to time-varying systems. The challenging problem of a time-varying system is that, the values of its output response depend on when the input is applied to the system. This is mainly due to the fact that the system parameters change as a function of time and, when these parameters periodically change in time, the system assumes a periodic behavior. The research group at the Department of Information Engineering started to investigate the time-varying and periodic systems starting from the 80's, contributing on the topics described in the following subsections.

2.1.1 Periodic Systems

In the field of linear and non-stationary systems, interesting results have been obtained from the Automatic Control group both for the analysis and for the control of periodic discrete linear time systems. In particular, a geometric theory of control was developed for this class of systems. A first step in this direction was made by extending the concepts of controlled invariant sub-space and controllability subspaces to the periodic case and introducing two new geometrical concepts, namely, the externally controllable subspace and the internally controllable subspace. Moreover, the notions of outer and inner controllable subspaces are allowed to derive the necessary and sufficient solvability conditions for the disturbance-localization problem with output or state dead-beat control and to give synthesis procedures for the solutions [92–95]. The existing periodic geometric theory is then supplemented with the notions of outer reachable subspace and controllability subspace [98].

In order to further investigate the analysis and control of this particular class of non-stationary systems, the concepts of zeros and poles have been introduced in the case of multiple input and output variables and without the hypothesis of reachability and observability with its multiplicity. For the zeros, three different notions were introduced, the zero of transmission, the zero invariant and the geometric zero. The analysis of these notions was then extended by introducing the notions of zero of input decoupling and of zero of output decoupling. As for the stationary case, these notions are strongly correlated with the structural properties of the system. Both for these new notions of zero and for the notions of zero of transmission, zero invariant and geometric zero, opportune ordered sets of structural indices were introduced and a new method of calculation of these zeros and of the relative structural indices was identified [96, 97].

2.1.2 Analysis and Control of Linear, Uncertain, Time Varying Systems

This is a particularly wide field of research including several topics: robust stabilization of time-invariant systems through switching control, supervised switching control of systems under highly variable operating conditions, gain scheduling control technique based on the perturbed frozen time approach for slowly time varying systems, numerically efficient LMI based robust stabilization of interval time varying systems, stability analysis of time varying systems in terms of "average" parameter variations, stability analysis and stabilization of linear uncertain polynomially time-varying systems, control of uncertain linear parameter varying (LPV) systems. The results of these topics can be found in [68, 103, 104, 108]. Among the above topics, it is emphasized the novelty and the importance of stability analysis and stabilization of linear uncertain polynomially time-varying systems. The new approach proposed is based on the physically meaningful assumption of a dynamical matrix with smoothly time varying elements. This makes it possible to well approximate the parameter variations with a polynomial time function, and, as a consequence, to transfer the uncertainty domain from the parameter space to the polynomial coefficient space. The significant advantage of this point of view is the possibility of dealing with uncertain plants whose parameters are not confined inside a relatively small region: unlike all the other methods, both parameters and their first derivatives up to a fixed order may take values over arbitrarily large sets and theoretically unbounded dynamical matrices can be considered.

2.2 Structural Methods for Analysis and Control of Complex Dynamical System

In many interesting situations, the standard paradigms of linear system and control theory can be suitably adapted or reinterpreted to deal successfully with dynamical structures which are much more complex than linear ones. In particular, the

structural and geometric approach originally developed in the linear framework have shown to be particularly effective in dealing with analysis and control problems that involve singular and neutral systems; time-delay systems; systems with time-varying or uncertain coefficients, nonlinear systems; hybrid systems; jumping (or impulsive) systems. The work done along this line by the researchers of the Università Politecnica delle Marche in the past 30 years has produced many key results in each of the above areas, it has provided valuable solutions to specific problems and, more important, it has contributed to the development of a better insight of solvability conditions.

A first step for extending structural methods was that of considering dynamical systems whose coefficients belong to a more general algebraic set than the field of rational number: namely to a ring. Dynamical structures such as delay-differential systems, parameter dependent systems, time-varying systems, uncertain systems can be conveniently modeled as dynamical systems with coefficients in a ring. The main advantage of this choice is the possibility of dealing with finite dimensional state spaces, although these are no longer vector spaces over a field, but modules over a ring. Finite dimensionality, make it possible to develop geometric structural tools and methods and to construct efficient computational procedures to synthesize solutions to several problems. In this way, solvability conditions for noninteraction and observation problems (including decoupling problems; model matching problems; tracking and regulation problems; inversion and functional reconstruction problems; observation and fault detection problems) that involve systems of the above-mentioned classes, as well as singular and neutral time-delay systems, have been stated and constructive procedure to find solutions have been given using algebraic and geometric algorithms [33, 38–42, 44, 46, 47, 51, 125–130]. This work has in addition contributed to define suitable notions of zeros and of relative degree in the considered situation and to understand their structural and dynamical meaning.

Application of structural methods to nonlinear dynamical systems was also successful in providing solutions to classical control problems [121, 133]. Further developments were made possible by exploiting the use of differential algebra and related methods in dealing with nonlinear differential equations. This approach was pioneered in [43] and completely developed in [34] and in its second revised edition [36]. The book was translated in Slovak [35] and more recently in Chinese [37]. The differential algebraic perspective is complementary to, and parallel in concept with, the classic differential-geometric point of view. In many cases, it makes possible to derive specific results that would be very difficult, if not impossible, to obtain by a different approach. The main topics discussed in [34, 36] include: the realization of input/output maps in a nonlinear context; the analysis of accessibility and observability properties within a differential-algebraic setting; the discussion and solution of basic feedback problems, like input-to-output and input-to-state linearization, noninteracting control and disturbance decoupling, together with results about dynamic and static state and output feedback.

More recently, the interest focused on switching and on jumping (or impulsive) systems that model complex, hybrid dynamical structures. In extending structural methods to this framework, stability issues have been taken into account. This has

provided original solvability conditions and procedures to synthesize solutions to output regulation, disturbance decoupling and model matching problems for switching systems [45, 48, 123, 131, 160, 161] and for jumping systems [50, 132, 162, 163]. Observation problems have been tackled using a dual, in a sense, approach, obtaining new insightful results on the construction of observers both for switching [49] and for jumping systems [52].

2.3 Optimal Control Techniques

In the field of optimal control, the research activity has been developed along different lines with the purpose of providing methodological contributions advancing the state of the art in the respective appliances. The main research topics of the research group of Ancona, addressed during the years, belong to the following lines of research:

- Event based sporadic control [105].
- Achievement of a very accurate transient tracking through numerically efficient techniques [107, 109, 110].
- Efficient implementation of the pseudo-inversion method for the solution of constrained optimal control problems [111].
- Near decoupling problem for linear, possibly uncertain, plants [106].

2.3.1 Event Based Sporadic Control in the Case of Unmeasurable State

This line of research concerns the so called "sporadic control", which is of a paramount importance for networked control systems. The purpose of sporadic control is to reduce the network occupation without appreciably degrading the control system performance. Many authors considered this problem in the general framework of event-based control and proposed several communication logics (CLs) whose common feature is invoking a message among the control system components only if a "significant" event occurred. The main drawback of these methods is the restrictive assumption of a measurable state. This hypothesis is removed in the proposed event-driven CL. The SCL is based on the computation of a quadratic functional of the tracking error and of a corresponding time-varying threshold: a network message from the sensor to the controller is triggered only if the functional equals or exceeds the current value of the threshold. The CCL is directly driven by the SCL: the dynamic output controller sends a feedforward message to the plant only if it has received a message from the sensor at the previous sampled instant. Formulation of the controller in discrete-time form facilitates its implementation and provides a minimum inter-event time given by the sampling period. Future developments concern the extension of the proposed event based sporadic control to the class of LPV systems affected by noisy parameters measurements.

2.3.2 Achievement of a Very Accurate Transient Tracking Through Numerically Efficient Techniques

Achieving a very accurate transient tracking is a long standing problem which has been generally addressed using stable inversion techniques. Classic stable inversion methods are very complicate and require a very long pre-actuation which tend to infinite for near non hyperbolic systems.

To alleviate these drawbacks, the so-called "pseudo inversion" approach, has been proposed. The stable inversion of the possibly non minimum phase plant is obtained as the solution of an optimal control problem. The control input is "a priori" assumed to be given by a piecewise polynomial function. Once the desired trajectory to be tracked has been specified, this allows the computation of the parameters describing the unknown input as the approximate least squares solution of the Fredholm's integral equation corresponding to the explicit formula of the output forced response.

The main advantages of the pseudo inversion approach are: (1) the initial conditions can be arbitrary and possibly uncertain; (2) the method does not require pre-actuation; (3) the approach can be extended to the class of non-hyperbolic systems; (4) the method applies to the more general tracking problem of a switching reference; (5) the approach allows the definition of a multi-functional for the simultaneous fulfillment of several control requirements. Future developments concern the application of pseudo-inversion approach to Model predictive Control (MPC). The purpose is to reduce the technical difficulties deriving from two typical and major issues of MPC: the complexity of stability analysis and the very demanding computational effort due to the on-line optimization.

2.3.3 Efficient Implementation of the Pseudo-inversion Method for the Solution of Constrained Optimal Control Problems

This topic is the natural continuation of the previous one. Shaping the external reference and the control effort as B splines functions allows the development of very efficient pseudo-inversion algorithms for the solution of constrained optimal control problems. The key point is to translate hard constraints on some physical variables to hard constraints on their optimal approximations. If the approximation is really satisfactory, also the actual control variable is expected to exactly satisfy the constraints. To this purpose, B-splines have been used because of their appealing features: (1) they belong to the convex hull generated by control points, (2) B-splines are defined in such a way to automatically satisfy the continuity constraints at knot points. Property (1) can be exploited to impose the approximating spline to exactly satisfy hard constraints. Property (2) can be exploited because it allows an arbitrary increase of knot points without increasing the number of continuity constraints to be satisfied. These features allows the B-spline to practically overlie the function to be approximated.

2.3.4 Near Decoupling Problem for Linear, Possibly Uncertain, Plants

This research line concerns the near decoupling problem for linear, possibly uncertain, multivariable plants. This problem consists of achieving an independent set point tracking for the controlled outputs and is of a fundamental importance for industrial applications.

In this regard, a major critical issue to be faced is the complexity of the design procedure of a MIMO controller simultaneously fulfilling both the usual control specifications and the further requirement of a nearly decoupled closed-loop output response. The new proposed decoupling scheme is given by a closed-loop control system endowed with a twofold feedback loop. The internal feedback action is designed to satisfy the usual control requirements, the purpose of the external feedback loop is to yield an overall control system with an enhanced degree of approximate decoupling, still keeping internal stability. In this way, the usually complex design procedure for the simultaneous achievement of common control specifications and near decoupling is decomposed into two independent and simplified sub-problems.

3 Fault Diagnosis and Fault-Tolerant Control

The increasing availability of sensors of reduced dimensions, good performances and at low cost, together with the exponential growth of computational power of modern microcontrollers, have been modifying the way in which automation is designed. The classical automation pyramid, which separates the field, control and supervision levels is now evolving into a more comprehensive and fuzzy paradigm, in which field, control and supervision levels strictly interact together. This new paradigm permits to address new challenges, and among them one of the most promising is to cope with faults in real-time, in order to increase reliability and autonomy of the controlled/supervised system. From a formal point of view, a fault can be seen as an unforeseen deviation of at least one characteristic property of the system from the acceptable, usual or standard condition [102]. A Fault Detection and Diagnosis (FDD) system is thus responsible for detecting possible faults before they degenerate into a failure, i.e. a permanent interruption of a system to perform the required fucntion, and to provide information on the faults (such as time of occurrence, magnitude, severity). A FDD system can therefore be thought of as a data processing system based on information redundancy. Depending on the type of data and how they are processed, FDD methods can be classified into three categories [72]: model-based (or online data-driven), signal-based (or data-driven) and knowledge-based (or history-data-driven). Once a fault is correctly detected, isolated and identified, it is possible to exploit its knowledge

- in the so-called active fault-tolerant control paradigm, where the control law is modified in order to guarantee the satisfaction of desired specifications even in presence of the fault;
- at supervision level, for condition monitoring and/or prognosis purposes.

The first papers on fault diagnosis and fault-tolerant control of dynamical systems were published in the early 70's: from that time on the interest of the scientific community increased and now it is regarded as a specific field of research. The research group at the Department of Information Engineering started to investigate these aspects in the first half of the 2000s, and focused its activities on the following topics: model-based fault diagnosis and fault-tolerant control, and data-driven fault diagnosis.

3.1 Model-Based Fault Diagnosis and Fault-Tolerant Control

This activity concerns the study and implementation of algorithms for the detection and isolation of faults, affecting the input or output channels, in the case of systems described by specific models, both linear and nonlinear. For the linear case, the main results regards the methodology, and in detail the use of the geometric approach to solve the problem of detecting faults in periodic discrete-time systems [114, 115]. An observer-based residual generator is designed in [136], where each residual is sensitive to one fault, whilst remaining insensitive to the other faults that can affect the system. In case the linear system is affected by non-Gaussian noise, the state estimation and thus the fault detection results a challenging problem which could be improved using a Kalman-like filtering approach [78]. For the nonlinear case, the main results are of applicative nature, and related to the use of nonlinear observers to detect faults in unmanned vehicles [83, 85], and the use of structural analysis to detect and isolate faults on unmanned ground vehicles [118, 119].

Once a fault is correctly diagnosed or estimated, it is possible to exploit the information contained in it to modify the control algorithm. By following a model-based approach, the study and implementation of fault-tolerant control algorithms have been investigated in the case of systems modelled by nonlinear differential equations. This activity is mainly focused on adapting existing techniques in order to apply them for the control of unmanned vehicles. Marine vehicles, ground vehicles and aerial vehicles have all been investigated: a brief description of the main results is proposed in the following. In [112] the problem of fault tolerance is faced on a specific unmanned aerial vehicle, namely a quadrotor vehicle, in case of actuator loss. The paper proposes a solution to this loss of control action by spinning the vehicle in the yaw direction, thereby maintaining flight control of a spinning vehicle: flight control is achieved through the combination of robust feedback linearization and H_∞ loop shaping technique. When the vehicle has more actuators than degrees of freedom, control allocation can be used to deal with faults without modifying the control law [70]. This is the case faced in [4], which presents a strategy for trajectory control of a Remotely Operated Vehicle (ROV) in case of actuator failures: Dynamic Surface Control is used to achieve trajectory following, where a fault-tolerant allocation policy is used to distribute the load on the motors, assuming that the fault information is known. In [69], an actuator fault-tolerant control scheme, composed of the usual modules performing detection, isolation, accommodation, is proposed and designed for a class of nonlinear systems, and then applied to an underwater remotely operated vehicle used for inspection purposes.

3.2 Data-Driven Fault Diagnosis

This research activity takes into consideration the study and implementation of algorithms for the detection and classification of faults for systems where a significant input-output dataset of samples is available. From a methodological point of view the research involves mainly statistical analysis, while the application fields are that of rotating machines and industrial plants.

In detail, [24] proposes a new method, called *Statistical Spectral Analysis*, which allows robust diagnosis of faults in rotating machines by analysing a data set, even in case of poor signal-to-noise ratio, different time segmentation and different operating conditions. The research on industrial plants, instead, aimed at finding solutions to overcome to the growth of complexity in the analysis of process faults that typically involve many variables and where variables may exhibit a slightly different behaviour from the training case due to different environmental and/or operative conditions. The system combines the Principal Component Analysis (PCA) approach, Cluster Analysis and Pattern Recognition techniques [146]. The development of a rigorous way to determine the dimension of the PC subspace is a major contribution of this research which is particularly effective when approaching fault diagnosis problems with PCA techniques in real contexts such as refinery plants. The proposed Principal Component (PC) selection method is based on the statistical test ANalysis Of VAriance (ANOVA); furthermore, an innovative procedure based on the power spectrum of the input signals, provides adaptive thresholds used to identify a fault condition. Finally, Cluster Analysis and Patter Recognition has been combined to develop an automatic procedure, implemented in a Fuzzy Fault Classifier. Classification of the most probable faults has been performed taking into account the data correlation by the use of the Mahalanobis distance metric [142]. This sensitively increased the performances of the overall system.

4 Industrial Automation

4.1 Model Predictive Control

The research activity of LISA (Laboratory for Interconnected Systems Supervision and Automation) is focused on the study of Advanced Process Control (APC) techniques aimed at applications oriented to energy efficiency achievement and improvement for energivorous process industries [148]. Studies about theoretical and practical aspects of APC have been conducted, focusing on Model Predictive Control (MPC) techniques. A proprietary APC framework based on a two-layer linear MPC architecture has been developed, based on a linear state space approach that provides an explicit time delays compensation. The developed APC scheme has been suitably characterized: innovative contributions concern a coherent and consistent formula-

tion of the two MPC modules within the two-layer scheme, together with improvements on the online cooperation policy between them [152]. Specific methodologies for parameters and constraints changes handling have been formulated and infeasibility prevention has been achieved [155]. Additional contributions about input-output time delays handling have been provided. In particular, in order to perform an efficient handling of critical situations due to the presence of different time delays on single inputs-output channels, the lower layer of the MPC scheme has been redesigned performing a structural decoupling on output variables constraints softening [151]. Additional innovative contributions in the controller formulation concerned the online inhibition of selected control inputs with respect to defined outputs [154] and the online introduction of process variables status values [124]. In the developed APC framework, a status value for each process variable has been introduced and included in the two-layer MPC formulation, in order to correctly manage the process variables in all conditions. An innovative unified approach has been formulated for the inhibition specifications and the status values information related to control inputs and outputs [153]. The developed APC framework has been customized for its installation on real industrial processes, represented by steel industry billets reheating furnaces and cement industry clinker rotary kilns. These processes are characterized by high energy consumption and large energy efficiency margins have been observed [147]. With regard to steel industry billets reheating furnaces, specific needs for the plants conduction have been taken into account and a customized APC framework has been developed [3]. Considering the lack of information on billets temperature within the furnaces, a virtual sensor based on a first principles adaptive nonlinear model has been introduced. In order to introduce the billets temperature information within the customized linear MPC scheme, a Linear Parameter-Varying (LPV) model has been accordingly derived [149]. Methodologies for online adaptation of the time horizons have been provided. Furthermore, as additional issue, an ad hoc stoichiometric ratios control method has been developed introducing a tailored linear formulation [153]. The formulated control method for steel industry billets reheating furnaces has been awarded with an Italian patent. Up to now six installations on reheating furnaces located in steel industries of various European countries have been commissioned. In all real applications energy efficiency certificates have been obtained, together with improvements on process control. The developed APC systems received the Industry 4.0 Certification. The customization of the developed APC system for the cement field confirmed the validity of the proposed constraints softening decoupling strategy oriented to time delays handling [151]. An additional contribution has been provided with regard to the usage of sporadic feedback information related to clinker quality (free lime laboratory analysis) in the MPC scheme, establishing a direct relationship between the sporadic feedback and the constraints of selected control inputs [157]. The customized cement industry APC system has been installed on several cement industries [158]. The resulting fuel specific consumption reduction allowed obtaining energy efficiency certificates [156].

4.2 Robust Control Design

This research activity was carried on for several years as the result of cooperation between Università Politecnica delle Marche and Università di Camerino. In addition to the authors of the present contribution, the scientific activity involved several researchers in both universities, whose names can be found in the references list. The main subject of this partnership has concerned the control of electrical, electromechanical and robotic systems characterized by a considerable degree of uncertainty. The most significant results have been achieved in the field of robust control design for Electrical Drives and for Wind Energy Conversion Systems (WECS).

4.2.1 Electrical Motors

As is well known in literature, parametric uncertainties and disturbances are a crucial issue when dealing with electrical motors control design. As a consequence, a robust control approach is needed to have a feasible control system with satisfactory performances. Another important aspect to be considered is the introduction of suitable observers, or estimators, to get an estimation of mechanical variables not convenient or impossible to be measured, such as the rotor speed. In order to cope with these topics, in [62] a robust speed estimator has been presented, to get the rotor speed using the position measurements supplied by an encoder. The proposed estimator, based on a sliding mode approach, guarantees a bounded estimation error and good performances, as fare as tracking precision is concerned. The solution reported in [62] has been extended in [23], by the introduction of a neural network aimed at evaluate the system uncertainties, obtaining a significant improvement in the overall control system performances. Finally, the contribution [61] is based on a suitable and innovative sliding mode observer-controller couple, ensuring the estimation and tracking errors boundedness.

4.2.2 Power Converters

Power electrical devices have been given a growing attention in recent literature, since they can be used in several applications and their features make possible a better use of the electrical energy. Also in this field it is essential to develop robust control strategies, in order to improve the system performances. In the paper [26], the classical passivity based control techniques have been extended and applied to boost converters operating in an interleaved mode, while a similar approach is introduced in [28] for converters operating both in CCM and in DCM mode. Finally, in [27] a unified current observer is presented for sensorless control of DC-DC converters.

4.2.3 Wind Energy Conversion Systems

Control problems for Wind Energy Conversion Systems (WECS) has been the more relevant activity carried on within the research collaboration between Università Politecnica delle Marche and Università di Camerino. In particular, wind turbines with variable speed have been considered, in order to make wind turbines to work at the maximum efficiency point for a large range of wind speeds. As a first contribution, paper [64] solves the problem described above without using any wind measurements, by the introduction of a robust sliding mode observer of the aerodynamic torque. This observer generates the reference signal for the field-oriented control system, regulating generator electrical currents, in order to supply the required electromagnetic torque. As a development of this approach, a robust fully sensorless control system for wind turbines equipped with a permanent magnet synchronous generator is presented in [63], whose extension to the case when the drive-train is present is proposed in [65].

Another important aspect of WECS control concerns the high wind speeds region, the so called region 3, where control of blade pitch is typically used in order to limit the captured wind power, so that safe electrical and mechanical loads are not exceeded. In [66], a wind robust observer and a sliding mode pitch controller are used, in order to minimize the error between the rated wind turbine power and the actual one.

Finally, the problem of faults in the generator electrical currents is solved in [67], using a robust control approach.

It is worth to be noticed that the work on WECS has been supported by the National Grant PRIN 2015, called “Smart Optimized Fault Tolerant WIND turbines”.

5 Robotics

Research and development of robotic systems has been attracting the interest of both the academic and professional world since the early 60’s, when robots were employed for the very first time in industrial applications. Since then, they have experienced an exponential growth, which led to modern robotic systems ranging from industrial to medical, and from exploration to service applications. The research group of Università Politecnica delle Marche focused its activity mainly in the fields of marine robots, wheeled robots, robotic manipulators and assistive robots.

5.1 Marine Robotics and Applications

Almost all activities that are carried on nowadays in marine research and in marine industry make use of robotic systems and platforms. In this field, problems to face are numerous and more difficult if compared with those encountered in other application areas of robotics. In the past 25 years, the research activities carried on at

the Laboratory on Modelling, Analysis and Control of Dynamical Systems (LabMACS) of the Department of Information Engineering of the Università Politecnica delle Marche have addressed control, modelling and data acquisition and processing problems that are related to the construction of Navigation, Guidance and Control (NGC) systems for unmanned underwater and surface robotic vehicles.

In 1999-2001, the LabMACS team coordinated the National Research Project "NGC VERAS: Navigation Guidance and Control of Robotic VEhicles for Submarine Activities". The project addressed several problems in control and guidance of underwater unmanned vehicles and, in that framework and in the following years, the LabMACS team concentrated on the study of different control laws for depth control, attitude control and trajectory tracking of underwater vehicles exploring the potential of various nonlinear, robust and fuzzy control techniques. Visual control techniques for navigation and guidance and the use of acoustic sensors for positioning and obstacle avoidance [29, 32, 54–57, 137, 150] were also investigated. The project put the basis for a strong cooperation between national research groups that continues today.

In 2006–2008, the LabMACS team took part in the "VENUS: Virtual ExploratioN of Underwater Sites" European research project. The aim of the project was to set new standards in the use of robotic tools and methods in the exploration of underwater archaeological sites. The LabMACS team contributed significantly to the development of advanced best practices in the exploration of fragile underwater environments and of scientific methods and tools for their reconstruction in virtual reality. These results were achieved by introducing logic feedback loop in the execution of exploration missions and in merging navigation information with visual and acoustic images of the explored site in order to facilitate its 3D reconstruction [31, 74–76, 140]. Cooperation between European partners with expertise in various disciplines produced practical efficient procedures for the use of underwater robots and control technologies in underwater archaeology and it fostered further advances in that discipline.

More recently, starting from the experience of several missions at sea, the LabMACS team coordinated the National Research Project "ROAD: Robotics for Assisted Diving" [53]. The aim of the project was to develop robotic and automatic devices and systems to monitor the behavior and the physiological conditions of divers during the dive. The main product was the development of a wearable patented device [Italian Patent n. 102015000053133] that, evaluating the response of a subject to a flickering light, can detect abnormal and dangerous stress conditions [135]. Other results are related to the development of a hybrid surface/underwater robotic platform consisting of a small autonomous surface vehicle (ASV) that can deploy and recover a micro underwater vehicle (micro-ROV) [30]. The platform serves to collect behavioral and physiological data of divers to be sent to a remote supervisor and to provide assistance in moving and positioning in the underwater environment.

Activity has further grown in recent years thanks to participation in a number of European research projects (EPOCH [143], Sunrise-OptoCOMM [20]; Green Bubbles [139, 159]; Lab4Dive [141]; EUMR-Marine Robotics) and cooperation with

the Interuniversity Centre for Marine Environment-ISME, the NATO and the Italian Navy. The main results are the development of electro/optical underwater modes for the construction of underwater communication networks that may support an IoT structure in the underwater environment; the development and testing of data acquisition procedures and data processing algorithms that can produce accurate, geo-referenced 3D reconstructions of underwater sites during the mission time; the study and development of underwater scooters that can assist divers in a number of tasks.

Thank to cooperation with marine biologists, archaeologists, oceanographers, professional and recreational divers, the research effort in the framework of the above-mentioned projects has contributed to enhance the use of robotics and of control technologies in scientific and industrial communities that operate in the marine and underwater environment. To promote further this action, the LabMACS team has recently engaged in the development of innovative curricula and tools to teach eSTrEM (environment Science Technology robotics Engineering Math) in a comprehensive STEM education framework. The primary product of this work is a biomimetic underwater autonomous robotic vehicle (AUV) that replicates the aspect and the locomotion system of a fish, developed, in cooperation with the Department of Industrial and Mathematic Sciences Engineering, within the OpenFISH.science Project. The AUV is a cost effective, modular and highly extensible platform that students can use to design and test new technologies for underwater robotics and its applications in exploring, surveying and the monitoring underwater environment [22, 71, 138].

Always remaining in the field of Marine Robotics, the activities carried out at the Robotics Laboratories focused instead on the control of single and multiple vehicles. In detail, in collaboration with Snamprogetti for the development of an underwater vehicle, various control systems were analyzed and developed taking into account that the dynamic model of the vehicle is non-linear and with parameters strongly dependent on operating conditions [58, 100, 116, 117]. The formation control of a fleet of unmanned underwater vehicles is faced in [84]: a networked decentralized model predictive control algorithm is developed, which can cope both with communication faults and vehicle faults, namely when the communication between two vehicles is lost or one of the vehicles can no longer function properly. Recent results regard the development of a control strategy to face the dynamic positioning of an offshore supply vessel [6].

5.2 Wheeled Robots

The main research activities on wheeled robots are related to the problems of localization and navigation, and the main results are described in [2, 13, 73, 101]. In detail, [2, 73] propose the LabMate mobile robot and its real-time system for the solution of the tracking problem in a real context with environmental disturbances and parameter uncertainties. Localization is performed by using internal sensors like odometers and

optical fiber gyroscopes, and three simple localization algorithms based on different sensor data processing procedures are presented in [101]. A modular navigation solution for electric wheelchairs is proposed in [13] by using commercial and low cost devices.

5.3 Robotic Manipulators

Robotic manipulators have been designed in order to replace workers in challenging industrial activities, such as moving heavy or dangerous objects, assembling mechanical structure, and others. At present, industrial robots are transforming into collaborative robots, and both kinematic resolution and dynamics control are increasing their importance.

5.3.1 Kinematic Control

In [86] the redundancy analysis of two cooperative manipulators is presented, showing how they can be considered as a single redundant manipulator through the use of the relative Jacobian matrix. In this way, the kinematic redundancy can be resolved by applying the principal local optimization techniques used in the single manipulator case. In [122] the problem of cooperative manipulation of a rigid object when the manipulators are subject to joint constraints and priority task policy is faced. In [87], instead, a scheme is proposed for the fault-tolerant control of a two-arms system subject to faults on the actuators: the scheme provides both fault estimation via non-linear observers, and compensation at the kinematic level.

5.3.2 Dynamics Control

In [59] a discrete time sliding mode controller has been coupled with a robust observer, able to make an on-line estimation of the uncertainties characterizing the plant. This solution allows to improve the control system performances, especially when load variations or torque disturbances are present. A different approach is presented in [60], where a sliding mode controller, coupled with an efficient training algorithm for neural networks, based on Kalman filtering, guarantees the boundedness of the tracking error also in the presence of large parametric uncertainties.

5.4 Assistive Robotics

Assistive technology is defined as any item, piece of equipment, or product, whether acquired commercially, off the shelf, modified, or customized, that is used to increase,

maintain, or improve the functional capabilities of individuals with disabilities [13]. The research activity on assistive robotics is projected towards human-robot cooperation, such that people who need assistance can be monitored by service robots [5] or in assisted environments [120], localized indoor [25], assisted during rehabilitation [21] and supported during their movements [13, 81].

6 Intelligent Manufacturing

6.1 From Control Theory to Intelligent Manufacturing

Control theory made significant strides in the last 100 years, since fifties (a few years before the foundation of the Università Politecnica delle Marche) the new mathematical techniques made it possible to control, more accurately, significantly more complex dynamical systems than the starting ones. The complex control processes that regulate the daily life of the human beings have represented a motivation and a blueprint not only for the control theorists but also for the modern robotics and automation disciplines, the information and communication technologies, the computer science, and eventually the artificial intelligence. All the former disciplines, since a decade, have been collected under the unified framework of the cyber-physical system (CPS) modelling and design. CPS are at the groundings of the new developments in all the entities of the systems that range from the single mechatronic or electronic device to the large scale of hierarchies and interconnected networks of them. Such systems and their complexity are studied today with a system of systems approach in the context of the Industry 4.0 and the automotive sector.

In the previous context, Bonci et al. [17] proposed a lightweight framework for the modeling, control, simulation, planning, optimization, and scheduling of industrial processes. It is based on the pervasive use of relational database systems that actively support the transmission, storage, and elaboration of information across the multidimensional levels defined in the new reference architecture RAMI 4.0 that covers all the ranges from sensing and actuation to the management of a network of enterprises across the whole life-cycle and sustainability issues. It was developed to include new generation of mechatronic actuators [19], smart sensors and multiagent systems [14], but mostly the proposed infrastructure and framework is the key enabling prerequisite for the inception of new computation means in the CPS as the systems of systems. In [18], with the use of proper distributed and recursive computation approaches, the complexity of the control of the CPSoS (cyber-physical systems of systems) is attacked through a unified and human-centered simple framework that introduces the automation of the management by means of knowledge-based performance metrics. The technique has been already challenged in industrial robotics [99], in highly flexible and human-centric manufacturing [144], in service processes [145], and in the construction and building automation sector [134].

The former technique is also a fundamental tool in the new grand challenges of the management cybernetics, which needs the introduction of embodied artificial intelligence at the core of the CPSoS seen as viable living system [16], constituted pervasively by autonomous multiagent systems [15].

6.2 How Control Theory Has Influenced Automotive Manufacturing: Case Study

Automotive is key relevant in the European manufacturing system. Intelligent Manufacturing and Services in Automotive will be more and more pervaded by intelligent control systems supported by ICT technologies. Over the last decades the automotive sector has been experiencing great technological innovation contributing to improve performance, efficiency and mostly, vehicle safety. This also thanks to the support of the control systems theory. Thinking about the near future, we expect autonomous and connected cars to make their way onto the roads with consequent benefits of reduced accidents as well as better traffic management and driver comfort. A virtuous trend is being established among technologies providers, manufactures and governments such that it is encouraged the need for enhanced regulations making important safety features mandatory for vehicles. An example of what EU (European Union) proposes in order to reduce deaths and fatal injuries on the roads is reported in [77]. Among innovative safety devices, in the spotlight are the Intelligent Speed Assist, the Advanced Driver Assist system and the Intelligent Emergency Braking. These devices will strengthen the vehicle safety by collaborating with wellknown active systems such as ABS (Anti-Lock Braking System), TCS (Traction Control System), ESC (Electronic Stability Control System) for cars or MSC (Motorcycle Stability Control).

Notoriously, the evolution of the technological trend for cars have also paved the way for two-wheeled vehicles, although with some delay. Indeed, starting from 70', when BMW conceived the first helmet as passive safety system for the rider, commercial motorcycles deployed their first ABS only in 1988, by the same manufacturer, the TCS in 2008 and the first stability system controller (MSC) in 2014. Nowadays, top level devices such as the MSC, are far from being regulated for two-wheeled vehicles and their deployment is still prerogative of high-end motorcycles.

In addition to safety issues, the impact of the vehicles on the environment is no longer considered as a feature of secondary importance. The Eco-friendly requirement is leading to an increased share of market of electric cars and that is expected to happen to motor-cycles as well. Even though the concept is not new in the field, advanced traction systems for motorcycles with electric actuation may become appealing if we look at the proven benefits brought by the active torque distribution in a four-wheeled car.

In this scenario, the automation group of the Università Politecnica delle Marche is engaged on the modelling and control of the dynamics of two-wheeled vehicles

(PTWs) and cars. Over the last years, the state of the art on the motorcycle models proposed in literature have been further shifted towards the development of motorcycle models with minimum complexity [7, 11], which still offer sufficient accuracy in the simulation of the major motorcycle's dynamics. In particular, the proposed tools represent the first attempts present in literature to address analytically the dangerous falls such as the Lowside and the Highside falls [13, 14]. The critical dynamics that arise and favour the falls may put at serious risk the life of the rider. Such dynamics are usually sparked by important phenomena such as the wheels slippage in cornering due to abrupt accelerations, braking or adverse road conditions. These critical driving situations can be well described by the proposed models thanks to the inclusion of an adequate nonlinear characterization of the tyres [12]. The models were validated using commercial multibody software. Also, the study of the structural properties of the are undergoing. The same tools may be also deployed in a model-based design of vehicle stability controllers for active safety devices.

In the context of the issues relative to the vehicle safety, the researches are addressing the development of traction control systems. A first traction controller for two-wheeled electric vehicle with rear traction has been designed and proposed in [9]. This controller acts on the longitudinal dynamics of the vehicle and it is based on a nonlinear model predictive approach (NMPC). The designed controller prevents the driven wheel from spinning out when accelerating in order to maintain driving performance and comfort. An alternative traction control was developed and sliding mode approach was followed [8].

Further investigation on the non-trivial and complex effects of a longitudinal traction control on the lateral dynamics of the vehicle was proposed in [10]. Here the optimal controller still follows the NMPC approach with a simple rider model driving the vehicle along a chosen circular trajectory.

With the goal of designing safety devices increasingly performing, the automation group will be concerned on providing faithful vehicle models. Furthermore, more efficient drive solutions based on electric systems and involving torque distribution among more wheels will be considered.

Looking more further, it will expect to deal with alternative systems for the vehicles' movements, e.g. involving the reconfigurability of the treads, as long as the classic wheel is still considered the interface between the vehicle and the road. Of course, a bunch of innovative and clever systems such as the Bosh jet thrusters applied on the motorcycle are making their way in a competitive scenario where the vehicle safety will be the primary concern.

7 Conclusions and Future Challenges

In this chapter, the main results achieved in the last 50 years by the Automatic Control group of Ancona have been revisited emphasizing, in particular, the recent contributions which range from control system theory, to fault diagnosis and fault-tolerant control, industrial automation, robotics and, finally, to intelligent manufacturing.

Although there are many successful embodiments of control theory and automation, there are still significant scientific challenges that have be to overcome in the next future where the control and automation are going to play a key role for the enhancement of the society. In a time where people and things will be more and more connected by network, the automation and control engineers will have new opportunities making use of the huge amount of available data. One challenge will be to exploit this huge information to develop new and more accurate process identification techniques. Knowledge-based method will probably become more reliable and fast. The challenge, then, will be to select the right features among those available, and to fuse knowledge-based method together with signal-based and model-based. The availability of huge amount of data (big data) will permit diagnosis to evolve to prognosis, which will be used to change the paradigm of maintenance from planned to on-demand according to the real state of the monitored plant. In the next future, techniques of Artificial Intelligence will be applied to control system design, providing new control structures where controllers will be able to learn and to self-organize whenever the system structures change. Similarly, robotic research will benefit from the above mentioned techniques, and this will open the way towards full autonomy of robotic systems.

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From Artificial Intelligence and Databases to Cognitive Computing: Past and Future Computer Engineering Research at UNIVPM

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Abstract In the last decades, Computer Engineering has shown an impressive development and has become a pervasive protagonist in daily life and scientific research. Databases and Artificial Intelligence represent two of the major players in this development. Today, they are quickly converging towards a new, much more sophisticated and inclusive, paradigm, namely Cognitive Computing. This paradigm leverages Big Data and Artificial Intelligence to design approaches and build systems capable of (at least partially) reproducing human brain behavior. In this paradigm, an important

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role can be also played by Mathematical Programming. Cognitive systems are able to autonomously learn, reason, understand and process a huge amount of extremely varied data. Their ultimate goal is the capability of interacting naturally with their users. In the last 50 years, UNIVPM has played a leading role in scientific research in Databases and Artificial Intelligence, and, thanks to the acquired expertise, is going to play a key role in Cognitive Computing research in the future.

1 Introduction

In recent decades, Computer Engineering has shown an impressive development in both research and technology. It has become extremely pervasive, so that there is currently no area in which it does not play an important role. The action field of Computer Engineering is extremely vast; in fact, it extends from computer architectures to software engineering, from databases to cybersecurity, from Artificial Intelligence to distributed systems.

Databases and Artificial Intelligence (hereafter, AI) are two areas of Computer Engineering that have certainly shown a great development in the past.

Databases were created to allow a more efficient, effective and secure management of data, while ensuring their integrity and controlled access, possibly in parallel. Over the last few decades, the development of this technology has been truly spectacular: we have moved from flat data files to reticular Database Management Systems (hereafter, DBMSs), to continue with relational and object-oriented ones. Over time, available data have become first semi-structured and now increasingly unstructured. In parallel to the need of creating new databases, the need of exploiting data stored in the existing ones has arisen and, then, has becoming increasingly urgent. From

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this trend, the need of analyzing data has arisen, which led to data analytics whose spread has made it almost a discipline independent of databases. Finally, the large amount of data currently available has led to Big Data and to the extremely powerful and innovative technologies characterizing it.

At the same time, AI has had an equally fascinating development. Born at the end of the 50's with the objective to simulate every aspect of the human learning and intelligence, this discipline has developed more and more challenging themes and results. Just think of the advent of neural networks, the definition of programming languages, such as LISP and Prolog, image processing and robotic vision, intelligent agents, model checking, natural language processing and, more recently, machine learning and deep learning.

In this context, Mathematical Programming (hereafter, MP), a branch of Operations Research (hereafter, OR), contributed to the development of these two areas of Computer Engineering. Its root came from the '40s to efficiently manage very scarce resources. But, thanks to both the increase of computational resources and the development in the computational complexity theory, its diffusion had received an impulse in the last 50 years. MP and, more in general, OR provide mathematical tools to solve complex decision problems in several fields, e.g., Industry, Computer Science and Finance.

Researchers working on Databases and AI have always interacted to each other, and this interaction has led them to strengthen each other. It has become increasingly strong and, today, is taking on the appearance of a real integration, with the birth of the so-called Cognitive Computing. This discipline aims at creating self-learning systems that use Big Data Analytics and advanced AI to perform specific human-like tasks in an intelligent way. A cognitive system must be:

- *Adaptive*: Like the human brain, a cognitive system must have the ability to adapt to any situation. Therefore, it must be dynamic in acquiring data and understanding objectives and requirements.
- *Interactive*: A cognitive system must be able to interact easily with users, allowing them to easily define their needs. It must also be able to interact with other processors, devices and computer systems.
- *Iterative and stateful*: A cognitive system must always have sufficient information to operate; therefore, the information sources on which it is based must release reliable and up-to-date information. These sources can be structured, semi-structured and, above all, unstructured. As a matter of fact, it is estimated that currently, unlike in the past, 80% of available information is unstructured.
- *Contextual*: A cognitive system must be able to understand, identify and extract elements useful to define the context which it operates in, and, therefore, the corresponding meaning, syntax, time, location, domain, regulations, user profiles, processes, tasks and, finally, objectives.

Cognitive computing is destined to change the way we live, work and think. For this reason, it represents a great and fascinating challenge for the incoming decades.

In the last 50 years, UNIVPM has played a leading role both in scientific research on Databases and in that relating to AI. Similarly, at this University, also the research

on MP has had a great impulse. The know-how acquired in these fields will certainly represent the cultural background that will allow this University playing a leading role also in Cognitive Computing research.

This chapter wants to be a "trait d'union" between past and future. It aims at illustrating what has been done in the past 50 years in the fields of Databases, AI and MP and what could be done in the future in these areas that, presumably, are destined to converge in Cognitive Computing.

2 Research on Databases, Artificial Intelligence and Mathematical Programming at UNIVPM

2.1 Databases, Data Analysis and Social Networking

2.1.1 Databases and Data Analysis

Database technologies date back to '70s. However, the strategic impact of data and of information and knowledge that it is possible to distill from them has become widely recognized rather recently. Database and data analytics research fields have undergone significant changes in the last decades.

Research activities on databases developed at UNIVPM has been focused on two mainstreams: fundamental methods for data analysis and semantics-based techniques to support analysts.

As for the former, a major investigated issue was how to learn *classification* models and drive *feature selection* starting from first principles of statistical learning theory. In fact, at the time of research, state of the art algorithms were able to only provide approximated solutions, due to inherent difficulties in the classification problem. The result has been the design of the Bayes Vector Quantizer (BVQ) classification algorithm. BVQ is a multi-class learning algorithm allowing the adaptation of the nearest neighbor decision rule defined by a Labeled VQ toward the optimal Bayes decision rule. To this end, BVQ uses a gradient-descent algorithm to minimize the average misclassification risk. This feature makes it particularly suitable for class imbalance and cost-sensitive classification problems [31, 35]. Imbalanced and cost sensitive problems have become of extremely important in modern big data applications, and BVQ has been successfully applied in diverse domains, like medical diagnosis, image recognition, and quality control.

With the advent of the Web and with the explosion of the big data phenomenon, new kinds of data and analysis tasks took the scene. Among them the study of social networks and their contents is of particular importance. In this field, we contributed with *Sentiment analysis* approaches aiming at determining the sentiment conveyed by social contents (e.g., Facebook or Twitter posts) in the presence of polysemous words (i.e., words bearing different semantic meanings and related sentiments) and negations [30].

Recent research activities have been also directed towards the emerging area of *Process Mining*, whose goal is to extract insights about a business process elaborated upon event logs collected during process execution [76]. In this field, we have proposed the Building Instance Graphs (BIG) algorithm which is aimed at discovering process instance models in highly variable domains (e.g., innovation, medical diagnosis, writing of research papers), where a complete process model is difficult to obtain and even more difficult to interpret [29].

The widespread adoption of advanced data analytics among non-expert users, especially in distributed and collaborative domains, soon raised the need of environments supporting the correct application and composition of different algorithms. Semantic techniques can help formalizing the description of a domain and the automatic reasoning about it. Some work dating back in the first decade of the 2000s pioneeristically developed a framework and a related ontology (called KDDOnto) for the characterization of the Knowledge Discovery in Databases (KDD) tasks, techniques, algorithms and services. KDDOnto led to the development of KDDVM, a suite of semantically rich modules enabling the effective composition and sharing of KDD experimental processes [32].

Semantic techniques have been also applied to model performance indicators and metrics in the KPIOnto ontology, dealing with the semantic heterogeneity of this complex kind of data, and developing reasoning tools to: (1) enforcing the coherency of a common repository of indicators definitions [33], (2) supporting the integration of autonomous data marts and the querying of the logically unified global data mart generated in this way [34], and (3) supporting the design of intelligent environments where metrics and indicators are of interest [9, 28].

2.1.2 Social Networking

Having become a mass phenomenon on a global scale, Social Networks (hereafter, SNs) are currently a powerful tool to support the aggregation of users on the Internet, as well as one of the most advanced forms of network communication [74]. The main feature characterizing SNs is their capability of allowing interpersonal relationships, which daily intertwine in the various areas of social life. In fact, SNs allow the materialization of human relationships in a concrete information system capable of evolving over time and of continuously enriching itself with new contacts. The extent of the SN phenomenon is evidenced by the number of memberships to the most widespread SNs, which now exceeds one billion for some of them. The number of social contexts in which SNs are largely used is also remarkable.

The existence of such a vast number of heterogeneous SNs introduces important problems for their increasingly effective usage. In particular, it seems necessary to guarantee a sort of "interoperability" that can favor the exploitation of the information disseminated on more SNs. This leads to the idea of *Social Internetworking* [18] as a possible level of intermediation, which allows the management of involved SNs, thus guaranteeing their interoperability and the one of the users who access them.

The key element in a Social Internetworking System (hereafter, SIS) is represented by the so-called *bridges*, i.e., users who simultaneously join several different SNs. In [18], the main characteristics of this category of users are investigated. A clear "identikit" of them is thus built, allowing us to draw a series of non-trivial considerations about their role in a SIS.

The Social Internetworking paradigm offers many research cues for the future. For instance, in a SIS, in order to proceed with the study and analysis activities, a preliminary step consists in the definition of new crawling techniques. Unlike the classic ones, they should be based on bridges. The discovery of hidden bridges or the identification of potential ones is also a research topic of great interest for the future. In a SIS, a new notion of assortativity [61] appears necessary, which, once again, must take strong account of bridges. A similar problem emerges for centrality measures. For example, the classic notion of Betweenness Centrality [7] is not able to capture the centrality of nodes with respect to paths crossing different social networks.

Many of the issues addressed in the context of SNs can be extended to the analysis of complex networks, used in various application contexts, ranging from biomedical engineering to innovation management, from data lakes to telecommunications.

For instance, in [52], the authors present a new approach based on complex networks to supporting experts in their analysis of those neurological disorders in which connections between brain areas play a key role. This approach receives the EEG of a patient and associates a complex network with it. The nodes of this network represent the electrodes and the arcs denote the (dis)connection degree between the corresponding brain areas, measured by means of suitable metrics previously proposed in the literature, such as Permutation Disalignment Index [53] or Coherence [68]. Then, it makes appropriate projections on this network, depending on the neurological disorder to be analyzed. After this, it computes the values of a new coefficient, called connection coefficient, on the complex networks thus obtained. These values can be used to help neurologists in their analysis. The neurological diseases considered in [52] are Alzheimer's Disease, Creutzfeldt-Jacob Disease and Childhood Absence Epilepsy. Several other diseases could be investigated in the future.

The Social Networking paradigm is one of the most effective ways to analyze and implement the Internet of Things (hereafter, IoT). In recent years, researchers working on this topic have introduced new models capable of capturing the growing complexity of this scenario. Baldassarre et al. [5] analyzes the possibility of applying the key ideas characterizing the Social Internetworking System to IoT and proposes a new paradigm, called MIoT (Multiple IoTs), capable of modelling this scenario and encouraging the cooperation of objects belonging to different IoTs. The same work proposes a crawler specifically designed for a MIoT. Once the MIoT paradigm has been defined, a number of challenging issues can be addressed. For example, it could be possible to define a profile for each object and to compute the trust and reputation of an object in an IoT or of an IoT in a MIoT.

Finally, complex networks can be a useful tool in the data lake field [40]. In fact, they allow the uniform representation of structured, semi-structured and unstructured data sources of a data lake. Furthermore, they can support approaches to at least partially "structuring" unstructured data. Once this is done, they can support

the extraction of semantic relationships between data belonging to different, even extremely heterogeneous, sources. Starting from this consideration, in the future, approaches based on complex network analysis could be defined to manage data lakes and to extract knowledge from them.

2.2 Computer Vision—Perception and Learning

In 1988, UNIVPM organized and hosted the "First Conference of the Italian Association for Artificial Intelligence" (AI*IA), and that event marked the birth of a local research group in AI focused, over the years, on computer vision, agent and multi-agent systems, knowledge representation and automatic reasoning, Natural Language Processing, cybersecurity and semantic Web. This section presents the research results obtained in computer vision, while Sect. 2.3 the activities carried out on the other fields.

Many areas of AI research find in Computer Vision (hereafter, CV) a privileged application field. Firstly, any CV process ends with a recognition and classification process using Machine Learning and, more recently, Deep Learning techniques. Secondly, the representation of knowledge about objects, features, categories and relationships between objects is fundamental for any CV system aimed at extracting situations, events and behaviors from images and scenes. Thirdly, the symbolic representation of the state of the world for deduction, reasoning and problem solving systems have to consider complex aspects, such as uncertainty or incompleteness of information in images acquired. Finally, Robotics is a discipline closely related to AI and, in particular, Robotic Vision allows intelligent systems (robots) performing tasks that require cognitive level skills for manipulating or moving objects and planning and executing movements and for locomotion (e.g., vSLAM visual Simultaneous Localization And Mapping).

The main interests of researchers working in CV at UNIVPM are in the areas of robotics, intelligent mechatronic systems, pattern recognition, image processing [78], image understanding and retrieval, learning and e-government. The main application areas are in mobile robotics, intelligent retail environments, intelligent transportation systems, geographical information systems and thematic mapping, medical imaging, ambient assisted living, e-health and e-government. Researchers working in CV at UNIVPM played and are playing a leadership role in the scientific communities related to the European Conference on Mobile Robotics (ECMR) and IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA).

2.2.1 Robotic Vision

Mobile robots are the most concrete example of an intelligent artificial system. The computer vision in mobile robotics (Robotic Vision) has been the most important aspect of the research, as well as organizational, activity carried out. In particu-

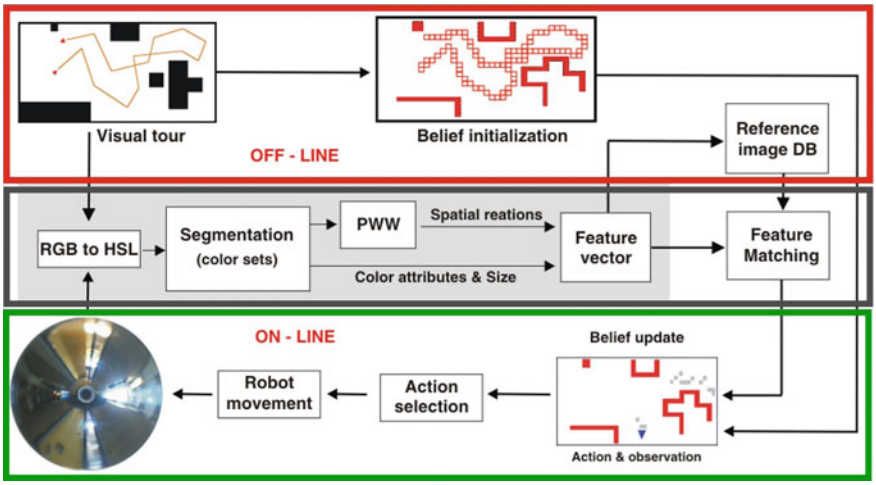

Fig. 1 Appearance-based localization framework

lar, Remotely Operated Vehicles [79], ground (indoor and outdoor) [54] and air unmanned robots [21] were used.

The most innovative approach followed was the appearance-based approach, whereby the location of a robot is carried out without using explicit object models, but comparing the entire current view with those available from previous explorations of the environment Fig. 1. This required the definition of a new metric for the comparison of the images acquired by sensors.

Using simulation frameworks, developed for both educational and research purposes, and variants of Scale-Invariant Feature Transform [51] and Speeded Up Robust techniques [8], now the most widely exploited in this scientific community, different aspects of localization and navigation of mobile robots, both indoor and outdoor, have been analyzed. In particular, several relevant projects on the advanced use of vision for the autonomous navigation and landing of UAVs have been developed.

2.2.2 Understanding Human Behaviors

Understanding complex human behaviors has an increasing interest on computer vision community in recent years, with relevant applications in complex and crowded spaces (i.e., IREs) and E-Health and AAL [1]. All recent trends in this area have a common research point on the extensive application of deep learning methods with an increasing availability of public datasets on both application areas. UNIVPM reached relevant results in two main topics, namely: (i) shopper behavior based on RGBD vision; (ii) non invasive pre-term infant monitoring for intelligent care and Clinical Decision Support Systems.

In retail environments, there is great value in understanding how shoppers move in the space and interact with products. While the retail environment has some favorable characteristics for computer vision, such as reasonable lighting, the large number and diversity of products sold, along with the potential ambiguity of shopper movements, accurately measuring shopper behaviors is still challenging [73]. Over the past years, machine-learning and feature-based tools for people counting, interaction analysis and re-identification were developed, based on RGB-D cameras in a top-view configuration, with the aim of learning shopper skills. However, when moved into the era of multimedia big data, machine learning approaches evolved into deep learning ones, which are a more powerful and efficient way to deal with the complexity of human behaviors. In [50], CV researchers at UNIVPM introduced a novel deep learning framework that uses three concurrent Convolutional Neural Networks (CNNs) to simultaneously count people passing by the camera area, perform top-view re-identification and measure shopper-shelf interactions on a single RGB-D frame, and also promoting three data-sets TVHeads, HaDa and TVPR 2 demonstrating the ability to gather data and extract interesting insights [42].

Despite automatic segmentation being crucial to automate infant movement monitoring, no efforts can be found in the literature in this field. In [20], inspired by successful approaches for semantic segmentation based on deep learning, CV researchers at UNIVPM investigated for the first time in the literature the use of fully-convolutional neural networks (FCNNs) for the task of preterm-infants' silhouette segmentation from depth images, which is of primary importance for the early diagnosis of brain disorders.

2.2.3 Precision Agriculture

According to a recent report of the European Agricultural Machinery Association,

> Agriculture 4.0 paves the way for the next evolution of farming consisting of unmanned operations and autonomous decision systems

while

> Agriculture 5.0 will be based around robotics and (some form of) artificial intelligence.

It is clear how Agriculture is experimenting a "Copernican Revolution" for which AI could be the engine. The availability of distributed sensors ranging from unmanned aerial vehicles to IoT sensors opened new ways to gather (big) data with different spatial, spectral and temporal resolutions.

In this scenario, efficient and effective pipelines are required to process this large heterogeneous amount of data for deriving simple and useful information that could be implemented on real fields (e.g., variable rate treatments supported by auto-steering). In particular, multi/hyper-spectral sensors have been applied in Precision Agriculture applications (e.g., weed detection, water/nitrogen stress identification). The state-of-the-art technologies today acquire hundred of bands in the VISible, Near InfraRed and Short Wave InfraRed also on-board of unmanned platforms.

High resolution data introduce new challenges as the reduction of noise (e.g., leaf and soil) and new advanced algorithms are required to segment images. By extending our previous work [72], the use of 3D models (e.g., Digital Surface Models) linked to orthophotos is one practical way to segment soil vs crop also for complex crops as vineyards, where the canopy area has a spectral response that is really close to the grassed soil.

Useful data could be then classified by supervised or unsupervised approaches [11] to evaluate the water/nitrogen stress or the presence of weeds to generate management zones that the agronomist uses to output prescription maps [69]. Processing is also affected by the number of available spectral bands/channels that sensors are able to acquire. In this context, the proper selection of features plays a role to discriminate the source of an issue (e.g., nitrogen stress). Imagery could be also used to model and predict the trend of pest/insect population, especially for high value crops as vineyards, orchards and olive groves. Deep learning could have a great impact to distinguish among different types of insect also with a continuous learning supported by the photo-interpretation of agronomists and domain experts, which could improve the accuracy and precision of classifiers.

Images actually represent one of the most promising data in modern and future agriculture, but many challenges are still open as the smart processing on serverless architecture, the advanced analysis of stress (water, nitrogen), the identification and classification of pests and weeds. In this scenario, as any precision agriculture approach requires the interaction of several actors, in cooperation with the D3A Department and the Experimental Farm "Pasquale Rosati" of UNIVPM, the CV researchers at UNIVPM performed several precision agriculture trials to collect multi/hyper-spectral cubes. They also developed new approaches to processing data. These approaches include ground spectrometer and aerial sensors on heterogeneous crops with different nitrogen and irrigation configurations.

2.3 Artificial Intelligence and Cybersecurity

2.3.1 Knowledge Representation, Automated Reasoning and Multi-agent Systems

In a scenario where different cognitive agents with different beliefs and goals interact, two problems were interested to deal with, namely:

- *Belief Revision*: when an agent receives new information (from his sensors or from other agents) contradicting some previous knowledge (and "recognizing contradictions" is a problem by itself), what strategies should he put in place to restore consistency in his representation of the external world and of the other agents' mental states?
- *Plan Recognition*: if an agent observes another in action and ignores his objectives, how can the former infer them before the latter agent completes his plan?

These problems share the formal logic approach, i.e., *abductive reasoning*, and the need to evaluate uncertain and partial knowledge in order to choose among different hypotheses; therefore, they belong to the same line of research: *automated reasoning*.

Belief Revision is a central topic for the realization of any cognitive system interacting with others in a dynamic world subject to changes. It is involved in specific areas of AI, such as judicial investigations [62], and in broad fields as data and knowledge engineering [10]. The contribution given in this context was the definition of a new model that integrates symbolic approaches (for the restoration of logical consistency) and numerical methods (for credibility and reliability assessment), introducing the so-called *principle of Recoverability of Information* derived from the Occam's razor (minimum change). When revising beliefs about a static world "if a piece of information A is discarded because of its incompatibility with a subsequent piece of information B, the further acceptance of another piece C that contradicts with B should 'recover' A, even if C does not logically support A, just because C discards B and so it yields a cognitive state in which there is no more reason for A to remain not believe" [39]. This principle for belief revision was implemented in an effective algorithm and tested within a system supporting complex investigations of the criminal police [38] (see Fig. 2).

Algorithms for *Plan Recognition* were applied in various sectors of advanced computing. The first contribution was the definition of an abductive method for hypothesizing beliefs and goals that caused the emission of a "Speech Act". Rather than recognizing plans from visual information, it was a matter of recognizing mental states from the reception of communicative acts, a technique that enriched the extensive literature on user modelling in the field of intelligent user interfaces and constitutes a further means of acquiring specific knowledge for objectives and knowledge owned by other agents.

Great interest was also devoted to distributed information and decision support systems. In the realistic hypothesis that the competence and correctness of each agent is limited, an attempt was made to evaluate, on a simulation basis, how the overall behavior of the agency is affected by locally defined strategies for belief revision, communication rules and methods for selecting the most reliable partner [37]. In recent times, these lines of research joined the medical domain [45], to meet the needs of medicine, and that of Real-Time Systems, to move towards the realization of Distributed Cyber Physical Systems.

2.3.2 Natural Language Processing

Natural Language Processing (hereafter, NLP) is a sub-field of AI focused on the study of methods and technologies for (semi) automatic processing of human language. Its target is to get computers closer to a human-level understanding of language for a range of tasks or applications, such as machine translation, speech recognition, question answering, information extraction and sentiment analysis.

The research activity in NLP at UNIVPM started in the late nineties, with the definition of an innovative technique to support one of the fundamental tasks in

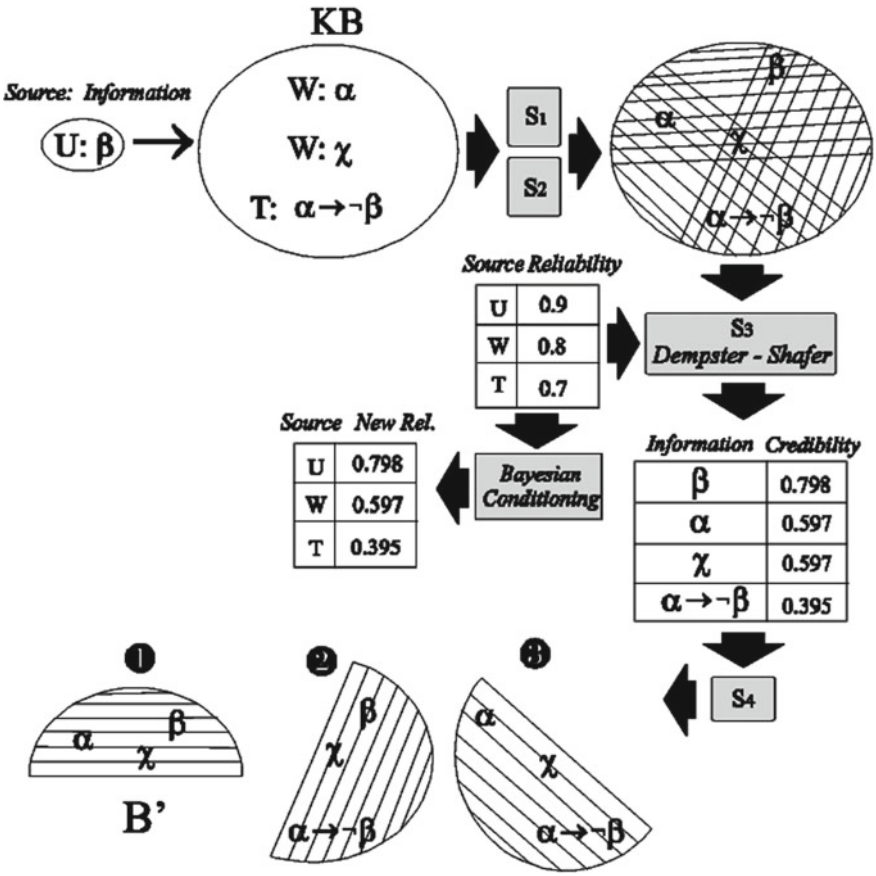

Fig. 2 The proposed model for revising beliefs and degrees of reliability in a multi agent environment

text processing, i.e., entities recognition. The following research step has been the organization of named entities into lexical taxonomies, a knowledge representation method considered at the basis of the definition of a formal ontology of a domain, as suggested by the METHONTOLOGY framework [41]. One of the relevant results of this research activity has been the formalization of a general-purpose semi-automated methodology to speed up and facilitate the design of a domain taxonomy [77]. Its effectiveness has been tested with an application for improving accessibility of knowledge and data repositories in a research web community, INTEROP NoE. The application was able to produce a Knowledge Map of partner competences, to perform a periodic diagnosis of the extent of research collaboration.

Taxonomies representing domain entities can be enriched with relationships between entities so as to enable logical reasoning. The result of this process leads to the definition of ontologies [71]. Lexical ontologies can be used in Web com-

munities characterization, to identify collaborations among members. However, to enable the integration of on-line communities, secondary sources of information, such as documents, e-mails, blogs and discussions, can be exploited. This research topic, focused on the extraction of information from texts shared among members of virtual communities, led, among other things, to the definition of a new methodology for content-based social network analysis [23]. The proposed approach was able to automatically extract the relevant topics shared among community members from documents and to analyze the evolution of the network also in terms of emergence and decay of collaboration themes.

In recent years, the skills acquired on the analysis of contents shared in social communities have been used in the field of on-line community information needs elicitation [49]. In micro-blogging platforms (like Twitter and Tumblr) people share points of view and information to satisfy their communication needs on a given topic. Through the analysis of communicative and informative patterns, it is possible to identify which aspects of a topic are of interest to the members of the community. The recommender system described in [24] is an example of application of this approach. It is capable of suggesting to a journalist, for a given event, the aspects still uncovered in news articles on which the readers focus their interest, detected through the analysis of Twitter and Wikipedia.

In the near future, the research activity in NLP field will be focused on two directions: the definition of methods for a deeper characterisation of on-line communities information needs and the definition of techniques able to cope with the huge amount of textual data produced by these communities.

2.3.3 Cybersecurity

Tackling cybersecurity has always represented a hard challenge which AI can support to provide an answer. For this reason, since the 90s, UNIVPM has found in cybersecurity an interesting and challenging application domain of AI techniques, in particular *automated reasoning* in order to formally verify security requirements. Briefly, this consists in proving the absence of any design and implementation flaws of a system (a protocol, a software, a procedure, etc.), even before its testing or its release. This requires a logical-mathematical *model of the system* to be analyzed, a logical *formula to specify the requirements* that it must satisfy, and a verification algorithm (e.g., *model checking* [19, 48]). The peculiarity in formally verifying cybersecurity consists in the need of having an *attacker model*, along with the system model, i.e., proving that the system is able to meet certain requirements even in presence of an attacker.

Regarding *system modeling*, UNIVPM has explored both non-deterministic [63, 64] or probabilistic (Markov Decision Processes [6]) models. These models are generally obtained manually from the specification documents [63, 64]. However, recently UNIVPM has contributed to the development of a tool *to automatically extract the models* directly from the code [70]. These have been applied to the description of cryptographic protocols (e.g electronic payment protocols [64]), grid

computing systems (e.g., the job manager of Condor [63]), and dispersed storage systems [6]. Furthermore, a system is often composed of an arbitrary (at verification time) number of components, i.e., *parameterized models*. However, under appropriate conditions, such a system can behave equivalently to a system with a specific number (called a *cutoff*) of components. UNIVPM has obtained the cutoff for some interesting classes of systems, such as grid computing systems [63] and dispersed storage systems [6].

Regarding *attacker modeling*, an attacker is usually modeled as an agent who has at its disposal a set of actions and at every step non-deterministically chooses any of those. The model checker, by systematically exploring the space of system executions, looks for at least one sequence leading to the completion of an attack. UNIVPM has provided a contribution to such models by proposing a Markovian attacker model for dispersed storage systems [6].

Regarding *security requirements*, consider that they usually are *hyperproperties* [22] (instead of simple properties), i.e., they analyze multiple executions at the same time (because what happens in one execution can affect another one). UNIVPM has proposed a mapping between hyperproperties and properties of a parameterized system [63], transforming an arbitrary number of executions of a single instance in an arbitrary number of system instances and, thus, applying cutoff theorems.

As for the future, the UNIVPM research is moving towards verification (and enforcement) at runtime and its application to blockchains and smart contracts.

2.3.4 Semantic Web

The Semantic Web [12] is an extension of the Web architecture enabling what is called a Web of Data, where information is semantically structured and interconnected at a global scale. The aim is that of allowing machines to query, perform reasoning and, to a certain extent, understand the meaning of information. Today, the Semantic Web and Linked Data technologies, such as Resource Description Framework (hereafter, RDF) and Web Ontology Language (hereafter, OWL), are widely adopted in a variety of contexts, both in research and industrial settings, to drive intelligent applications and automate data-driven processes.

At UNIVPM, research activity in the Semantic Web field started in 2003 and led to relevant contributions addressing challenging issues like efficient remote synchronization of RDF graphs, digital signature of RDF sub-graphs and P2P based algorithms to share semantic data within online communities. Based on these contributions and ideas, an innovative knowledge management platform, called DBin [75], has been implemented and applied in different domains, such as, for example, the management of geo-spatial information. In 2006, DBin was awarded with the third prize at the Semantic Web Challenge held within the International Semantic Web Conference.

The outcomes of such a research strand found a fertile ground in the Digital Humanities. A fundamental activity in the Humanities scholarship is *annotation*,

that is adding information to media content (as text and images). This activity is traditionally done by writing side notes in books. Transposing it in the digital world, and using Semantic Web data representation techniques, enable new interesting scenarios where annotations can be shared in real time within scholarly communities and can be edited in a collaborative fashion. Furthermore, once annotations are represented in a machine readable format and made available on the web, they can be harvested and collected to enhance Digital Libraries, e.g., to improve search or provide new ways to explore digital content.

These ideas were developed and applied in different EU funded and national research projects [58], leading to the development of the *Pundit* Semantic Web annotation tool [44], awarded with the first price at the LODLAM competition in 2013.[1] Pundit was one of the first projects addressing the problem of representing and managing distributed Semantic Web annotations, which gained notable interest in the research community, leading to the W3C Web Annotation specification.[2]

Ongoing research directions include the application of Semantic Web-based annotation techniques in the management of historical buildings, as well as the exploitation of Linked Data to extract temporal information from text documents, such as, for example, estimating the document focus time [27].

2.4 Mathematical Programming and Algorithms

2.4.1 Mathematical Programming

Operations Research and *Management Science* provide the mathematical tools to solve complex decision problems where activities and/or limited resources have to be managed while maximizing/minimizing one/more objective functions (and, of course, at least two feasible alternatives exist). Among all feasible alternatives, they look for the best one and, therefore, OR is also known as the "Science of Better".[3] Its roots come from the Word War II when the management of a scarce resources availability led to the creation of a first group of operations researchers. For instance, these operations concerned the optimization of the radar equipments distribution across the territory and of the military convoys provisioning [43]. However, it is only in the last 50 years that OR had received a strong impulse thanks to the increase of the computational resources and to the progresses in the computational complexity theory [65]. Although born in an engineering context, OR also benefited from the results reached in economy and mathematics. For example, significant contributions came from Kantorovich, Von Neumann, Nash's non-cooperative game theory [59] and Koopmans, who addressed one of the most frequent decision problems in econ-

[1] http://summit2013.lodlam.net/challenge/.

[2] https://www.w3.org/TR/annotation-model/.

[3] http://www.scienceofbetter.org.

omy, where the best use of the resources of a company has to be planned [47]. Instead, substantial mathematical contributions came from both *Combinatorial Optimization* [66] and *Graph Theory* [36].

Mathematical Programming is an OR branch aiming at solving decision problems in which an objective function $f(x) : \mathbb{R}^n \rightarrow \mathbb{R}$ (or more than one) has to be minimized/maximized and is expressed in terms of n decision variables belonging to a set, i.e., the *feasible region*, $\Omega \subseteq \mathbb{R}^n$, defined through m inequalities (*constraints*), e.g., $g_i(x) \geq b_i, \forall i = 1, \ldots, m$, where $g_i(x) : \mathbb{R}^n \rightarrow \mathbb{R}$ and $b_i \in \mathbb{R}$. Those constraints usually reflect technological/organization aspects. Indeed, "programming" means "planning" and therefore, MP is a mathematical representation aimed to optimally allocate scarce resources or to optimally plan production schedules, for instance. If both objective function(s) and constraints are linear, a *Linear Programming* (hereafter, LP) formulation of the decision problem is given [25]. In this context, a significant contribution is the definition of an iterative approach, known as *Simplex method*, proposed by Dantzig [26] for solving LP problems. Instead, if all decision variables have to be integer, the problem is formulated through *Integer Linear Programming*, ILP [60].

One seminal work on ILP applications is [46], where some significant decision problems regarding both production organization and planning were addressed for the first time, e.g., the 1-dimensional *Bin Packing* (1-BP) aimed at assigning some items of different length to a minimum number of bins of unit length. Indeed, the 1-BP can be seen, in some way, as a "core" problem for several application areas, e.g., *Production Scheduling and Planning*, *Logistics* and *Vehicle Routing* that are also the main research fields which the OR group at UNIVPM is focused on. Generally speaking, the focus is on solving optimization problems with a huge number of variables and/or constraints, modeled through ILP and solved by combining the features of Branch and Bound and Column Generation (CG) techniques or by metaheuristics or matheuristics. For example, the 1-BP has been recently formulated as a time-indexed ILP model, solved through a CG-based approach [3].

As for manufacturing, both heuristic and exact CG-based algorithms have been developed for the *Cutting Stock Problem* where small objects have to be cut from large ones (stocks) to satisfy the requirements of the former as well as all technological/organizational constraints and optimize one/more performance indicators [2, 4]. For planning and managing manufacturing processes, a Genetic algorithm has been proposed for the *Job-Shop Scheduling Problem* where a set of non-preemptive jobs (each denoting a sequence of consecutive operations) has to be processed on a set of continuously available machines, minimizing the total completion time [67].

As for Vehicle Routing for promoting ecosustainable transport solutions, the efficient use of Alternative Fuel Vehicles (AFVs) is investigated. Particular interest is paid to the solution of both the *Green Vehicle Routing Problem* (GVRP) and the *Electric Vehicle Relocation Problem* (EVReP) for improving the carsharing systems' performances. In particular, the GVRP aims at efficiently routing a fleet of AFVs, based at a common depot, for serving customers geographically distributed, thus minimizing the total travel distance. Due to the AFV's limited driving range, intermediate stops at the alternative fuel stations have to be also planned a-priori along the

trips. A two-steps approach has been recently proposed for the GVRP in which, feasible non-dominated paths are firstly generated and then, feasible routes are selected by solving a path-based ILP model [13]. Instead, an ILP-based meta-heuristic has been designed for the GVRP with: only Electric Vehicles (EVs), customers to serve within Time Windows and partial battery recharges allowed along the trips [17]. While, the EVReP, i.e., the problem of efficiently relocating the EVs of a carsharing system through operators, to balance the EV demand and supply at the stations, has been heuristically addressed [14, 15] and extended to a three-objective version [16]. New EVReP variants, as well as the application of (I)LP-based methods to both medical and micro-grid contexts, are being investigated.

2.4.2 Algorithms

Since the end of '70s one of the main topics of algorithm definition in real case applications concerns the field of Hydraulics and Hydraulic Constructions, with the definition of groundwater mathematical models, of models for the study of flood propagation of a river, and of models of fluid transport networks and aqueduct models, facing not only dimensioning problems but also simulation ones. In particular, the possibility of applying a first-order analysis probabilistic approach to the design of urban drainage systems was investigated, and the variability of some of the most significant parameters in the usual calculations for urban sewer sizing was examined.

In [55], the authors illustrate the implementation of an algorithm to address the issue of identifying underground water transmissibility in porous ground by means of an approximate approach. The algorithm is based on the assumption that transmissibility is steady compared to gradient but not to divergence. The proposed solution adopts the same mathematical model as the direct approach (calculation of piezometry) founded on the finite difference method. However, it introduces a parameter to change the calculation of the matrix coefficients of the linear system ensuing from discretization. This parameter handles the switch between two possible behaviors of the algorithm, namely the computation of the piezometry given the physical parameters (trasmissivity and storage coefficient) of the area under investigation, or vice versa.

In [56], an enhanced version of the model presented in [55], in which the authors refine the method for the identification of the trasmissibility in the porous aquiferous grouns, is defined.

Another model [57] was defined for the simulation of the wave lamination of an Italian river flood routing along a reach enbanked but not led again into a cylindrical bed, made interesting by the presence of three important confluences which, in three kilometers' distance, affect the extent of the flow (when the river is in flood) by 50%. The simulation uses a mathematical model of the water flow based on the classical equations of varied motions known as De Saint Venant Equations. This model is associated, in the case study, with the one of upstream and downstream sections and with the outflow scale defined by the Manning formula. It has been transformed

in accordance with Crank-Nicolson implicit scheme discretization, and an iterative algorithm based on the Newton method has been implemented.

3 Conclusion and a Look at the Future

In this paper, we have provided an overview of the main research issues that we have addressed at UNIVPM in the last 50 years as far as Computer Engineering and MP are concerned. We have seen that, at UNIVPM, Computer Engineering research can be summarized to two main areas, namely Databases and AI. Both of them, along with MP, are converging towards Cognitive Computing. We think that this will be one of the main research topics in ICT Engineering in the future, and we believe that, thanks to the knowledge background already acquired, in the next decades, UNIVPM will be one of the main protagonists in this research area.

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Fifty Years of Biomedical Engineering: From Origin to Smart Technologies

Laura Burattini, Francesco Di Nardo, Micaela Morettini, Federica Verdini and Sandro Fioretti

Abstract In Italy, the Bioengineering Community was founded in 1980. The kick-off meeting was held in Montesicuro, a little village near Ancona and organized by Prof. Tommaso Leo from the then-named "Università degli Studi di Ancona" (now Università Politecnica delle Marche, UNIVPM) in cooperation with the nascent National Group of Bioengineering. This chapter aims to produce a brief review of the main results in Biomedical Engineering by UNIVPM during the first 50 years useful to understand the present and to track future contributions for the next 50 years. It is also an occasion to recall the pioneering work on the Bioengineering of the Neuromuscular, Cardiovascular and Metabolic systems performed by our leading colleagues Tommaso Leo, Paolo Mancini and Roberto Burattini, as well as to describe significant research achievements obtained by professors, researchers, post-doc fellows and Ph.D. students who worked and/or are currently working at the UNVPM. Though mainly focusing on research findings in the above cited physiological systems, it is also worth mentioning in this chapter that UNIVPM has also an educational mission, provided by the two Biomedical Engineering courses currently active at the Engineering Faculty: the three-year Bachelor and the two-year Master (in English) courses.

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1 Motion Analysis

The interest in Motion Analysis (MA) started by the very beginning of the research work at UNIVPM and is still lasting on the topics treated below.

1.1 Joint Kinematics

Since the beginning of 80's particular attention was devoted to 3D and in vivo analysis of human joints with advanced techniques. Initially, the attention was focused on the kinematics of the metacarpo-phalangeal joint (MCP).

This research started in collaboration with the Catholic University of Rome that put at disposal a photographic system constituted by two Polaroid cameras and an electronic chronophotographic apparatus based on LEDs emitting light in the visible band. Data were manually digitized on a commercial digitizer, 3D marker coordinates were computed by Direct Linear Transformation approach and joint angles computed with classical joint kinematic equations. Preliminary results were interesting but at the same time prone to errors that were successively minimized by the following innovations:

(a) use of an automatic optoelectronic stereometric system (firstly, a prototype version and successively a commercial system)
(b) use of Kalman filtering techniques for data processing and derivative estimation
(c) joint kinematic characterization by means of the Instantaneous Helical Axis (IHA) descriptor.

It has been shown that the determination of direction and position of axes of rotation at each time instant during motion can be improved if a continuous-time rigid body model is adopted. In this case, with respect to its finite counterpart (i.e. the Finite Helical Axis—FHA), IHA parameters are characterized by a more favorable signal-to-noise ratio but their estimate requires the knowledge of the first derivative of displacement data, i.e. of velocity of points). Unfortunately, numerical differentiation of noisy data as those derived by any measurement process, belongs to the class of ill-posed problems. Consequently, great attention was paid to the accuracy of data acquisition and processing in order to obtain reliable IHA estimates. In particular, an automatic stereophotogrammetric system (CoSTEL) very accurate and precise was used in order to record movements of point body landmarks and to interfere as little as possible with the subjects. Moreover, very accurate stereophotogrammetric and numerical differentiation algorithms based on Kalman filtering methodology were properly developed.

The idea at the basis of the filtering and differentiation algorithm based on Kalman filtering, or better on Kalman Smoothing, is that every band-limited signal (such as the trajectory of a marker placed in correspondence of a moving body segment)

belongs to the class of C^{∞} function. Hence it is possible to define a state vector *X(t)* composed of the signal $x(t)$ and its derivative $x^{(i)}(t)$ up to *N*th order:

$$X(t) \triangleq \left[\frac{d^i x(t)}{dt^i}, i = 0, \ldots, N\right]^T, N = 0, 1, 2, \ldots \tag{1}$$

Differentiating *X(t)* with respect to *t*, the following equation results:

$$\dot{X}(t) = FX(t) + Gw(t) \tag{2}$$

where F is an $(N+1) \times (N+1)$ matrix with elements $f_{i,j} = \delta_{i+1,j}$ (δ is the Kronecker delta), G is an $(N+1)$ vector given by $\left[0 \ldots 0\ 1\right]^T$ and $w(t) = x^{(N+1)}(t)$.

Under the hypothesis of a sampling frequency $f_c = 1/\Delta$, the integration of (1) between t and $t + \Delta$ results in:

$$X(t + \Delta) = AX(t) + W(t) \tag{3}$$

where:

$$A = e^{F\Delta} = \begin{bmatrix} 1 & \Delta & \cdots & \Delta^N/N! \\ 0 & 1 & & \Delta^{N-1}/(N-1)! \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix} \tag{4}$$

$$W(t) = \int_0^{\Delta} e^{F\theta} G w(t + \Delta - \theta) d\theta \tag{5}$$

Taking into account that the only observation is that of the signal (i.e. the point marker position), the following measurement equation can be associated with Eq. 3:

$$y(t) = CX(t) + v(t) \tag{6}$$

where C is a $(N+1)$ row vector given by $\left[1\ 0 \ldots 0\right]$ and $v(t)$ is the white observation noise $\sim N\left(0, \sigma_v^2\right)$.

Equations 3 and 6 have a form suitable to the Kalman filter implementation provided that *W(t)* is modelled as white gaussian noise. Because Kalman filtering methodology gives at each time instant the best estimate of the state vector *X(t)*, it is evident from the definition of the state vector *X(t)* that by this approach one obtains contemporaneously the best estimate of the position and of its first *N*-order time derivatives that can be used to compute the IHA parameters characterizing the joint kinematics.

1.2 Standardization of Clinical Protocols Used in Movement Analysis for Rehabilitation

By the end of 80's, Movement Analysis obtained number of significant results used mainly in research contexts like kinesiology, ergonomics, sport medicine and obviously in rehabilitation. However, in this latter field, MA had received limited clinical acceptance, at least in Europe. The major causes which justify the transfer of laboratory based research findings into clinical practice can be summarized as follows:

(a) At that time, MA had limited diagnostic capability. It was mainly a tool for quantitative, functional movement assessment usually in already diagnosed diseases. Consequently, MA was mainly a useful tool in the clinical decision-making process and in monitoring the effects of conservative and surgical treatments. Today with the advent of artificial intelligence tools MA is becoming also a diagnostic tool.
(b) There was a lack of consensus on what motor ability is, and of the simplicity of the motor tasks required in the usual clinical protocols used as functional evaluation tools.
(c) There are many technical questions that gave rise to some doubts about the reliability of MA methods and techniques in managing relevant and intrinsic inaccuracies.
(d) The lack of standardization in the clinical and experimental protocols, hampered a coalescence of findings into coherent and agreed knowledge bases. Consequently, results obtained in individual laboratories were poorly or not at all communicable to others.

The above considerations have led a consortium of academic public-health and industrial european entities to the development of two main European Projects CAMARC and CAMARC-II leaded by Prof. T. Leo in order: to build-up a Europe-wide network to practice Movement Analysis; to define agreed clinical and experimental protocols; to integrate existing and new instrumentation; to define suitable User Interfaces driving the clinician in the tests; to define a comprehensive Knowledge Base (KB) of the MA experience; to build-up suitable databases (DB) of MA data accessible through the Network; to assess criteria for the definition of normative data for a conventional age-related classification of normality, impairment and disability for motor behavior. All these activities ran for a decade providing the basis for further EU projects and represented a recognized milestone in the development of MA in Europe.

1.3 Posturographic Analysis

Preliminarily, it is right to mention that all the studies cited in the present subsection that involved the presence of pathological subjects were conducted at INRCA Movement Analysis Laboratory in collaboration with the Rehabilitation, Diabetology and Neurology Departments of INRCA geriatric hospital.

Static posturography: A third topic that was studied both at the methodological and at the clinical application levels has been the study of equilibrium maintenance while subjects maintained a quiet orthostatic position.

Various methods to analyze healthy and pathological subjects were implemented and tested, starting from those usually applied in clinical contexts. Though the protocol is very simple to apply because it is required to maintain an upright posture for half a minute in open and closed eyes conditions while measuring by a force platform the trajectory of the point of application of the resultant ground reaction force vector, i.e. the center of pressure (CoP), results are prone to a great variability and to an unfavorable signal-to-noise ratio [52].

Traditional stabilometry techniques indicate just a descriptive way of characterizing body movement patterns, which mainly look at the geometrical-temporal and frequency characteristics of CoP.

Conversely, nonlinear analysis offers a way to characterize qualitative changes in the dynamics of this complex system and promises to be important for clinical practice because, unlike traditional (linear) models, it can extract hidden information related to the complexity, stability and variability of the human postural system. Because methods of nonlinear analysis and chaos theory may give effective quantitative descriptors of underlying system dynamics, the properties of neuromuscular control can be determined analyzing the CoP signal.

In [59] the largest Lyapunov exponent (LLE) was estimated to quantify the chaotic behaviour of postural sway. LLE is a parameter that nonlinear analysis methods allow to determine in a reliable manner. LLE values were found to be positive although close to zero, that suggested that postural sway derives from a process exhibiting weakly chaotic behavior. The same technique was also applied to parkinsonian patients (PARK) in order to study the stability of posture system, the role of visual input and the influence of an acute administration of levodopa. Results showed positive LLE values that, in the case of PARK, tend to be higher than LLE estimated for controls. This is particularly true before levodopa assumption thus showing a higher instability that is reduced after levodopa intake. This instability is not always evident looking at the classical posturographic parameters.

Static posturography was also applied to identify the presence of peripheral neuropathy in type-2 diabetic (T2D) subjects at an early stage [54] and to distinguish, retrospectively, non-fallers and frequent fallers in the elderly population [63]. In both cases, classification methods based on the principal component analysis were applied and a structural approach based on the sway-density plot resulted more indicative with respect to the classical, geometric, posturographic parameters.

Dynamic posturography: The stimulus to face this way to analyze equilibrium maintenance was the VAMA project financed by the ISS (Istituto Superiore di Sanità). Its aim was the functional evaluation of the motor ability of elderly people by means of simple but significant movement tests by the use of simple and low-cost instrumentation. The simplicity in the use of protocols and instrumentation was counterbalanced by the complexity of models used to pursue the Minimum Input Measured Model (MIMM) approach. The kinematics and dynamics of the functional reach (FR) test, usually used in rehabilitation to estimate the risk of fall of elderly people, was studied by the use of only one force-platform. The model and the optimization techniques used to obtain reliable results from the measurement of the ground reaction force data are shown in [53]. A more detailed study of the FR test by means of a complete set of classic movement analysis instrumentation has been applied on diabetic subjects in order to understand if there exist differences in the motor strategies employed to execute the FR test by patients with or without peripheral neuropathy. Results reported in [62] show that individuals adopt different motor strategies (both for kinematic and muscle behaviour) also when they exhibit the same clinical score.

As reported earlier, the instrumental assessment of balance is nowadays considered fundamental in order to characterize the principles governing the optimization and deterioration of postural control. However, in some cases a subject can maintain the upright stance without showing abnormal oscillation of both center of pressure and center of mass and at the same time exhibit abnormal responses when his balance encounters perturbations, of environmental as well as of proprioceptive origins. In the last years, the analysis of balance responses to various type of external stimuli, such as translation, tilt, rotation or backward and forward shift of the base of support, has been applied to subjects suffering of different neuro-muscular diseases. In this context the research group of the Movement Analysis Laboratory, is involved in a series of experimental activities aimed at investigating the motor control strategies carried out after sudden translation of the base of support produced by a motor driven device. Dynamic posture tests characterized by different translation velocities, backward and forward shift of the base of support and by different conditions, i.e. with open- closed-eyes and in dual task, are performed to analyze subjects behavior. The habituation rate and the effect of the first trial have been examined through dynamic, kinematic and surface electromyography (sEMG) analysis in normal young adults [68, 69], when repeated perturbations are administered without providing any specific indication to the subject. Furthermore, the ability to maintain balance when the base of support translates with increasing velocity has been investigated and different perturbation-related responses at the ankle and hip joints have been recognized. Currently, the same analysis is carried out also in healthy children to assess postural and balance maintenance strategies when motor development is still poorly developed.

To completely characterize the analysis of the dynamic posture in the experimental conditions above described, the interest of the group is now focused on the development of complex motor control models able to reproduce, as faithfully as possible, the dynamic control of the central nervous system [71].

1.4 Electromyographic Characterization of Walking

In the wake of preliminary studies performed at the beginning of the new millennium, the processing of sEMG signal was introduced (Fig. 1). Besides acknowledged methodologies such as time filtering, muscular activity assessment, and frequency analysis [67], a novel technique, named Statistical gait analysis (SGA), was adopted and validated to characterize the walking task. SGA is able to provide a statistical characterization of gait, by averaging spatial-temporal and sEMG-based parameters over hundreds of strides during the same walking trial of each subject. This technique is based on the fact that muscle activates a number of times which is usually variable from stride to stride, so that averaging is performed only over features assessed in strides including the same number of activations. SGA requires a large amount of data to run. A population of nearly 50 healthy adults was analyzed in our Movement Analysis Lab, monitoring 10 muscles for each subject during 5 min walking. The aim was to provide reference and normative data for activation during adult walking of the main muscles involved in this motor task, such as thigh and ankle muscles [46, 47]. Further purpose was to study and assess the co-contraction activity of joint antagonist muscles, acknowledged as marker of pathophysiology of the neuromuscular system. Normative data were produced [72, 99] and novel techniques aimed at quantifying co-contraction in time-frequency domain were developed [100].

The effect of gender was also studied in the population. A more complex muscular recruitment was detected in female population, that seems to reflect a female need for a higher level of joint stabilization [73]. In collaboration with Politecnico di Torino, Italy, a population of more than 100 healthy school-age children was recruited at Santa Croce Hospital, Moncalieri, TO, Italy, with the aim of providing reference and normative data also for children walking and studying the maturation of gait. Findings support previous studies which indicate adolescence as the time-range where gait is completing its maturation path [45, 50, 51]. Further advancements will focus on developing new techniques in time-frequency domain, on evaluating of muscle

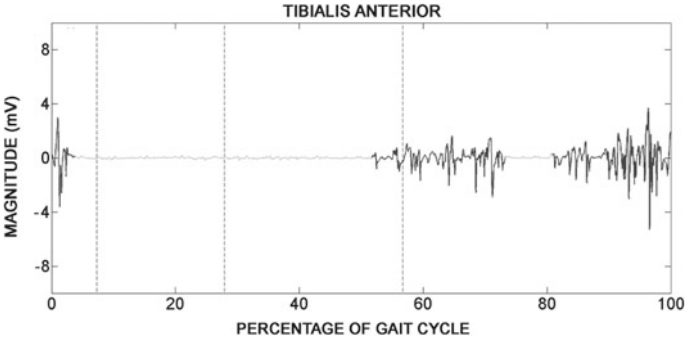

Fig. 1 sEMG signal acquired in the Movement analysis Lab during walking. Muscle activations detected by sEMG processing are highlighted in black

synergies by non-negative matrix factorization method, and on extracting significant features by data mining approach.

2 Cardiovascular Biomedical Engineering

Research studies on the cardiovascular system have always being performed at UNIVPM since 1977. Initially, the cardiovascular system was studied from a modellistic point of view to assess the cardiovascular hemodynamics, and in particular to quantitatively evaluate the physical properties of arterial systems through its input impedance, mathematically described by the windkessel models. In 1996 these studies allowed a critical comparison of linear and nonlinear formulations of the three-element windkessel model, from which it was concluded that the nonlinear three-element windkessel model cannot be preferred over its linear version. In 2007 Prof. R. Burattini proposed the four-element windkessel to study the development of systemic arterial mechanical properties from infancy to adulthood; the inductance and low-resistance terms of this model were finally physiologically interpreted in 2011.

Since 2006 the study of the cardiovascular system has been carried on mostly under the supervision of Prof. L. Burattini and focused on the computerized analysis of cardiovascular related signals, such as the electrocardiogram (ECG). Several filtering procedures have been developed in order to obtain signals of good quality from which to derive clinical information [4, 10, 55, 56, 91, 93, 94], and a great effort has been put in identifying noninvasive indexes of risk to develop malignant ventricular arrhythmias able to discriminate subjects to be treated before the occurrence of major cardiac events [24, 26, 57, 58, 61, 95].

Recently started research activities in the cardiovascular field still performed at the UNIVPM include, but are not limited to, the search for indexes of cardiovascular risk in athletes during sport activity [7, 84] and the automatic fetal monitoring [6, 9, 87, 89]. The automatic processing of the cardiovascular signals will surely remain a hot research topic for UNIVPM in the next years.

2.1 Automatic Identification of T-Wave Alternans

T-wave alternans (TWA) is an electrophysiologic phenomenon characterizing the ECG: it consists in beat-to-beat oscillations of T-wave morphology, concerning its amplitude, shape or polarity, unaccompanied by evident changes in the heart cycle length [17, 19, 32]. There are two types of TWA: the macroscopic one, first observed by Hering in 1908 and visible at naked eye, and microscopic one, first studied by Adam in 1984 and identifiable only through automatic methods [11]. Literature recognizes both macroscopic and microscopic TWA as useful markers of ventricular arrhythmias leading to sudden cardiac death [32, 33]. Given this clinical usefulness researchers have proposed many automatic methods for noninvasive detection and

quantification of microscopic TWA and their performances can be tested and compared using TWA simulators [15, 19, 82]. Prof. L. Burattini first proposed the Correlation Method [17, 35, 39], implemented during her doctorate course in Rochester (USA) and later, at UNIVPM, the Heart-Rate Adaptive Match Filter (Fig. 2), an effective method the advantages of which are robustness against noises or interferences and suitability to identify both stationary and time-varying TWA episodes [12, 16, 18, 20, 22, 34, 37]. Both methods were applied in case of several particular conditions or real diseases to detect the tendency to develop this kind of electrocardiographic anomaly. In order to mention some of them: TWA was studied in ICD patients [25–28, 60, 61], in coronary-artery disease [21, 31], in acute myocardial infarction [14, 15, 36, 38], in epilepsy [64], in sleep apnea patients [23], but also during exercise [13] or during pregnancy [65, 66].

2.2 *The Segmented Beat Modulation Method*

The Segmented-Beat Modulation Method (SBMM) [10] was proposed in 2014 as a template-based filtering technique to clean noisy ECG (SBMM algorithm has also been patented in 2014). Template-based techniques usually do not reproduce beat-to-beat heart-rate variability. Instead SBMM, thanks to its modulation procedure that prolongs the template for short beats and shortens the template for long beats, is able to adjust for short-term as well as long-term heart-rate variability. SBMM has been tested for robustness and ability to extract clean ECG signal [10, 83, 88] from recordings affected by low, medium and high levels of noise of various kinds.

SBMM has been successfully applied to several physiological signal processing applications such as (1) fetal ECG signal extraction from indirect ECG recording and (2) low-frequency component analysis and ECG noise removal in electromyography signals [88, 90, 96]. In these applications, some variations of the algorithm have been performed to adapt it to the specific problem [5, 83, 85].

The future work will include extending SBMM algorithm to detect cardiac arrhythmias (such as presence of premature ventricular beats) which could provide clinicians with valuable indications to specific diseases. An additional field of

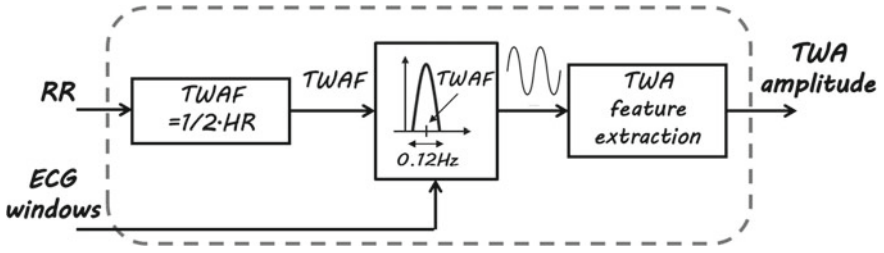

Fig. 2 Block diagram of Heart-Rate adaptive match filter

investigation will be using SBMM to extract ECG-derived respiratory signal from ECG recordings. Simultaneously directly acquired respiration signals will be used to evaluate SBMM performances. Eventually, another application for SBMM will be using SBMM for filtering ECG tracings obtained with wearable sensors, instead of conventional, in-clinic ECG systems. This will be a promising application for athletes requiring prolonged monitoring during exercise and sport activity, and for diseased patients who could be continuously monitored at home.

2.3 Automatic Fetal Monitoring

Fetal monitoring during pregnancy and labor is essential in clinics for establish fetal health status and thus to take prompt clinical decisions in critical cases. In the last four years, Prof. L. Burattini and her collaborators have developed several applications for fetal monitoring in order to support this sensitive practice. The focus was on standard fetal monitoring, like cardiotocography (CTG) [1, 2, 8, 87, 89, 92] as well as on challenging techniques, such as fetal electrocardiography [3, 6, 9, 65, 66] and phonocardiography [97, 98]. An example of these instruments is CTG Analyzer (Fig. 3), a graphical user interface for CTG feature extraction [87].

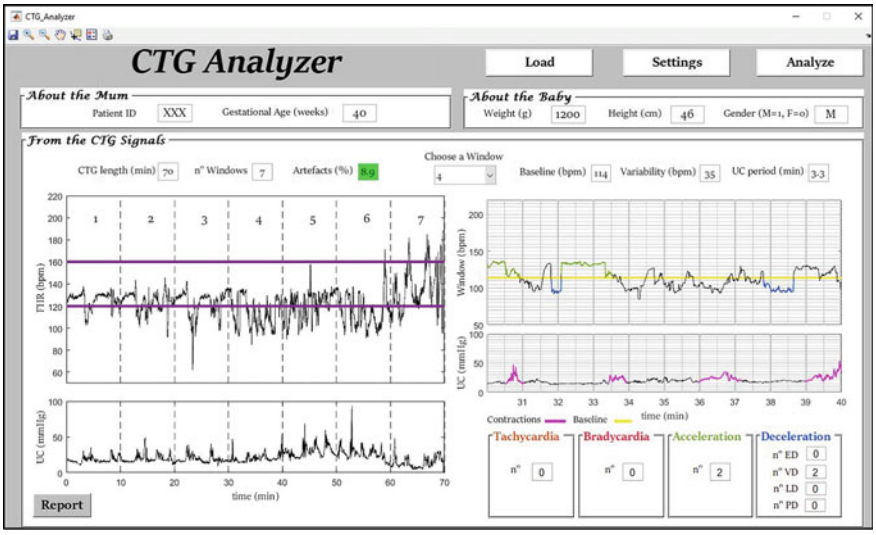

Fig. 3 CTG Analyzer, a graphical user interface for CTG features extraction

3 Metabolic Biomedical Engineering

Physiological processes regulating glucose tolerance can be described and quantified through a class of mathematical models called "compartmental models". The compartmental models defined as "minimal models" provides indexes that allow an indirect quantification of glucose-tolerance processes. Besides "minimal models", more complex integrated simulation models can be designed for a more detailed description of glucose-tolerance processes.

Development and application of model-based methodologies to describe glucose-insulin regulatory system and pathological changes of glucose tolerance, has been a key research area at UNIVPM since late 1990s. Research activities in this field have been started by Prof. R. Burattini who gave substantial contribution especially in better understanding glucose tolerance deterioration in hypertension, both in man and in animal models. Over the years, important research collaborations in this field have been established and are still ongoing; it is worth recalling the collaborations with the Metabolic Disease and Diabetes Unit of INRCA (Ancona), the Department of Experimental Medicine of the University of Genova and the Metabolic Unit of the CNR (Padova).

3.1 Glucose Tolerance Deterioration in Hypertension

Insulin-dependent and insulin-independent processes deterioration in human hypertension have been extensively investigated at UNIVPM. Main results showed that hypertension significantly deteriorates insulin sensitivity but not glucose effectiveness, as assessed by glucose kinetics minimal model (GKMM) interpretation of frequently sampled intravenous glucose tolerance (FSIGT) test data (S_I and S_G indexes, respectively). Dynamics of insulin action in hypertension was also investigated by using the dynamic sensitivity index (S_I^D); results showed that hypertension deteriorates S_I^D index, similarly to S_I [30]. In normoglycemic hypertensive subjects, this reduction in insulin sensitivity was shown to be compensated by an increase in insulin secretion, as assessed by C-peptide minimal model (CPMM) [30]. Hepatic insulin degradation was not found deteriorated in hypertension and model-based techniques were also proposed to allow a reliable estimation of such process [48].

3.2 The Role of Animal Models in the Study of Glucose Tolerance Deterioration

Animal models have played an important role in the exploration and characterization of glucose tolerance deterioration. One of the most studied is the Zucker Fatty Rat (ZFR), in which a mutation of the leptin receptor-coding gene impairs the

ability of leptin to suppress food intake. ZFR are characterized by a reduced insulin sensitivity (insulin resistance) and hyperinsulinemia. UNIVPM contributed to investigate in ZFR the existence of a relation between changes in sympathetic activity and alterations of glucose tolerance; results suggested that stronger sympathetic nervous reactivity in ZFR is associated with a severe insulin-resistant state before the onset of hypertension. UNIVPM contributed also to provide model-based [44], as well as empirical methods for the quantification of processes regulating glucose tolerance in ZFR [49, 76, 77, 79, 80].

3.3 Quantification of Insulin-Independent Processes

Insulin sensitivity is one of the insulin-dependent processes regulating glucose tolerance and is defined as the ability of dynamic insulin response to stimulate glucose uptake and reduce glucose production. At the same time, glucose tolerance is regulated also by insulin-independent processes. In fact, also glucose, per se, can stimulate its own uptake and suppress its own production even at basal insulin concentration; this property is called "glucose effectiveness". Recently, there has been a growing interest on the role of glucose effectiveness in the regulation of glucose tolerance, although it was underestimated for many years. It was demonstrated that glucose effectiveness is an independent strong predictor of T2D conversion and novel therapeutic agents acting on this process have been developed.

A reliable estimation of glucose effectiveness can be achieved by GKMM interpretation of FSIGT test data (S_G index). S_G index allows also to separately quantify the contribution of insulin-sensitive and non-insulin-sensitive tissues to the insulin-independent glucose disappearance; S_G components are called BIE (Basal Insulin Effect) and GEZI (Glucose Effectiveness at Zero Insulin). Studies performed at UNIVPM using GKMM-based methodology showed that S_G deteriorates with age but not with impairment of insulin sensitivity, if a normal glucose tolerance is maintained. In this latter condition, an increased proportional contribution of GEZI, when BIE declines, may allow the maintenance of normal S_G [78].

However, GKMM-based methodology suffers from two main limitations: it requires expertise to run GKMM and requires at least a 3 h-test. Studies performed at UNIVPM aimed to provide a simple predictor of S_G applicable to short tests (1 h) [75], thus allowing a simple but reliable quantitative estimation of insulin-independent processes.

3.4 Glucose Absorption and Incretin Effect Modeling

The modelling of glucose transit through the gastro-intestinal tract and its absorption represents a key issue in the modeling of glucose-insulin regulatory system. This issue became increasingly important after the finding that an augmented

glucose-dependent insulin secretion (insulin potentiation) exists in response to glucose transit through the gastro-intestinal tract. This phenomenon is the so called "incretin effect", mostly due to the gut-derived incretin hormones.

Incretin-based treatment for T2D have been proposed over recent years and simulation models contribute to improving knowledge of T2D pathophysiology and to assess the efficacy of hypoglycemic agents in clinical drug development. An integrated simulation model, intended to illustrate the importance of incretin effect, has been proposed by UNIVPM [29, 81].

4 Conclusion and Future Remark

4.1 Smart Technologies for Movement Analysis: Where Are We Going?

All the above cited MA applications are mainly based on classic MA instrumentation as stereophotogrammetric systems synchronized with force platforms and sEMG apparatus, and have been performed in a structured environment like a Movement Analysis Laboratory. The level of accuracy obtainable in such condition is very high but the type of instrumentation used avoids to perform analyses of daily living activities in non-structured environments like at home, or during working or just walking along a street. In recent years, new systems have been introduced in the consumer grade market based on very cheap sensors like 3D-accelerometers, 3D-gyroscopes, 3D-magnetometers that can be found integrated in smartphones or in light, cheap and wearable systems like IMU (Inertial Measurement Units). Very cheap gaming devices like the Microsoft Kinect (RGB-D camera) or force plates like the Nintendo Wii-balance board or webcams can be thought to be used in different scenarios like in ambulatory or in home environments. Attention has been given in the last years to this kind of devices as reported in [40–43, 70, 74, 86]. The low level of accuracy obtainable for example by wearable IMU devices can be counterbalanced by more complex digital signal processing techniques based on Kalman filtering that allows data fusion by redundant and different measurement sensors. In future we think that great attention has to be given by Machine Learning applications in order to extract from data, hidden features that characterize different motor tasks and behaviors.

4.2 Wearable Sensors and Smart Technology: The Future of Cardiovascular Monitoring

The future of cardiovascular monitoring will rely on the extensive use of wearable sensors and smart technologies. Indeed, wearable sensors are much more comfortable than traditional clinical devises and can be used routinely also at home allowing a

continuous monitoring of the patient. Patients' data will be sent real-time to cloud databases and computational center thanks to telemedicine techniques, where they will be analyzed by using deep learning and big data approaches. Self-monitoring will also become popular thanks to software applications running on smartphone that will be able to read the data recorded by wearable sensors and to provide alarms when the cardiovascular risk increases.

4.3 Toward Simple Quantification of Glucose Tolerance

Although the previously described modelling methodologies provide an easier assessment of processes mediating glucose tolerance, application to clinical settings is still prevented. In fact, tests required for the applications of model-based methodologies are usually time-consuming and expensive. In this context, the development of simpler but reliable methodologies is encouraged. Such simple indexes could be applied also in epidemiological studies, especially to understand the role of glucose effectiveness, on which new therapeutic agents are based, in the regulation of glucose tolerance.

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Citizen-Oriented Technologies in the Cities of Tomorrow

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Abstract The paper reviews some of the latest researches and future trends in the field of technologies to support sustainable, comfortable and healthy citizens life in the cities of tomorrow. A specific focus is on advanced methods to guarantee comfort and energy efficiency in the built environment, together with the support to the ageing people in their homes. Innovative sensing systems are presented to monitor both the environment conditions and people in a non-intrusive way, thus allowing the implementation of efficient management strategies and new social services. The review presents real case studies properly equipped with comfort measurement systems, sensor networks including physiological parameters or with specific HVAC and construction components to assess the effects on energy consumptions and comfort

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levels of different control strategies and configurations. In addition, distributed generation technologies installed at final users together with their increasing awareness in energy consumption patterns, result in the "prosumer": a citizen that simultaneously acts as an aware energy consumer and producer. Based on the achieved outcomes, a discussion about the most promising research lines for citizen-oriented technologies in the cities of tomorrow is finally presented.

1 Introduction

Human-induced warming is increasing at a global average of 0.2 ± 0.1 °C per decade [1]. Land, and notably urban regions are the hardest-hit areas to the point that 20–40% of the global population is already experiencing temperature increments of more than 1.5 °C above pre-industrial levels.

Ambitious and concerted counteractions are crucial, but they should be strategically devised not to fuel energy poverty [2]. People are the reason why cities and buildings exist, and occupants don't have energy problems but comfort problems Since people spend about the 90% of their time indoors [3] and comfort conditions can significantly impact on their wellbeing, health and productivity [4].

Thus, the monitoring and control of occupants' comfort has to be accurate and comprehensive to feed the optimal design and management of buildings while minimizing the required energy expenditure. Comfort perception is the sum of several factors: environmental, physiological and psychological. Therefore, the use of the only air temperature to evaluate if an occupant is or not in comfort conditions is far from the real human perception. For this reason, the accurate monitoring has to merge data acquired from different sources, including thermal, visual, acoustic comfort together with indoor air quality and human related factors. In this framework, new sensing technologies, data analysis techniques and smart controllers were developed and compared against a variety of boundary conditions, architectural solutions, innovative materials and technical equipment.

At the same time, the monitoring of occupant's comfort and behaviour allows the collection of data that can enable also new functionalities to support the life of fragile and ageing people in cities and buildings. The Ambient Assisted Living (AAL) scenario is providing important opportunities in the development of innovative products, services and systems. The policies toward a better AAL scenario are strongly supported by the policy-makers both at national and European levels. The specific solutions proposed by research and industry aim to improve the quality of life, autonomy, social life participation and employability of users, reducing the costs of health and social care [5]. A remote monitoring of the patient's health status and lifestyle within his personal environment is proved to be an effective tool to face the problem of the increasing healthcare costs and to improve the quality of life of users and caregivers at home [6, 7].

In the clear trend where the person is more and more at the center of cities and buildings developments, in recent years, also the traditional paradigm of the electric

energy system has been challenged by new technologies that empowered citizens who turn to be increasingly active final consumers. On the one hand, distributed generation technologies, such as PV and micro-chp [8], are transforming final consumers in "prosumers", a neologism meaning the twofold function of both "producer" and "consumer". On the other hand, new smart devices, such as smart appliances and smart home monitoring systems, entered the market allowing the final consumers to change their pattern of consumption. The main drivers that pushed this change were national and local scale policies [9, 10] that promote a clean and environmental sound energy system by means of renewable energy and energy efficiency at final users. The last effort in this direction was the "clean energy package" presented on 30 November 2016 by the EU Commission [11] aiming at fulfilling the Energy Union and at meeting the goals set by the Paris Agreement [12]. The key measures proposed by the "clean energy package" are: (i) to give priority to energy efficiency (energy efficiency first); (ii) to achieve a worldwide leadership in renewables ("World leader in renewables") and (iii) a consumer centered energy market ("Fair deal for consumers").

In these research fields focused on citizen-oriented technologies for the cities of tomorrow the Department of Industrial Engineering and Mathematical Sciences at Università Politecnica delle Marche is very active. The paper reports therefore some of the latest developments in the area of:

- innovative sensor technologies for both comfort and AAL solutions (Par. 2);
- advanced control and HVAC solutions to improve energy efficiency whilst preserving comfort and flexibility (Par. 3);
- solutions based on advanced materials, as e.g. Phase Changing Materials—PCMs (Par. 4);
- distributed generation technologies for prosumers (Par. 5).

Based on the findings, a short discussion about future trends (Par. 6) in the intended fields is finally presented.

2 Innovative Sensor Technologies in Buildings and Cities

2.1 Innovative Solution for Comfort Monitoring in Indoor Environments

Thermal comfort is probably the most important aspect of Indoor Environmental Quality (IEQ). It has a direct impact on the energy consumption of building as any sense of discomfort of occupants leads to the tweaking of controls to non-optimal levels. Thermal comfort is generally measured by sensors compliant with mathematical models that express the overall interaction between the human body and the environment (body heat production and exchange, influencing factors, etc.). The balance between the human body and the surrounding environment has been deeply

investigated to determine mathematical models that express the overall interaction (body heat production and exchange, influencing factors, etc.). The Fangers' comfort theory enumerates six factors to determine the heat balance and provide a formula to calculate the PMV (Predicted Mean Vote) index. Four of the six are environmental parameters: relative humidity, air temperature, mean radiant temperature, and air velocity. The remaining two are personal factors: the metabolic rate and clothing insulation. The PMV measurement requires thus the capability of sensing not only environmental parameters but also factors related to occupants' characteristics.

An innovation for the monitoring of thermal comfort is represented by the Comfort Eye sensor, developed in H2020 and regional projects. As presented in [13] the concept of the Comfort Eye is based on an IR scanning system (Fig. 1), installed on the ceiling of the room to measure the indoor surface temperatures.

The thermal maps are sent to a gateway, which calculates the mean radiant temperature and, using the data from environmental sensors (i.e., air temperature, relative humidity), the Comfort Eye returns the PMV index. The calculations are performed for different positions of the room, near and far from the glazed surfaces, and for typical room occupants' profile. A new methodology for the real-time measurement of the metabolic rate has been integrated into the Comfort Eye. The approach is based on the work presented in [14], where a wearable device is used to measure the heart rate (HR) of the subjects occupying a room to calculate the actual metabolic rate using calibrated curves as shown in Fig. 2. The proposed innovative comfort monitoring solution has been applied to a real case study, a meeting room into a

Fig. 1 The IR scanning device of the Comfort Eye

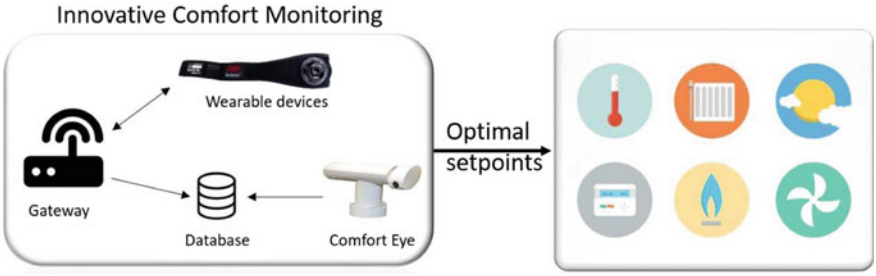

Fig. 2 Scheme of the innovative comfort monitoring for the optimal HVAC management

curtain wall building located in Italy, where the sub-zonal monitoring and control of the room has been validated [15].

The system was tested in a summer day, where cooling was provided by the HVAC system presents in the demo case. Different tasks were performed by three subjects considering a real-time and continue evaluation of metabolic rate (calculated by HR) to obtain the indoor thermal comfort level. The total duration of each test was 30 min divided into three sessions of 10 min. During the first session, the occupant conducted sedentary work in front of the PC; in the second session the subject walked into the room and in the last he/she returned to the sedentary activity. Figure 3 shows the results from the experiment.

It is possible to observe that an increase in metabolic rate (a symptom that the subject has increased its activity), corresponds to a higher value of the PMV. Consequently, the system of comfort monitoring provides to the HVAC control a lower set-point temperature in order to restore a comfort condition. The experiment demonstrates the importance of measuring the real human behaviour in buildings to perform accurate management of the indoor environment.

2.2 Sensor Technologies for Active Assisted Living

The development of systems able to automatically detect and predict future behaviours or abnormalities is remarkably attractive for many applications, both in the field of healthcare monitoring [16, 17] and Smart-Home technology [18]. This kind of information can be obtained through the combination of multiple heterogeneous measured quantities (e.g. physical, physiological and environmental) achieved by integrated sensor networks and data mining technologies.

The interest in continuous data acquisition from wearable [19] and non-contact devices has been widely increased in the last years, focusing on how to efficiently process such quantities to gather more refined information, linked to the quality of life of users. In this context, the EU AAL project eWare—Early Warning Accompanies Robotics Excellence ([20], where UNIVPM is partner) introduces an ICT eco-system to monitor without contact and assist a fragile user (subject with initial

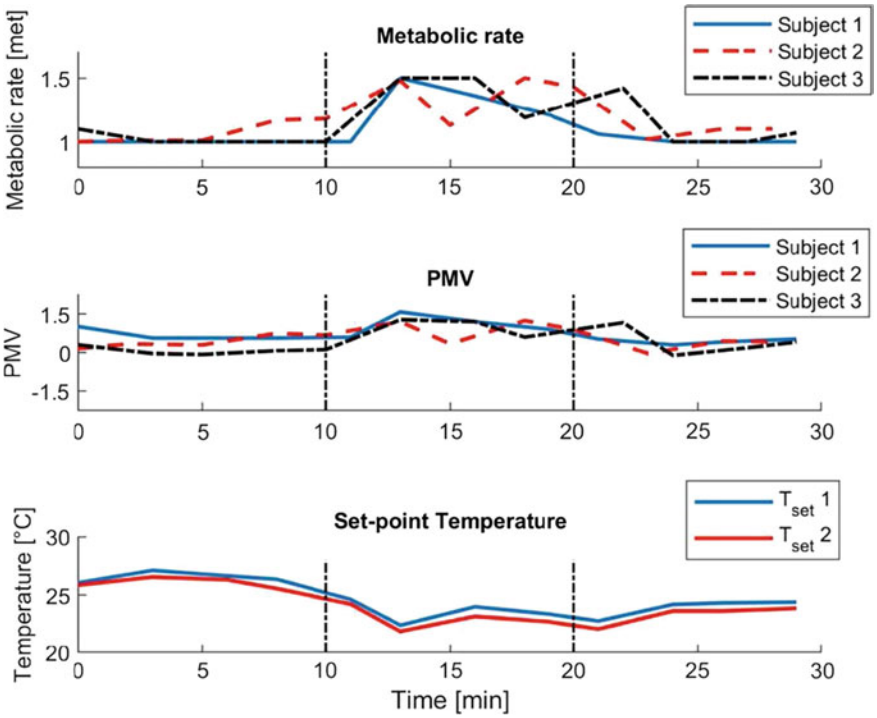

Fig. 3 Time-series of the metabolic rate of each subject, PMV values and set point temperatures provided by the Comfort Eye

stage of dementia) at home. The innovative idea developed by the eWare project is the integration of sensors, to monitor the Activities of Daily Living (ADLs) of the older adult at home with a small social robot to provide context-relevant suggestions and stimuli to the user and, in parallel, important feedbacks are also sent through a web-app to the caregiver. In particular, the robot interacts with the user having cognitive disabilities in achieving their ADL goals. Goals such as having breakfast on time every day, eating dinner at appropriate times, leaving the house for activities or going to bed at the right time. In fact, individuals with cognitive disabilities such as dementia often have difficulties in initiating activities.

ADLs are defined based on a measurement methodology that can be reassumed in three actions, Fig. 4. The first step is devoted to the actual measurement setup characterized by set of sensors (PIR and door sensors) placed in the home environment. These sensors, once installed in the home environment can provide information regarding the user‘s behaviour using algorithms in the analytics stage framework. The sensor network and the artificial intelligence (AI) phases compose the measurement process. The output is the measurand, i.e. the real behavioural patterns identification called ADLs.

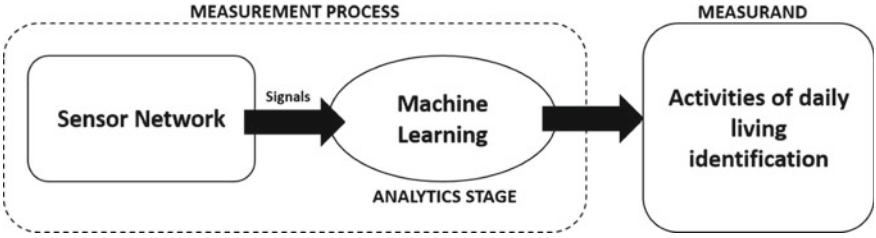

Fig. 4 Measurement approach to extract ADLs

The measurement process has an important role to identify ADLs. Many aspects can compromise the accurate identification of ADLs. All these aspects are part of the measurement process.

1. Sensors choice: identification of the sensors required to monitor the behaviour of the user considering the information to be extracted and the accuracy of the transducers. This first aspect of the measurement process can have an important role for the generation of the measurement uncertainty (e.g. [21]).
2. Machine learning: identification of the processing strategies (e.g. [22]). In this second step of the measurement process uncertainty can propagate, to be coupled with the model uncertainty itself.

These aspects can be solved using specific strategies to manage the risk caused by the uncertainties of the measurement process on the results. In the eWare context, definition of goals for the resident and a strong decision procedure can decrease the biases in the measurement process and so, in the results.

To represent the measurement approach, a tool for the simulation of indoor human trajectories able to represent the relationship among ADLs and recorded PIR sensor outputs, starting from Smart Home environment and sensors' number and characteristics, has been realized. The simulation approach allows to quickly generate sensor data, useful to evaluate sensor network optimization before the installation on a real environment and to develop machine learning methods for ADLs recognition and behavior monitoring. In this sense, in order to demonstrate the applicability of this simulator, the analysis of a certain case study was proposed, which is the detection of overnight wandering (Fig. 5), a common behavior in people with dementia. The tool has been used to create synthetic normal and wandering trajectories and their related datasets of sensor activations. By using the generated sensor data, it has been developed a classificatory model to assess if it is possible to distinguish normal behavior from wandering one using solely sensors outputs.

Results show that a binary classification algorithm, such as Decision Tree, is reliable to distinguish by PIR sensor activations normal trajectories from wandering ones, obtaining an accuracy level above 95% using a cross-validation approach. Obviously, with only one PIR sensor for each room, it is not possible to discriminate which type of wandering trajectory the user has performed [23]. The same kind of

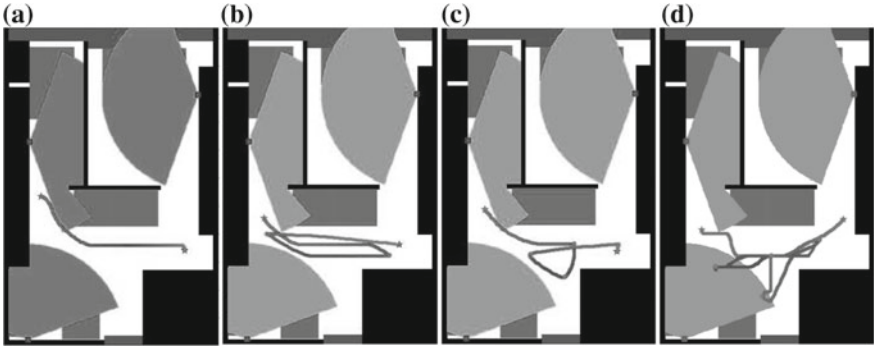

Fig. 5 Examples of computed wandering trajectories in an apartment characterized by 3 rooms and 1 PIR installed in each room. **a** Direct path with high efficiency; **b** Pacing path with lower efficiency; **c** Lapping path with high efficiency; **d** Random path with medium efficiency. Starting and target points are indicated with stars, repeated locations with points

approaches and information can be used to detect occupant's behaviors for integrated health, comfort and energy efficiency purposes.

3 Advanced Control and HVAC Solutions

The development of advanced monitoring techniques can enable optimal building management strategies. Thus, research on efficient control implementation is another fundamental step. A first investigation was conceptualized to compare the performance of on-off, PID and fuzzy algorithms, used to govern radiators' emission, given the market availability and widespread use of such components [24]. To date, their regulation relies on room thermostats or thermostatic valves [25].

Tests were carried out on an experimental, energy-efficient building in Central Italy, geared with an articulated sensor network that simultaneously collected information on the internal and external microclimatic conditions and mapped the envelope response to the heat transfer mechanisms at stake (Fig. 6). The monitoring period lasted from December 2014 to April 2015, under non-occupancy, winter/midseason weather conditions.

The following options were compared:

on-off controller, set with a hysteresis value of 1 °C;
on-off controller, set with a hysteresis value of 0.5 °C;

PID controller, tuned by trial-and-error procedure until an optimal coupling with the specific process was achieved (proportional band of 2 °C, an integral time of 10 min and derivative action annulled to avert too close tracking of the sensor fluctuations [26]);

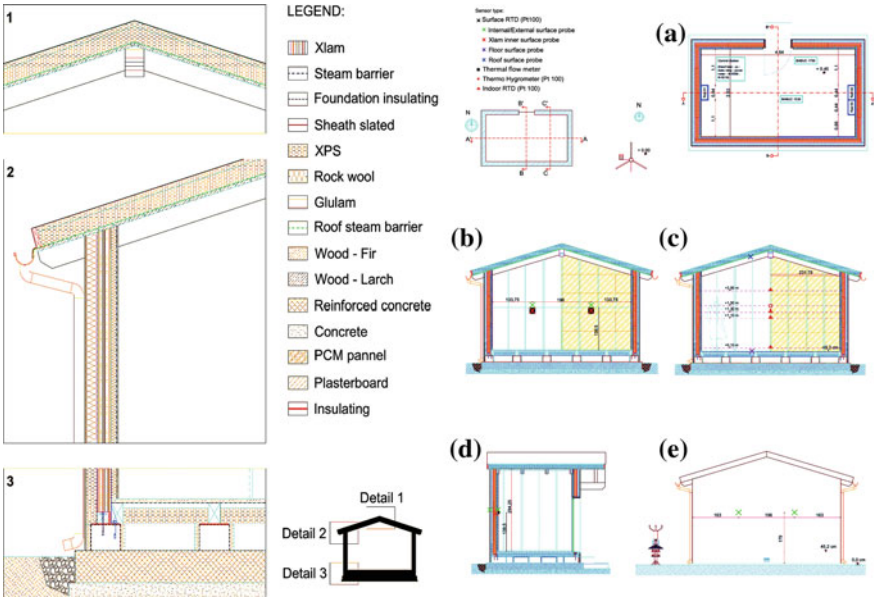

Fig. 6 Left: experimental mock-up wall composition; right: sensor network inside and outside the mock-up [24]

fuzzy MISO controller, namely a multiple input (ambient temperature, its derivative and outdoor air temperature) single output, rule-based controller.

Note that the selected hysteresis values refer to the Standard UNI TS 11300 part 2 [27].

All configurations were assessed in terms of thermal comfort and energy consumption to return an exhaustive scenario of possible strengths and weaknesses.

The energy consumption was normalized over the absolute value of the difference between time-averaged ambient and outdoor temperatures, and then two energy signatures were plotted, one in function of the outdoor air temperature and the other in function of the global solar radiation.

The comfort assessment was conducted in a long-term perspective: the PMV and PPD time trends were visualized and processed to calculated the excess weighted PPD (PPD.h) [28] to account for the whole observation period.

The results highlighted that the fuzzy controller outperformed the others, providing the highest comfort standards with the minimum energy cost. In detail, it consumed 67.8, 43.8 and 31.4% less than the on/off-1 °C, the PID and the on/off-0.5 °C controller respectively (normalized energy consumption) and averted any discomfort phenomena (the only one with PPD.h equal to zero).

A second topic of the research was the smart management of windows' opening/closing cycles [29]. School buildings were targeted with the aim of maximizing thermal comfort and indoor air quality (IAQ) through a customized adaptive comfort algorithm (ACA).

When it comes to educational environments such targets are essential requirements for the correct accomplishment of the core functions, as teaching and learning are remarkably sensitive to poor environmental quality and adaptive actions to restore comfortable conditions are generally not promptly adopted.

Naturally ventilated schools are the most vulnerable cases. The conducted research turned out to provide that CO_2 levels can be tweaked in an efficient, comfort-respective way without threatening students' attention (by making noise or triggering local draughts) and without making them feel deprived of their direct control over the surroundings.

Between March and April 2015, two identical and adjacent classrooms were monitored, featuring both hopper and casement windows: one was in free running mode (FR), the other, in parallel, was equipped with a stepper motor on the hopper window (MT). The opening/closing loop was piloted by a tailor-made ACA platformed in LabVIEW and based on Humphrey's algorithm [30] to provide adequate user-centred approach and flexible structure.

The trigger parameters were identified by means of linear regression analysis: the main environmental driver was the offset between operative temperature and the comfort temperature, yet through a nested decision-making loop, CO_2 overabundance could possibly take over. This prioritization was in line with previous works' findings [31, 32].

The tuning procedure led to a threshold of 1250 ppm for the carbon dioxide content (trade-off between ASHRAE [33] and Building Bulletin [34] suggested limits) and a reduction of the acceptability range around comfort temperature from $\pm$ 2 to $\pm$ 1 °C.

According to the collected questionnaires, the clear majority of users (both students and teachers) witnessed a sensation of thermal neutrality in both the classrooms, but with no control over the ventilation rate, the tendency was to suffer warm microclimates, while comfort-model based methods highlighted a stronger vulnerability to cool conditions.

In terms of IAQ, the CO_2 level in the MT classroom trespassed 1500 ppm three times less frequently than in free running conditions (8.7% vs 30.7% of the time). Besides, the indoor operative temperature stayed within the comfort boundaries almost all the time (see Fig. 7) with a very smooth time trend. This implies that no extra calls to the heating terminals would be required in presence of the proposed controlled system to catch up the gap caused by strong temperature drops (like the ones recorded in the FR classroom).

From a functional perspective, the automatic operation of the hopper windows allowed students and teachers to never interrupt their activities just to restore their comfort, preserving attention, concentration and responsiveness without any distraction.

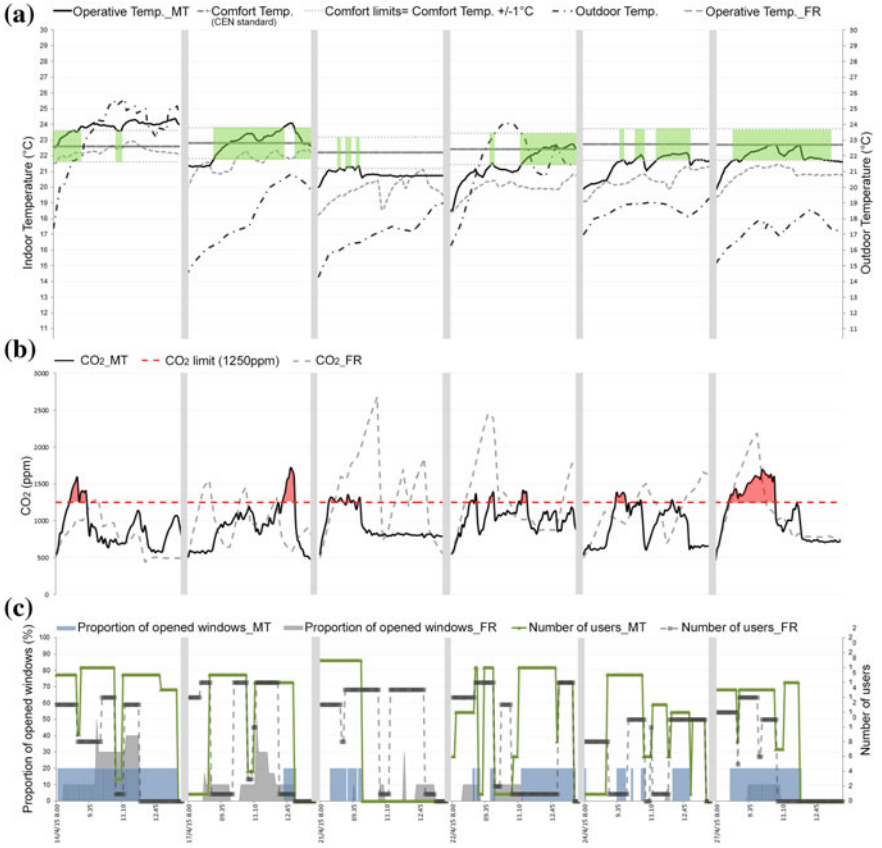

Fig. 7 Thermal **a** IAQ **b** and occupants related information **c** recorded over six representative days for both MT and FR classrooms [29]

4 Solutions Based on Advanced Materials

In order to increase personal comfort keeping the energy consumption at the minimum, also solution based on advanced materials for building components have been developed. For example, the behaviour of the external envelope of a building is affected by the contribution of construction components. External walls made with hollow clay bricks or blocks are widely used for their thermal, acoustic and structural properties. However, the performance of the bricks frequently does not conform with the minimum legal requirements or the values required for high efficiency buildings, and for this reason they need to be integrated with layers of thermal insulation. A research carried out in the laboratory of Environmental Energy evaluated the possibility of increasing the energy performance of thermal bricks through integration with two different technologies: the first one is based on the insertion of phase change material (PCM) inside the enclosures of the bricks, while the second one involves

covering the internal surface of the enclosures with low emissivity coating. PCM was employed to increase the thermal mass while the low emissivity coating reduces the overall heat transfer coefficient value. To demonstrate the effectiveness of the solutions, energy evaluation was carried out on the bricks using both theoretical and experimental analyses. Stationary and dynamic analyses were performed. The investigations were made according to Italian, European, and international standards: theoretical analyses were based on Finite Element methods, while experimental tests were carried out with the heat flow meter method. Finally, a comparison was made between the theoretical and experimental data and the error was estimated. The purpose of the application of low emissivity treatment is to obtain a reduction in the thermal conductivity of the block by lowering the radiative heat exchange in the enclosures. The aims of the work have been to indicate a methodology for evaluating the thermal performance of the brick and to provide information about the benefits that should be obtained. Theoretical evaluations were carried out on several bricks (12 geometries simulated with two different thermal conductivities of the clay), using a finite elements model. The heat exchange procedure is implemented in accordance with the standard, so as to obtain standardized values of the thermal characteristics of the block. Several values of emissivity are hypothesized, related to different kinds of coating. Finally, the values of the thermal transmittance of walls built with the evaluated blocks have been calculated and compared. The results show how coating the internal surface of the cavity provides a reduction in the thermal conductivity of the block, in the range between 26 and 45%, for a surface emissivity of 0.1 [35].

Continuing in this field, a second remarkable research was carried to verify the performance of a cold room for food conservation with a novel air heat exchanger containing PCM [35–39]. Experimental activity was devoted to investigate the effect of PCM air heat exchanger on the temperature of the evaporator, cold room compartment and finally on electricity consumption. Results indicate that the amount of PCM used, melting-point temperature and air heat exchanger geometry played relevant role in energy saving. The results indicate that the PCM freezing/melting process allowed the reduction of compartment temperature fluctuations over time, avoiding the destructive effect of frequent compressor starts and stops on food quality. Lastly, the compressor ON/OFF time was optimized (the number of the ON/OFF compressor cycles was equal to 6 in the novel cold room instead of 13) and energy consumption was reduced (16%). For further improvement of energy efficiency under steady operating conditions, the amount and the melting temperature of PCM should be optimized in accordance with heat gain of the cold room at environment temperature. Moreover, its effect could be also represent a benefit on preserving the food quality during a period of power outage given that PCM air heat exchanger stored energy can be released in case of power loss.

5 A Consumer-Centered Energy Market and the Role of Distributed Generation Technologies

Active consumer and prosumers will play a pivotal role in the energy markets of the future, being able to change their pattern of consumption and to self-produce electricity. In this context, distributed generation technologies are key technologies in a consumer centered energy market promoting renewables and energy efficiency. Distributed generation (DG) means to produce electricity where, or close to, it is consumed. DG leads to several advantages: (i) reduction of grid transmission losses; (ii) increased resilience of the electric grid; (iii) better exploitation of renewables at local scale; (iv) higher energy efficiency, for fossil fuel fed DGs, in the case of recovery of waste heat for cogenerative (CHP—Combined heat and power) and trigenerative (CCHP—Combined Cooling Heat and Power) applications. Research activity on DG technologies at the Department of Industrial Engineering and Mathematical Sciences (DIISM) of Università Politecnica delle Marche is strongly focused on DG form both fossil fuels and renewables. In particular, several DG technologies have been investigated during the last twenty years: Stirling engines, internal combustion engines (ICEs) [36, 40], micro-gas turbines (MGTs) [41–44], high concentrated photovoltaic (HCPV) [45] and hybrid systems [46]. In particular, Stirling engines, ICEs and MGTs have been deeply investigated in cogenerative applications both under environmental (curbing of fossil fuel consumption) and economic point of view [47]. Indeed, CHP technology is a very effective high efficiency measure since it allows to strongly reduce fossil fuel consumption; the main KPI used to assess CHP is the primary energy saving (PES), a non-dimensional index which quantifies the amount of primary energy saved by producing useful heat and electricity by means of cogeneration with respect to the separate production of the same amount of useful heat (in a traditional boiler) and electricity (in a centralized power generation plant). Thanks to CHP plant it is possible to produce electricity locally and to heat/cool an urban energy district thanks to a district heating/cooling network [48]. The integration of CHP technologies, renewable energy sources and, in the near future, energy storage contributes to the way towards the so-called “low carbon districts”. For this reason, in recent years, due to the widespread of DG at local scale, in particular of PV, the research activity has also been focused on the integration of different energy systems in urban districts. In particular, the research activity was related to the optimal management of renewable energy sources, energy storage and load control in residential [49] and industrial [50] microgrids, through monitoring systems [51] and smart energy management systems.

6 Future Trends

Achieving optimized standards of life quality and sustainability in cities and buildings is not an easy task, whether the target is energy or comfort, or both. Yet, it is crucial as only a satisfied user does not intervene with the design concept.

In the past decades, efforts have been largely put into the "hardware" side of the problem (buildings and technologies) with little or no attention on the human perspective. There is, therefore, huge potential for an industrial base to provide comfortable, healthy and safe indoor environment. However, technologies and building codes only address the "hard" facts and tend to disregard the "soft" human factors. The large diffusion of personal devices and wearables are stimulating the research community to include the human perspective in the traditional solution, also given the endless availability of data derived from the large deployment of IoT and connected systems. So, the actual trend in the comfort monitoring and management is to overcome the traditional "thermostat", using the information derived from the human interaction with the environment, that is becoming itself an high-efficiency sensing system. The challenge is now moved to the investigation on how to use the large amount of data, coming from multiple sources and complex domains, to obtain reliable information on human perception and satisfaction. In this field, most of the effort will be oriented on the application of learning techniques (machine learning and deep learning) to capture the human reaction to the environmental conditions. In this regards, the research team at DIISM is involved in several H2020 projects where these concepts are being developed and will be demonstrated in real pilot cases.

The same trend applies for supporting fragile citizens in their houses with innovative services. The core of technology development is turning into using increasingly intelligent algorithms to the detriment of the number of information acquired in place, with potential integration with energy, comfort and maintenance services. Also in this area DIISM is contributing in the future challenge to improve quality of life of aged subjects and their caregivers, with flexible and user-adapted technologies.

In the field of smart control, UNIVPM researchers in last years proposed a suite of possible and substantiated solutions, basically relying on fuzzy logic. Going further, quite promising developments might be achieved by imparting adaptive features, as in adaptive neuro-fuzzy inference systems -ANFIS- or cooperative fuzzy model predictive control -CFMPC [52]. On the other side, buildings' thermodynamics and thus HVAC efficiency are strongly integrated and influenced by the outdoors, that cannot be thus ignored. In this vein, already in progress and future studies will be devoted to Urban Heat Island mitigation advanced technologies, mostly relying on evaporative cooling. A first run focused on smartly controlled water nebulization: significant results have already been achieved, yet much is still to be disclosed.

At the same time, in future prosumers will play an active role not only in "urban low carbon districts" but also in the whole "consumer centered" energy market. The pattern towards a consumer centered market passes through a progressive evolution from being passive consumers to become active and engaged consumer. In the next

future, energy market has to face several challenges: an even higher share of not predictable renewable energy sources (PV and wind), an increasing market penetration of energy storage and the entry in the market of electric vehicles. This is a sort of bottom-up energy revolution that puts the engaged citizen/prosumer in the front line of this the energy revolution.

DIISM is part of the cutting-edge research on this energy revolution thanks to three European and National projects awarded in 2018: Interrface (EU-H2020 on Smart Grids, with the final goal to engage consumers into electricity markets), Musegrids (EU-H2020 on multi energy systems), ComESto (National Energy Cluster project on Energy Storage focused on the concept of nanogrid). All projects deal with citizens becoming empowered prosumers.

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Smart, Eco-Sustainable and Human-Centered Product Development Processes: 21st Century Manufacturing Industries

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Abstract The development of new and valuable products, from conceptual design to production, is to date supported by advanced methodologies based on ICT tools allowing many controls and checks before proceeding to heavy spending investment decisions. The increasing use ICT allow highlighting product design process and solutions able to improve people's quality of life. Key product development principles based on human-centered approaches and eco-sustainability concepts prove to be the main factors affecting both the products' users as well as the product manufacturing staff. This paper outlines product's development approaches state of the art, foreseeing at the same time possible research trajectories to define manufacturing industry future scenario based on more sustainable economical, environmental and social design choices.

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1 Introduction

Economic, environmental and social sustainability of companies is a steadily growing challenge for the global business community. The sustainability models form the basis for the advice the companies provide and for decision-making. In particular, many companies try to implement the principles of sustainability in their organizational culture by adopting international standards and management systems, (e.g. Global Reporting Initiative [15]) guideline, ISO 14001, 9001, OHSAS 18001 and Social Accountability 8000 standard (SA8000). These guidelines and frameworks have gained in popularity over the last decades and they have been key components in the corporate strategic management and decision-making process [4, 32].

An area of particular interest for sustainability, which receives heightened interest concerns the impacts of products and services on people and the environment [27]. In particular, the life cycle thinking is a suitable approach for evaluating impacts derived from the behavior of all players involved in the life cycle of products [9]. In the context of life cycle thinking, the three basic dimensions of sustainable development (i.e. environmental, social and economic dimensions) have been identified and various methodologies and tools have been proposed. Specifically, Life Cycle Assessment (LCA) methodology has been developed in order to analyze the environmental impacts of a product's life cycle, while Social Life Cycle Assessment (SLCA) and Life Cycle Costing (LCC) methodologies evaluate the social and economic impacts of products, respectively.

The aforementioned methodologies have not been developed at the same rate. In particular, Social LCA is not fully developed and many authors stress that there is plenty of room for progress in this area [35]. According to [37], the main weaknesses of the SLCA approach are connected to the selection of the appropriate data and social indicators, the inclusion of stakeholder groups and impact categories as well as issues regarding the impact assessment methods.

The relevance of social impact assessment is particularly stressed if regarded the sustainable manufacturing in the widest context of sustainable development. In fact, as it well known, sustainable development must be regarded in as meeting the need of the current generation without compromise the possibility for future generations to satisfy their owns [6].

This anthropocentric perspective leads to joint objectives in particular between ergonomics/human factors and sustainable manufacturing. In fact, if social sustainability is realized in general through concepts such as preventive occupational health and safety, human-centered design of work, empowerment, individual and collective learning, employee participation, or work-life-balance [18] the sustainability of human resources based on enduring workability and employability have always been dominant elements in ergonomics/human factors. Consequently, the implementation of ergonomics in the product life cycle might support productivity and quality, promote the health of employees and improve competitiveness [19].

In this context, the present work aims to highlight the main approaches described in literature then a critical analysis of research open issues for the 2050 scenario is reported.

2 Life Cycle Approaches in Sustainable Product Development: State of the Art

A sustainable product development process should be based on three pillars: social, environmental and economic (Fig. 1). The following literature review is structured with the aim of emphasising and analysing such pillars.

2.1 Social Life Cycle Assessment

Social Life Cycle Assessment (SLCA) is defined as an effective technique useful to analyze social and social-economic aspects that influence different stakeholder groups. These social-economic aspects are linked to products and consequently with the production processes and other business practices which take place along the life cycle of a specific product.

The increasing interest in SLCA methodology has led to a growing body of literature that discusses the applicability and the usefulness of SLCA methodologies for assessing the social impacts connected to the life cycle of a product [20]. Some authors (e.g. [26]) developed theoretical approaches that examine different methodological issues in order to improve the effectiveness of the Social LCA methodology.

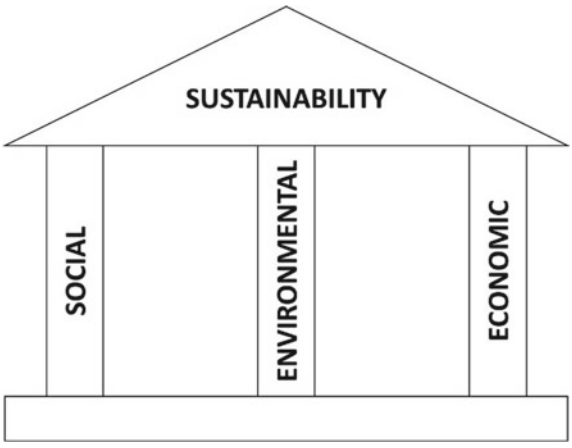

Fig. 1 The three pillars of sustainability

Reference [10] discussed the possible challenges and constraints derived from the implementation of SLCA in product-services systems (PSS). They suggested a "multicriteria indicator model" in order to evaluate social impacts of products. Reference [28] proposed a system dynamic approach to assist in facilitating stakeholders' participation in SLCA methods. A causal model and scenario-based methodology are defined to facilitate the integration of stakeholders' views in product life cycle thinking.

Many authors suggest several indicators to measure life cycle stages and social aspects. Reference [21] stress the importance of measuring aspects concerning the impacts of unemployment on production (e.g. physical and mental health problems, salary reduction) and on workers (e.g. skill degradation). Reference [17] developed a range of socio-economic indicators that are based on three criteria: relevance, practicability and validity. Some of these indicators are gendered labor costs, migrant labor costs, fair wages and discrimination. Reference [21] identified some methods to measure problems associated with child labor and developed essential indicators to improve.

Many authors (e.g. [37]) provide different case studies of the SLCA implementation that show the applicability of SLCA methodological frameworks to a wide range of products from different sectors and for diverse purposes.

An important aspect of social impact in manufacturing is related to human well-being (cognitive and physical) during their daily work. Ergonomics refers to the scientific discipline concerned with the understanding of interactions between humans and technologies, to make tasks, devices, interfaces, equipment and environments compatible with the needs, abilities and limitations of people and therefore to optimize this interaction to create the best working conditions. In the last decade it has been demonstrated how human factors highly affects the global efficiency and costs of industrial processes, from material handling to assembly, order picking or operations in line [3]. Low attention to human factors brings to unnatural positions and dangerous actions executed by workers during their jobs, with consequent lower performances, higher production time, greater absence from work, and a general increase of Musculoskeletal Disorders (MSDs), but also significant mental problems as depression. Understanding real MSD risks, especially related to manual tasks, represents a crucial objective. Given the quantity and complexity of the activities that an operator has to perform, to support the achievement of this objective can be very useful to implement systems that allow a constant monitoring of the operators during the working phases. To this end, in the last years, wearable and environmental sensing technologies aim to provide solutions able to observe the human behavior in order to identify problems and optimize roles [30]. The anthropocentric perspective cannot leave the Industrial and organizational Psychology out of consideration. The discipline is very wide and rich, and it covers a variety of specialty areas and many relevant issues. Job analysis is one the most relevant. It is the collection and analysis of the current work activities that is the starting point for their improvement. Job analysis methods include work-oriented methods, which seek to understand and describe the job in terms of the outcomes and the activities, and worker-oriented methods, which seek to detect the personal features required to successfully performing a job.

In recent years, many authors prefer to use the term "work analysis" instead of "job analysis". This change reflects a new focus on innovation and a distance from the rigid definition of job boundaries. The cognitive work analysis (CWA) provides an interesting approach to design and analyze complex sociotechnical systems [11] and integrate the concepts of cognitive awareness and human behavior.

2.2 Environmental Sustainability

In the recent years, the concept of sustainable product design and development is gaining more attention in research since the pressure for achieving sustainability objectives [2]. The environmental awareness is becoming a fundamental product design driver for a wide number of industries [14], through both legislative issues and market pressure.

Traditional design methods and software tools (e.g. CAD, CAE) are not effective solutions for supporting designers during environmental analyses. To overcome this limitation, several eco-design tools have been developed. Some solutions supply only qualitative results and are too general to be effectively used (e.g. checklists). Other tools require large amounts of data and time for application (e.g. Life Cycle Assessment tools). The analysis of such software solutions highlights the lack of effective integration between eco-design tools and traditional ones [31].

Since the environmental load of a product/service should be evaluated throughout its life span, it is possible to identify four main distinct research areas: (i) materials, (ii) manufacturing, (iii) end-of-life (EoL) and (iv) transport.

1. Sustainable materials are related to a research topic that is very common. Renewable materials can be manufactured or generated quickly to keep pace with depletion rate [8]. These materials, which can be produced without depleting non-renewable resources, are made from natural products or synthetically produced.
2. Sustainable Manufacturing (SM) aims at the development of industrial processes towards a more responsible use of natural resources as well as the integration of ecological aspects in the production processes [29]. SM practice requires a holistic view that covers multiple disciplines: (i) product design, (ii) process design and operational principles, (iii) material/energy/waste flow analysis, (iv) supply chain management and, (v) optimization and planning of production activities.
3. Product EoL and the appropriate management of industrial wastes is a key aspect for sustainable products [12]. Many studies in the literature focus on the detailed assessment and comparison of different EoL treatments [1] and optimization of EoL processes [22]. Even if such studies aim to improve the EoL treatments of post-consumer wastes, these ones do not suggest any solution for improving products at the design stage.
4. Transportation of goods consumes a significant amount of resources. Also, population growth and economic expansion create a bottleneck on transportation

systems, and thus sustainability of transportation is critical in delivering social and economic demand without sacrificing the environment [7].

The Circular Economy is considered as a global economic model for decoupling economic growth and development from the consumption of finite resources. It is recognized as the best economic model to efficiently face the rapid growth of world population and raw material consumption. To date, there are several pilot projects all over the world demonstrating the practical advantages (recycling of Waste of Electric and Electronic Equipment—WEEE and remanufacturing for automotive products). The EU (European Union) has issued directives for restricting the use of hazardous substances, which force manufacturers to respect environmental issues (Directives 2000/53/EC, 2002/95/EC and 2012/19/EU by European Parliament and Council).

Moreover, many manufacturing companies are shifting their business from products selling to services selling. In this transition, the take-back practice is one of the key elements for their economic advantages. Recycling processes, indeed, are becoming attractive for their economic potentialities to earn money from wastes, providing also new job opportunities. Furthermore, remanufacturing strategies are becoming even more attractive than recycling ones for their possibility to give a second life to used components. However, the connections between the product design and End-of-Life phase need to be straightened.

2.3 Economic Sustainability

One of the most important driver for the development of competitive products is the cost. Despite most of the companies are focusing at the procurement stage (strategic sourcing) to reduce the cost of a product, around 80% of the final cost is determined at the design stage [25]. The manufacturing/assembly cost is the most important economic indicator to be estimated yet during the design phases to rapidly compare different technical solutions. Design to Cost (DtC) is a methodology that allows designers to achieve cost targets decided by the management team or product leader [5]. The available approaches enable the application of such a methodology in different stages of the product design (from conceptual to detailed design). In addition to DtC, used at design stage, Should Costing is a methodology to determine what a product should cost based on materials, labour, overhead, and profit margin.

While the manufacturing cost considers only the production phase of a product, the Life Cycle Cost (LCC) refers to the total cost (capital and operational expenditures) throughout its life, including planning, design, acquisition and support costs and any other costs directly attributable to owning or using the product [13]. The LCC estimation, at procurement stage, encourages a long-term outlook to the investment decision-making process rather than attempting to save money in the short term. Beyond LCC (or TCO—Total Cost of Ownership), the Total Value of Ownership (TVO) is a methodology of measuring and analysing investments by considering the benefits of a certain good/service and not only the costs.

Despite the importance of estimating and managing the manufacturing cost or life cycle cost during the early design phase of a product, in order to improve the product margins and turnover, companies should implement the Design to Value paradigm (DtV). This is an integrated approach to product development that considers multiple perspectives: (i) what customers want, (ii) what competitors are offering and (iii) what is the costs to manufacture and distribute a product. By adopting DtV, companies are able to redesign their products, including features for promoting sales (value-added features) while eliminating unnecessary features that only serve to drive costs (not-value-added features).

3 Life Cycle Approaches in Sustainable Manufacturing: Research Open Issues for 2050 Scenario

3.1 Open Issues on Social Life Cycle Assessment (SLCA)

Since the publication of UNEP/SETAC guidelines [38, 39], several SLCA frameworks and characterization models have been suggested to assess the social impacts of products globally across various industries.

As the environmental LCA, the SLCA study have to follow four phases: (1) objectives and system boundary definition, (2) life cycle inventory, (3) impact assessment and (4) interpretation. The main difference between LCA and SLCA approaches is the way to measure the impacts. In the SLCA study, the characterization factor is defined in a more qualitative basis and the impact indicators should be established based on the stakeholders, such employees, the local community, society, consumers and the players in the value chain.

According to [36], SLCA is a valuable assessment tool for stakeholders along the process chain to collect data in order to redesign products including their entire process chains from 'cradle to grave' in a sustainable way. Reference [24] highlighted that the S-LCA methodology is less mature than environmental and economic ones. However, it should be noted that despite it is not possible to obtain the conclusive answers, this tool presents a great potential to support the decision making process.

We can hypothesize that in the next years many companies will be involved in a business process re-engineering in order to introduce essential information in relation to the social needs of consumers into the products. This implies that product designers will be able to introduce new basic attributes into the design of the current or new products. The SLCA framework encourage producers to design products which will have either less negative social impacts or a high positive impact on society thanks to the integration of stakeholders' needs into the social life cycle product design. The stakeholders' point of views allows product designers to have valuable feedback that could help them to design products that are in line with the demands of stakeholders.

Moreover, the SLCA framework could have different practical implications for all actors of the supply chain. For instance, the supplier selection could be carried

out according to this approach. Indeed, S-LCA allows developing a model to generate the social suppliers' profiles in order to support the decision-making process. The suggested SLCA aims to turn managers' attention to making their products more socially positive by addressing the needs of different stakeholder groups at a local or global level, instead of focusing only on making products more attractive to consumers or on meeting specific characteristics of consumers' tastes.

Another implication of the SLCA methodology is connected to the phenomenon of asymmetric information that occurs between producers and consumers. As the producers (i.e. companies) have (positive or negative) information regarding the social impact of their products, they do not disseminate such information to their consumers or other groups of stakeholders. A possible reason for this situation accrues from a lack of auditing and communicating systems to inform consumers. On this basis, the SLCA could be the precursor of a modern label for product social impact that temporarily supports the mutual exchange of information between the consumer/customer and companies.

On the other hand, improving the workers' wellbeing in factories is imperative for all companies, not only for the expected cost saving, but also for the higher process efficiency that can be realised due to reduced absenteeism and less frequent interruptions [23]. Traditional approaches are based on monitoring the criticalities and introducing optimizing actions. However, in order to concretely reduce the workers' injuries, illness, falls, and other diseases, higher benefits can be achieved by a more careful and ergonomic workspace. A challenging perspective is to introduce human factors in the design of the workspace and in the process planning, in order to ensure workers' safety and prevent potential risks.

Understanding real Musculoskeletal Disorder (MSD) risks, especially related to manual assembly tasks, represents a crucial objective for industrial manufacturing. Given the quantity and complexity of manual tasks that an operator must remember and perform, to support the achievement of this objective can be very useful to implement systems that allow a constant ergonomics monitoring of the operators during the working phases. At the same time, such systems should be able to support the operators' training and increase their awareness about correctness of their own postures, in order to stimulate them to behave correctly and reduce MSD risks.

The applications proposed in literature are not able to both support the achievement of these tasks. No studies proposed integrated systems able to guide operators in manual assembly tasks and provide them information about their MSD risk exposure. Moreover, the majority of them are not suitable for industrial application, because they require the implementation of invasive devices and they are not adequate for a large-scale use in industrial assembly lines. For example, in literature, there are a lot of studies that compare traditional assembly instructions methods (ex. paper manual), to AR-based applications that exploit several visualization devices (i.e., desktop screens, HMD, smartphone, tablet, projectors). Results highlighted that computer screen is not suitable for productive context, despite it does not have problems of visual occlusion, because it distracts the operator's attention. Wearable devices, in general, resulted invasive for the operator and limit the possibility to focus on short

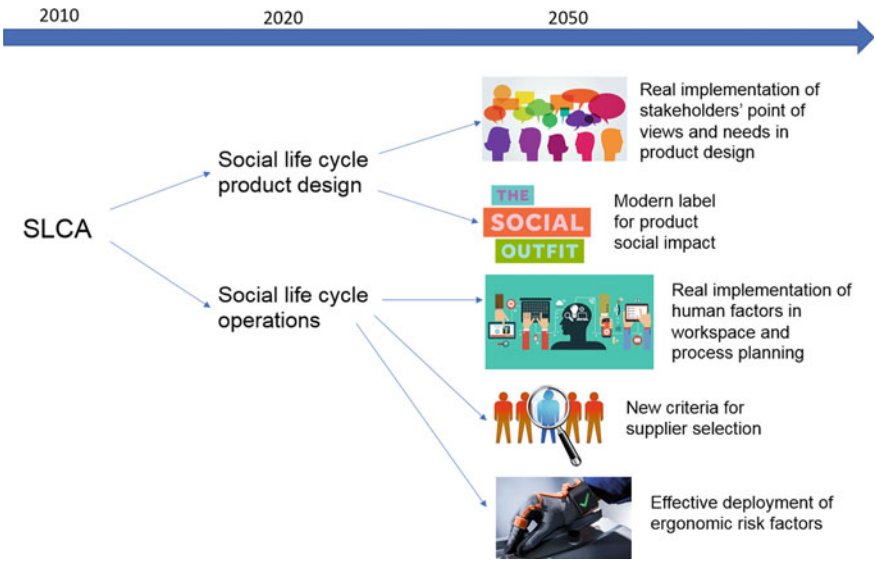

Fig. 2 Open Issues on SLCA

and long distance objects. Anyway, HMD have proved to be more suitable for the operator's training than paper manual and computer screen. Projectors seem to be more efficient, intuitive and fast than other visualization devices, but it can results in information occlusion problems. Consequently, at this time there is still the need of non-invasive solutions capable of effectively and safely support the operator in industrial manufacturing environment.

Another important opened issue concerns the limited methodological research focusing on how to select the most proper tools and technologies to better support ergonomic risk factors assessment and management for the specific context of application. Currently application of proposed methods (i.e. [3]) is very specific and difficultly transferrable to other context, so that companies interested to evaluate the human ergonomics along their processes can only find numerous techniques as checklists and recommendations, without having a precise guideline about the selection of the most proper ones and the joint interpretation of the obtained results. Figure 2 summarizes the main open issue on SLCA for 2050 scenario.

3.2 Open Issues on Environmental Sustainability

Nowadays, Design for Environment approaches are still theoretical concepts, with few industrial virtuous examples (e.g. there are very few applications in SMEs). For example, the academic and industrial state of art do not contain any virtuous approach

where the knowledge of dismantlers and recycling centres are formalized and organized in order to be used by designers for the re-design of goods and products. Many case studies demonstrate the advantages of applying eco-design guidelines during the product development but an approach for the dismantlers and remanufacturers knowledge formalization is missing.

Sustainable manufacturing can find new life from the Industry 4.0 and beyond paradigm. Data acquired by monitoring production lines will contribute in identifying environmental hot-spots to be solved, for example, by improving the plant OEE, revamping the assets, reducing or eliminating not-valued-added activities, etc. Future research topics (Fig. 3) are related to four elements of a sustainable business model: value proposition, supply chain, customer and financial justification. From the process point of view, for example, the design of sustainable processes addresses the holistic resource efficiency approach of Industry 4.0 by designing appropriate manufacturing process chains or by using new manufacturing technologies (e.g. additive manufacturing).

The circular economy is a very promising paradigm, but, nowadays, it is still under used. The key-concepts where enterprises and organizations have to focus on are:

- Eliminate the concept of waste: Design products and materials with life cycles that are safe for human health and the environment and that can be reused perpetually through biological and technical metabolisms.
- Power with renewable energy: Maximize the use of renewable energy.
- Respect human and natural systems: Manage water use to maximize quality, promote healthy ecosystems and respect local impacts. Guide operations and stakeholder relationships using social responsibility.

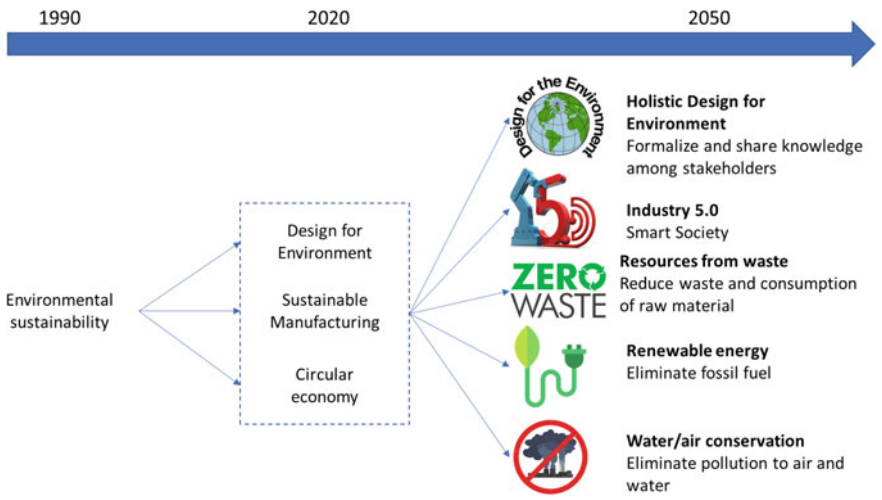

Fig. 3 Open Issues on environmental sustainability

In this framework, additional key concepts to be considered are:

- Decrease in energy and raw material usage combined with reduced emissions and waste generation can tackle a host environmental challenges facing the world.
- Clean manufacturing practices and energy-efficient design of equipment are also hallmarks of environmental sustainability.
- Water conservation is one of the most important environmental issues of this century and growing number of companies are using it to educate and change consumer behavior.

Most of such concepts are also discussed in the "Sustainability and reporting trends in 2025" [15].

3.3 Open Issues on Economic Sustainability

Future research activities (Fig. 4) in the field of the economic sustainability should be mainly oriented in the increase of the effectiveness of the current software tools used throughout the product development process. Despite the wide variety of instruments, their usage is still limited, especially in SMEs. For example, Conceptual Design to Cost approaches and tools are yet far to be widely applied and used within design departments.

Moreover, the models used for the economic analysis should leverage the potentialities made available by the Industry 4.0 paradigm (e.g. Internet of Things, Big Data and Cyber Physical Systems). The real-time analysis of manufacturing data gathered from production lines of the "extended enterprise" will allow designers and production engineers to develop more and more competitive products.

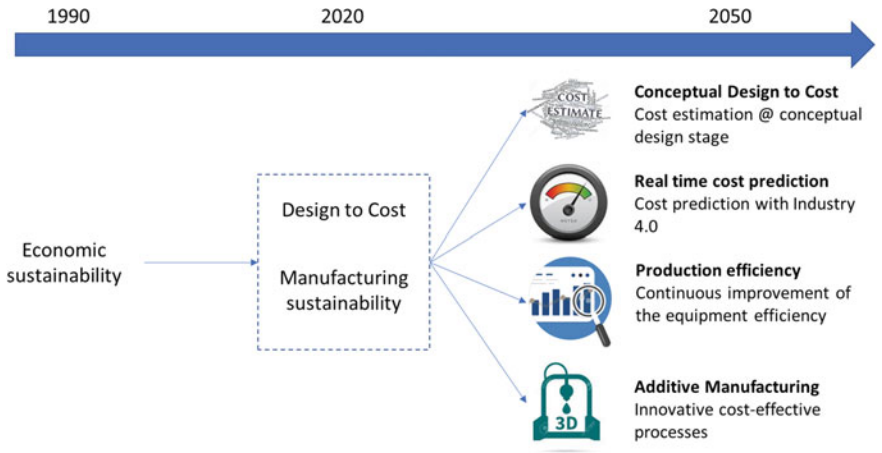

Fig. 4 Open issues on economic sustainability

The adoption of Artificial Intelligence systems for economic analysis will increase their impact on the competitiveness of products and processes. Software tools should be able to optimize the product design, the manufacturing process and the supplying strategy.

The future research related to product/service sustainability should be more and more focused on integrating the three sustainability pillars (economic, environmental and social). Indeed, more companies worldwide are incorporating sustainability into their strategic and operational goals and business planning decisions. Environmental accounting methodologies for collection, measurement, and disclosure of financial and environmental impacts of strategic and operational managerial decisions are used by business entities worldwide for effective management of both organizational and operational environmental protection policies [16]. The correlation among these pillars is also demonstrated by the UN's 17 Sustainable Development Goals (SDGs), which aim to improve the lives of people, increase prosperity, and protect the planet [33].

3.4 A Road Map to Education for Sustainable Development

Education for sustainable development becomes today a strategic objective for the present and for the future and this new national awareness can only begin with schools and students of all ages. Especially by the young, what we could call "environmental natives": a generation that in the everyday life of behaviour already finds as a natural perspective the respect for the environment in which it lives.

Another objective, equally ambitious, is to identify the educational path to sustainable development, so that this is increasingly integrated and convergent in the curricular paths specific to the different orders and degrees of education.

Environmental education, due to the complex nature of the themes dealt with and the need for a holistic approach in dealing with the various themes, cannot be completely exhausted in the treatment within a single discipline by a specific teacher, but it is appropriate instead that it is the result of interdisciplinary paths and coordinated with each other. These concepts are fully applicable in the field of manufacturing process management.

An analysis of recent scientific literature on Education in Sustainable Development (ESD) [34] highlights some interesting experiments discussing the activities of Baltic University Programme and the Mediterranean Universities Network in the field of higher education network organization for the promotion of Sustainable Development.

Sustainable development is a typical interdisciplinary topic including both scientific areas like engineering and humanistic ones like economy, management and politics.

The 2015 United Nations Educational, Scientific and Cultural Organization [40] report deeply analyzed the strategic and fundamental role of instruction organization in the ESD, recognized and one of the seventeen Sustainable Development Goals

(SDG). Teacher's training, under UNESCO point of view, represents a key factor for educators to become active facilitators for ESD.

The recognition of the holistic and interconnected nature of the SDG results in the need to tackle ESD issues from environment, economy and society point of view.

This is particularly relevant for the Italian manufacturing industry, a pillar sector for supporting a prosperous economy and a wealthy society. The transformation process taking place in manufacturing requires several resources whose efficient use can reduce waste as well as minimize impact of transformation processes on the environment. Designers and technicians being aware of Sustainable Development issues will become more and more fundamental for promoting "green" change in the manufacturing companies. The need therefore arises for educational organizations to promote new teaching modules and programs for both students and teachers so that to play a winning role in the international manufacturing competition.

The connection between teaching and research, key aspects of Universities mission, could then be used for academic organizations to provide both professional and students with tailored inter and transdisciplinary competencies, so that to fulfil the different teaching strategies for sustainable development. To this extent it is worth to stress the adoption of an Open Innovation paradigm in the field of Sustainable Development.

4 Conclusions

The paper main scope is to provide the reader with a holistic view of future scenarios and relevant issues in sustainable development in product development and manufacturing. To this extent social, economical and environmental aspects of future potential scenarios have been described trying to highlight possible research trajectories. It is Authors' belief that the three pillars of sustainability will be the main drivers of next decades in all aspects of society to have a better world where people lives. The industrial sector has a great responsibility to realize this objective. One fundamental pillar for a continuous improvement in sustainability awareness is the implementation of education in sustainable development. Systems thinking, interpersonal, integrated problem-solving and critical thinking competencies will be more and more crucial for students and educators to become active player, e.g. people able in learning to know, to do and to be. A strong educational institutions' commitment is thus necessary to design, promote and apply tailored policies for education to sustainable development and content-oriented priorities, defining new curricula with appropriate learning tools compliant with "glocal" cultural aspects.

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The Role of Advanced Materials in the Development of Innovative Manufacturing Processes

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Abstract The present contribution reports on the cutting-edge research activities performed by the authors in the field of innovative manufacturing processes applied to advanced light alloys. These include Friction Stir Welding (FSW), Friction Stir Extrusion (FSE), and Additive Manufacturing (AM). Two new FSW configurations are here introduced and described. A first double-side friction stir welding (DS-FSW), where the welding is performed on both sheet surfaces, one after the other. A second rotating tool FSW (RT-FSW), in which pin is made to rotate around its centerline welding direction, by 0.5 and 1.0 mm. The feasibility of solid-state recycling of a case study, such as an AA1099 machining chips, is exploited using FSE process. In addition, in order to optimize the die design and the process parameters, finite-element (FE) simulation of the process was carried out. The game-changing potential of the metal AM technology is un-veiled through results obtained on light alloys for biomedical applications produced by Powder Bed Fusion (PBF).

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1 Innovative Manufacturing Processes Applied to Light Alloys

In the following three different and promising new approaches to manufacturing processes applied to metallic materials will be described. These three processes start with well-known technological processes that were innovated by applying new methods and/or new starting materials, both in terms of new alloys or new material form. Thus, a friction-stir welding (FSW) with different and innovative layout is here presented; an innovative friction-stir extrusion applied to light-alloy chips is here described; new trends on additive manufacturing (AM) new trends on metal additive manufacturing (AM) of light alloys are here reviewed.

1.1 New Approach and Layout of FSW Applied to Aluminum Alloys

FSW produces a high-quality joint, compared to other conventional fusion welding processes, such as laser welding. In fact, FSW is a welding process particularly suited for joining non-metal materials to metals, especially in those cases where it is not possible by using conventional fusion methods [1, 2]. As for the induced structural modification during welding, the weld zone (usually called the nugget zone, NZ) undergoes a solid-state process promoted by the frictional heat between a rotating tool and the welding metal. A plasticized zone (that is both the nugget and the thermos-mechanically affected zone) is induced to form by the rotating tool. This is further extruded from the leading side (advancing, AS) to the trailing side (retreating, RS) of the tool during its steady translation along the joint line [3]. Another key advantage of the FSW is derived from the lack of need for filler material or shielding gas. The temperature involved is typically some 50–100 °C, which is well below the metal melting point and thus there is no volume change during joining. Moreover, it is generally agreed that FSW, compared to the fusion welding techniques, induces rather low residual stresses after welding. This implies process reduced manufacturing costs [4].

Moreover, FSW generally guarantees better tensile, bend, and fatigue properties than fusion welds. Taking advantages of these positive factors, this process has already been applied to a great variety of aluminum alloys, other than many other metallic materials ([3–7] and references therein). In the case of the aluminum alloys, the FSW technique has found may applications, such as external fuel tank of rockets, stock of railways, bridges [5, 6], to cite but few. Other interesting applications of FSW in the aerospace industry include fuselage, structural parts, cryogenic tanks, etc. [3]. Other interesting applications also include the marine applications (like offshore industry) [3, 7].

The microstructure modifications occurring at the central FSW zone (that is the NZ) most usually consists in dynamic recrystallization resulting in the formation of fine equiaxed grains [8]. Since this recrystallized zone usually reduces the welded alloy mechanical properties, an accurate choice of the process parameters, such rotational speed, welding speed, tilt angle and sinking and of the tool geometry (pin and shoulder geometry and size), is required. With this regard, the welding alloy mechanical properties can be optimized by increasing the pin rotational speed, or by decreasing the welding line progression [8].

One of the major possible drawbacks in using FSW against other fusion welding techniques, refer to the tendency to form oxide layers on the butt surface ("kissing-bond" phenomenon) whose formation is attributed to insufficient plunging of the welding tool during FSW [9], and it is usually responsible of the formation of small geometric discontinuities into the NZ [10].

In this context, the present contribution shows the effect of the process parameters, tool geometry and size on the mechanical properties of FSW joints by using a conventional pin, and a non-conventional pinless tool configurations. The potential advantages offered by the pinless tool configuration can be fully exploited only as thin sheets are welded since, as the thickness increases, the shoulder influence becomes ever more localised to the top sheet surface.

A new FSW approach and methodology is here presented, with the aim of promoting a better joint formability. This consists of carrying out the FSW process on both the sheet surfaces. In this process, the first welding operation is followed by a second welding performed at the plate opposite surface. Such an innovative methodology has been defined by three of the present authors (Cabibbo, Forcellese, Simoncini) as double-side friction stir welding (DS-FSW) [11, 12]. This new FSW methodology has proven to be able to seal the geometric discontinuities, possibly produced by the first welding process, by means of the second welding operation performed at the opposite surface at the same experimental conditions. It resulted that the recrystallized grain structure across the NZ is more homogeneous respect to the surrounding FSW zones, compared to the conventional FSW. Such improvement in the joint quality is very attractive, especially in those cases where the joint materials are meant to be subjected to post-welding forming operations.

A further novel approach to the FSW process (defined by authors as RT-type [13]) is also here reviewed. This new configuration consists on a combination of different plate-to-pin motions. In one configuration, the pin axial spin rotation is set perpendicularly to the sheet blanks travelling along the welding line, with a lateral rotation radius $R = 0$, 0.5, and 1 mm. In a second configuration, the pin translation along the welding plate is set parallel to the welding line.

Both these new welding approaches were compared with the conventional FSW procedures, using the same aluminum alloys.

1.1.1 Description of the New FSW Process Set-Ups

Double-Side FSW (DS-FSW) Method

As for the double-side FSW (DS-FSW) method, a conical pin tool geometry (H13 steel of HRC = 52), with a shoulder diameter equal to 12 mm and cone base diameter and height of the pin of 3.5 and 1.7 mm, respectively, with a pin angle of 30°. A 19-mm-diameter rotating tool was used. All the welding experiments were carried out with a nutting angle equal to 2°.

Two different sheet positions, with respect to the welding tool, were investigated and are here presented:

i. AS-AS, in which the sheet is placed in the AS, at the first FSW operation, and it is maintained in the same side during the following FSW passage at the opposite surface;
ii. AS-RS, in which the sheet, placed in the AS at the first FSW, to be reversed, in the RS, at the second FSW passage at the opposite surface.

The effect of the process parameters on the conventional and the DS-FSW were inferred using homologous rotational speed values $\omega = 1200–2500$ rpm, and same welding speed v = 60 and 100 mm/min. The conventional FSW was carried out using a tool sinking of 0.2 mm, the DS-FSW reached a sinking of 0.15 mm in the first pass and 0.05 mm in the opposite surface. In DS-FSW AS-AS pin-pin the advancing and retreating sides were maintained fixed for both welding procedures; AS-RS pin-pin consists of reversing the advancing side into retreating side, from the first to the second welding procedure. The third and fourth configuration differs from the first two only in the absence of the pin during the second welding process. In the last two (AS-AS, and AS-RS pinless-pinless) the welding process was performed with no pin in both processes. Figure 1 shows a schematic representation of the three DS-FSW configurations used.

Pin Rotation Deviation from Centerline (RT-FSW) Method

For this purpose, a conical pin tools in H13 steel (HRC = 52) with a 2.3 mm pin height, 3.9 mm in diameter at the shoulder, a 30° pin angle, and a shoulder diameter of 15 mm (applying a vertical force of 1.7 kN) was used (Fig. 2).

The welding motion combine two different plate-to-pin mutual motion set-ups:

(i) a pin axial spin rotation sets perpendicular to the sheet blanks, changing the rotation along the plate centerline by a radius equal to R (=0, corresponding to the conventional FSW, 0.5, and 1 mm);
(ii) a pin translation along a direction parallel to the welding centerline line.

The RT-type FSW innovative approach was compared with the conventional T-type (linear welding motion, i.e. for R = 0). In both the RT-type and T-type FSW processes, the stirring action was exerted by the pin tool rotation around its axis;

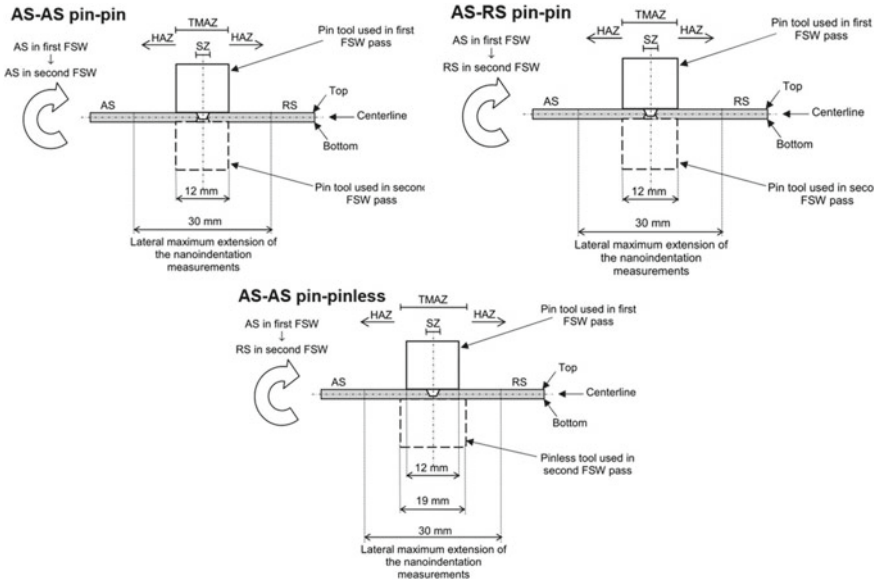

Fig. 1 Representation of the three DS-FSW configurations: AS-AS pin-pin (top left-hand side); AS-RS pin-pin (top right-hand side); AS-AS pin-pinless (bottom)

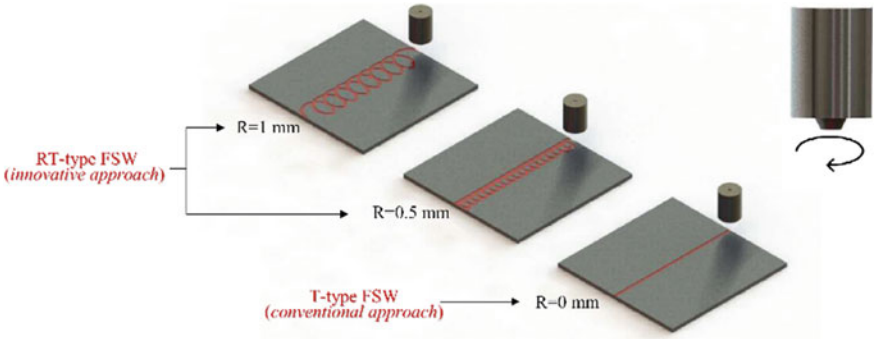

Fig. 2 Conventional (R-type) and T-type FSW configurations

the pin tilt angle was set at 2°, with respect to the normal direction to the plate surface. The RT-type and T-type FSW were performed using a pin rotational speed, $\omega = 2000$ rpm, a transverse speed, $v = 30$ mm/min, and a tool plunging speed of 1.5 mm/min. The above reported setting parameters were chosen by an optimization FSW processing study reported both some of the present authors in [13].

In DS-FSW new approach a heat-treatable AA6082 was used; in the second T-type FSW methodology, a non-heat-treatable AA5754 was welded.

1.2 FSE Applied to Aluminum Chips

Recent literature has revealed some potential variants to the aluminum recycling process compared to the conventional method, therefore without going through the recasting phase, where aluminum alloys are subjected to significant plastic deformations at temperatures below solidus. In 1993, TWI patented a new recycling process to be applied to metal shavings, named Friction Stir Extrusion (FSE).

The process is schematically represented in Fig. 3. This technique belongs to the same family as the Friction Stir Welding technique (FSW) and follows the same principles. It uses the heat generated by friction, between a rotating head and the chips to be recycled, contained within a cylindrical matrix where the head is inserted; the plastic deformation generated by the heat relative to the friction of rotation and the progress of the head involves the mixing, the compaction and the extrusion of the chips. In this way, the FSE process makes it possible to transform the aluminum chips into an extruded product, with high savings in terms of energy, work and economy in relation to the conventional direct extrusion recycling method.

In particular a detectable wires of AA2050 and AA2195 alloys was produced from machining chips by analyzing the amount of heat generated when the head rotation speed varies [14]. Studies have shown how the rotation speed influences the quality of the wires produced in AA7277; high rotational speeds involve hot cracking formation, while low velocity results in cold tearing [15]. Italian researchers have done a campaign on FSE of AA2024 aluminum alloy chips, aimed at the production of MMC within the recycling process by adding SiC powder to the chips [16]. Some of the authors of this research (El Mehtedi, Forcellese, Simoncini, Spigarelli) have studied also how the tool rotation speed affects the extrusion temperature thus influencing the plasticity of the chips [17]. Other researchers focus their studies on recycling of pure Mg chips and AZ31 alloy by means of FSE process [18–21]. A pure aluminum AA1099 was chosen in this study in order to investigate the recycling feasibility of chips and the effect of the process parameters on final properties of the wires. In the early stage, a FE simulation campaign was conducted in order to optimize the die design and the process parameters in terms of plunge rotational speed and

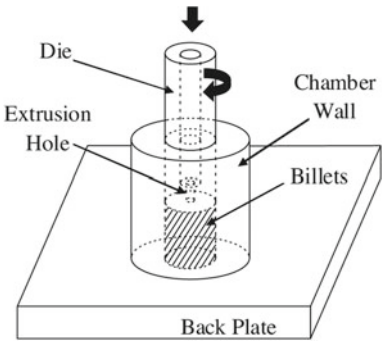

Fig. 3 Synthesis scheme of the FSE process

extrusion rate. The AA1099 aluminum chips were produced by turning of an as-received bar without lubrication. The chips were compacted on a MTS machine. The chip-based billet was FS-extruded at constant rotational speed and plunge rate. The extruded samples were analyzed by optical microscope in order to see the material flow and to characterize the microstructure.

1.2.1 Set-Up Description of Experimental Procedures

The aluminum chips used as extrusion material were produced through machining of AA1099 bar. AA1099 is a pure aluminum with 99.99 of Al (wt.%). The base material is characterized by Ultimate Tensile Strength (UTS) equal to 80 MPa, 38% of elongation and hardness Vickers HV = 22. The machining process was performed without any lubricant or cutting fluid. The approximate dimensions of chips are equal to 8 mm length, 5 width and 0.2 mm thickness.

The chips were compacted in one stroke on a MTS hydraulic universal machine up to 150KN of load (Fig. 4). The resulting chip-billets had a diameter of 40 mm and were 30 mm high. Figure 2 shows the die geometry and the chip-billet after compacting.

The numerical simulation was implemented on the commercial FEM code "SFTC DEFORM 3D", characterized by a Lagrangian implicit solver, in order to design dies and the inserted rotational punch head shown in Fig. 4.

The main components used in the process including a container and a rotating plunger with scroll faced head made of K720 tool steel. The shape of the scrolled face head influences the flow of the plasticized material and affects the final properties. The die is made by a computer numerical control (CNC) milling machine.

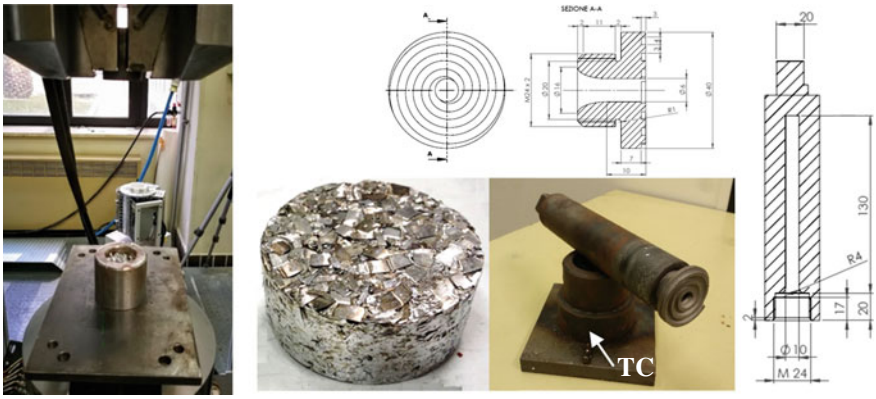

Fig. 4 Compaction machine with a sample of a compacted billet, section of the rotating plunger, front view and section of the inserted rotational punch head and complete set of components for FSE tests

The container cavity is 41 mm in diameter and 70 mm in height. The rotating plunge die has a 40 mm outer diameter with 8 mm central hole which defines the diameter of the extruded wire. The plunger rotates in a clockwise direction and moves toward the container which is charged with Al compacted chips. The rotation and movement of the plunge die relative to the container cause the mixing and stirring of Al chips, during which the contact and pressure between the rotating plunge die and Al chips lead to the conversion of mechanical energy to thermal energy due to the friction. The maximum wire length is limited by geometry of the plunger of 130 mm. Two rotational speeds of 400 and 1000 rpm were implemented under constant plunge rate of 15 mm/min, these values were chosen based on the FEM optimization results. Two k-type thermocouples were used to monitor the temperature changes during the process.

The microstructures of the FSE samples were investigated by optical microscopy (OM) from extruded wire cross-sections cut perpendicular to the extrusion direction.

1.3 Powder Bed Fusion of Ti-Based Light Alloys

Powder bed fusion (PBF), as defined by ASTM 52900:2015, is a widely used AM technique in which a high energy beam sinters or melts the metal powder, layer upon layer, to produce final parts according to a computer-aided design (CAD) model. The near net shape part is built by multiple, rapid heating-melting-solidification cycles, while non-melted powder supports the overall structure until the end of the process. The ability to build complex geometries, not achievable with traditional manufacturing techniques, give unprecedented freedom to designers. Moreover, the high degree of customization achievable makes PBF a great opportunity in wide fields of applications, from automotive and aerospace parts [22] to biomedical prosthesis [23].

If the fusion of the metal powder is performed by an electron beam, the techniques is frequently referred to as electron beam melting (EBM), while in the case of a laser beam the terminologies selective laser melting (SLM) or sintering (SLS), and direct metal laser sintering (DMSL) can be found in literature, according to the degree of fusion of the particles and to the equipment producer. While EBM is performed under vacuum conditions in a heated chamber, laser-based procedures require inert gas atmosphere and the resulting high cooling rates give rise to a finer microstructure [24–26]. These operating conditions reflect in EBM parts that are characterized by a remarkably high surface roughness but are also almost free from residual stresses, while SLM parts show lower surface roughness but high residual stresses, which should be reduced with thermal treatments.

Post-production surface treatments such as laser peening, cavitation peening, or shot peening, are usually performed to meet the surface finishing requirements given by the end-users, and to add local compressive stress to improve cracking resistance and fatigue life [27, 28].

Titanium powder and in particular pre-alloyed Ti-6Al-4V metal powders are among the most studied materials in terms of additive manufacturing [29, 30], owing to excellent mechanical properties (high specific strength and fatigue resistance) coupled with low weight and good biocompatibility. Moreover, the Ti-6Al-4V alloy is the most used titanium alloy for additive manufacturing and covers almost 50% of the overall titanium alloy market.

2 Technological Results and Overview

In the following the experimental results and the technological impacts of the new three innovative manufacturing processes are reported. An overview of the technological impact is also presented. This is intended to promote the here described new promising techniques among the scientific community working in the field of welding of metallic materials, new forming metallic materials from scraps, and the new trends on the AM of Ti-based light alloys.

2.1 DS-FSW and RT-FSW

2.1.1 Results and Overview of the Double-Side Friction Stir Welding Method: DS-FSW

Figure 5 shows the stress-strain curves of FSW joints in AA6082 obtained under different values of the rotational speed and welding speed. The joints ductility is shown to be lower in the NZ, respect to the base metal (BM), irrespective of the welding parameters and process methodology [31]. In general, in terms of both the ultimate values of tensile strength and elongation, the conventional FSW joints show a tensile behaviour better than the one exhibited by the DS-FSWed joints. Actually, the conventional FSW process requires a high sinking value in order to generate the frictional heating allowing the material flow necessary to obtain sound joints. Thus,

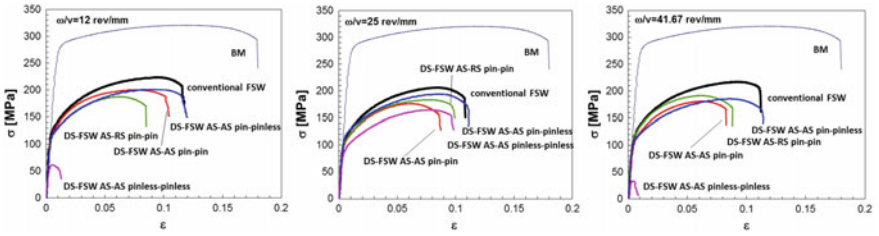

Fig. 5 Tensile stress-strain curves of the DS-FSW, with different welding parameters and tool configurations

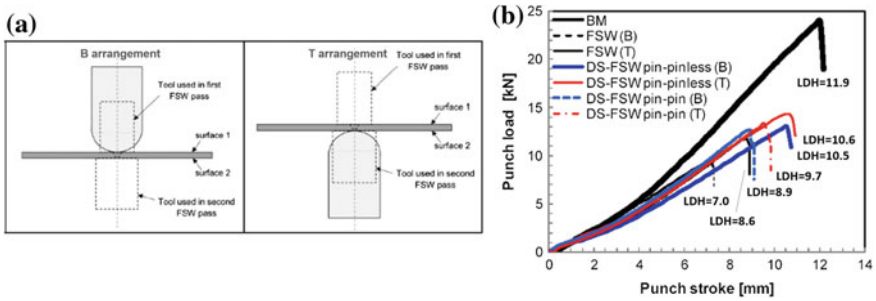

Fig. 6 Hemispherical punch test configurations: in the B arrangement, surface 1 is in contact with the punch, in the T arrangement surface 1 is opposite, (**a**); related test for different experimental conditions (LDH is the Limit Draw Height), (**b**)

in the first pass, by using the same tool sinking as of conventional FSW produces a step in the blank surface that acts as a notch during the second pass. Therefore, the tool sinking value imposed in the second pass had to be further decreased in order to reduce the formation of surface defects. The pinless-pinless configuration has provided the worst tensile properties. In particular, the AS-AS configuration showed low mechanical properties of the joint, while the AS-RS configuration did not reach a sound weldment.

The mechanical behaviour is strongly improved when welding is performed using the pin-pinless configuration. In a recent published work by Cabibbo, Simoncini, Forcellese, the FSW capability to obtain sound joints in 1- and 1.5-mm-thick sheets using a pinless tool was widely documented [12, 31, 32].

LDH (Limit Dome Height) values were lower than those obtained on the BM, no matter what welding methodology was used. Such results reveal that a noticeable formability reduction along the welding zone [10, 12, 31–33]. More specifically, the B arrangement leads to a LDH value lower than the T arrangement (as reported by the letter B, and T, in Fig. 6, and according to the configuration reported in the figure).

In the B arrangement, the local stress field intensity rise, caused by the notch, is responsible of the FSW sample failure at the geometric discontinuity. In the T arrangement, the failure of the deformed joint occurs at the step produced by the sinking action applied by the shoulder [11]. This is mainly due to the biaxial tensile stress state to which the notch is subjected. This appeared to be less severe in the T arrangements, respect to that in the B arrangement.

The DS-FSW joints showed LDH values higher than those measured on the conventional FSW joints. This second welding induces a dual beneficial effect: it allows both the closure of the geometric discontinuity, and the reduction in the height of the step produced by the first welding on the opposite plate surface. Furthermore, the DS-FSW is characterised by uniform recrystallized grains across the NZ, and partially across the thermos-mechanical affected zone (TMAZ), than in the case of the conventional FSW [11]. Finally, the joints obtained using the pin-pinless tool

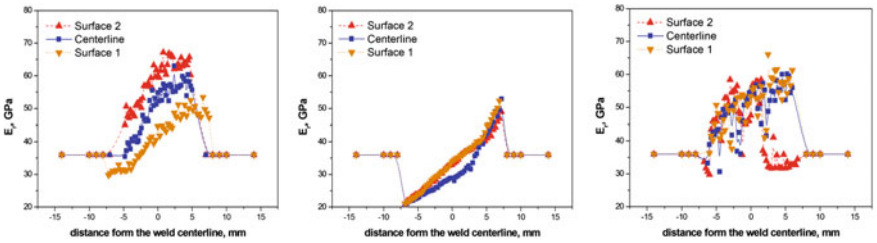

Fig. 7 Nanoindentation E_r profiles of the different used FSW configurations

Table 1 AA6082 DS-FSW mean grain size; the BM SZ had a mean grain size of 20 ± 2 μm

FSW configuration	Mean grain size (μm)				
	AS/TMAZ	Surface 1/SZ	Middle/SZ	Surface 2/SZ	RS/TMAZ
Conventional FSW	14 ± 2	7.8 ± 0.3	7.6 ± 0.3	6.9 ± 0.3	14 ± 2
Pin-pin DS-FSW	12 ± 2	6.3 ± 0.2	6.2 ± 0.2	6.4 ± 0.2	13 ± 2
Pin-pinless DS-FSW	12 ± 2	5.7 ± 0.2	5.7 ± 0.2	5.8 ± 0.2	13 ± 2

configuration lead to LDH values higher than the ones obtained by using the pin-pin configuration, irrespective of the sheets arrangement.

Both the aspects are also confirmed by the nanoindentation inspections on the reduced elastic modulus Er profiles taken across the FSW joints (Fig. 7), and by the corresponding mean grain size analysis carried out by polarized optical microscopy (POM) (Table 1).

The better formability of the DS-FSW, respect to the conventional FSW, is most likely related to the local elastic modulus uniformity (i.e. the reduced Young's modulus) across the weld, and to the less dramatic hardness variation, from top to bottom of the sheet section. In all the three DS-FSW configurations here described, the observed grain size uniformity and morphology across the SZ, from surface to surface, greatly favoured the soundness and better post-welding response of the welded Al-sheets.

2.1.2 Results and Overview of the Friction Stir Welding Method by Pin Rotation Deviation from Centerline: RT-FSW

The AA5754 was subjected to an annealing treatment at 415 °C/3 h followed by furnace cooling, in one case prior FSW (AA5754-O state), and in another case, after FSW (post-weld annealing: PWA) (Fig. 8).

It appeared that the closest mechanical response to the un-welded annealed AA5754 sheet is obtained by welding with R = 0.5 mm in the PWA condition, where UTS differed only by 5%, and ductility differed by 30% respect to the un-welded annealed condition. In the other conditions, the UTS remained within a range

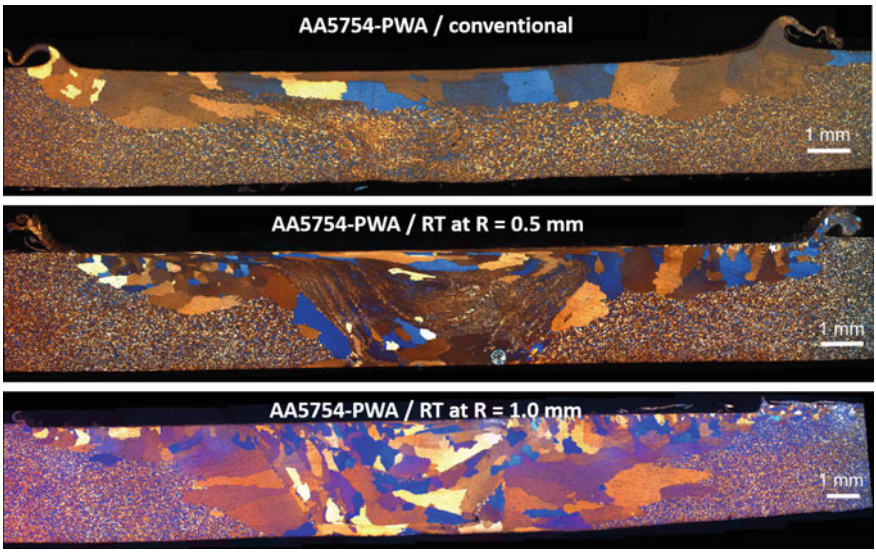

Fig. 8 POM RT-FSW PWA at R = 0 (conventional FSW), 0.5, and 1 mm

of 14% of difference, respect to the annealed sheet, with a ductility reduction ranging from 76 to 30% (Fig. 9).

Thus, based on the microstructure evidence, and the obtained hardness and mechanical response, the use of a RT-type welding motion is justified when the plate is homogenized prior, or, even better, after FSW. Conversely, there is no need to deviate the pin, from its welding centerline, in the case of not-annealed AA5000 FSW.

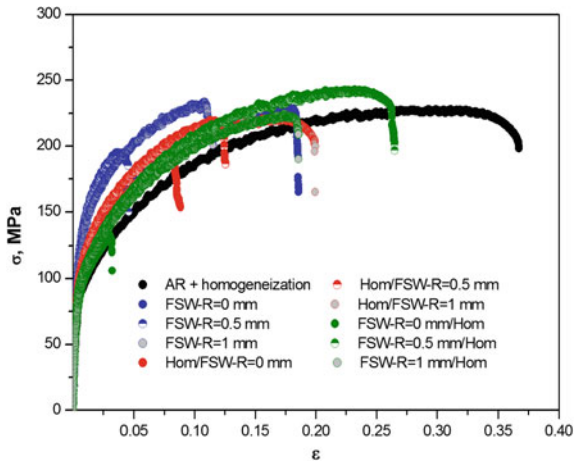

Fig. 9 Tensile stress-strain curves for RT-FSW, in the AA5754-O stare and in the PWA condition, at R = 0 (conventional FSW), 0.5, and 1 mm

2.2 FSE

2.2.1 Results and Overview of FSE Experimental Process

Since it is worth knowing that higher temperature assures better solid bonding between the chips, in order to guarantee extrusion temperatures greater than 400 °C, rotation speed of 1000 rpm were considered.

In fact, in the FSE process, the tool rotation speed affects the extrusion temperature. Figure 10 shows the maximum temperature registered during FSE at different rotation speeds.

The temperatures and the material flow obtained in FE simulations were confirmed by experiments as shown in Fig. 11.

Thanks to the simulations, it was also possible to evaluate the load trend that the CNC machine maintains during the process. Figure 12 shows the presence of a transitional stage lasting about 2 s, in which a sudden increase in the load up to values higher than 90 kN occurs and then an immediate lowering to constant values

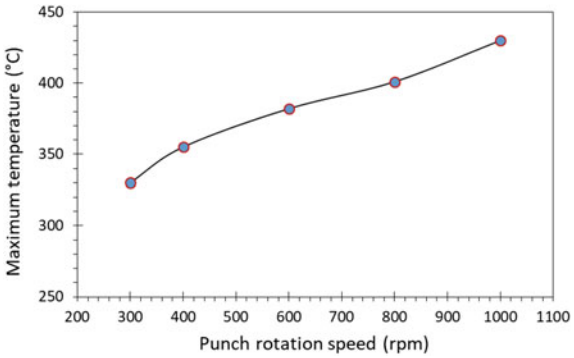

Fig. 10 Maximum temperatures reached at various rotation speed

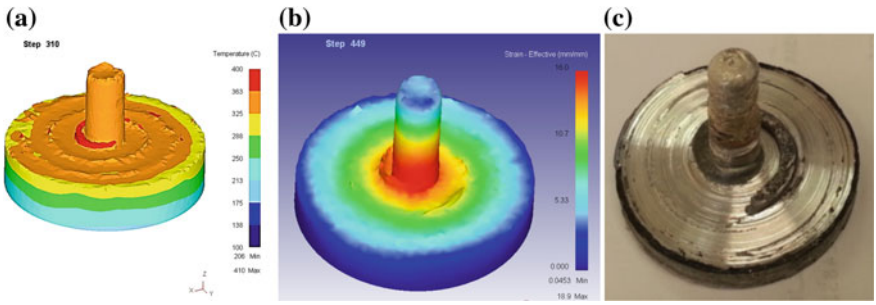

Fig. 11 Temperature and strain distribution during FSE from FEM simulation (**a**), (**b**) and sample obtained experimentally at 1000 rpm (**c**)

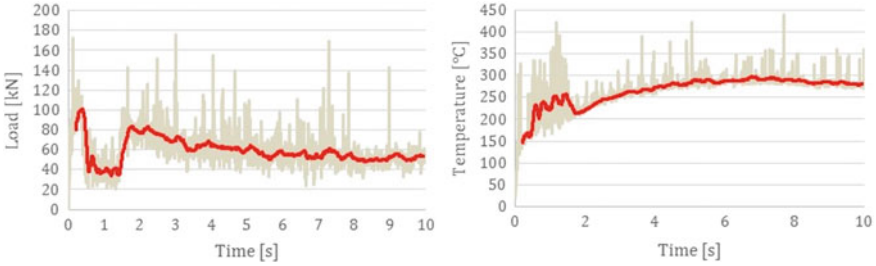

Fig. 12 Load prediction for the CNC machine and max temperature reached during the process

around 40 kN, evidently depending on the first contact between the rotating head and the billet, where the first chip re-meshing takes place.

Therefore, for the seconds part of the test, after the transitional stage, the load is increasing again up to 80 kN due to the low extrusion temperature. In the second stage, the extrusion load decreased slowly by increasing the chips temperature up to a constant a steady state value of 50 kN, as shown in Fig. 12.

The analysis carried out subsequently took place through the OM. In particular, the specimen was observed on the section of the obtained wire and on the section along the vertical plane. In Fig. 13 it is possible to observe the plans that have been analyzed in the OM. The metallography shows mainly the total lack of a homogeneous and uniform structure for the extruded product.

In fact, a set of undefined microstructures was obtained from the tests, with the presence of grains of varying sizes, and above all with defects sometimes not classifiable, accentuated by the presence of real holes (visible with the naked eye on the

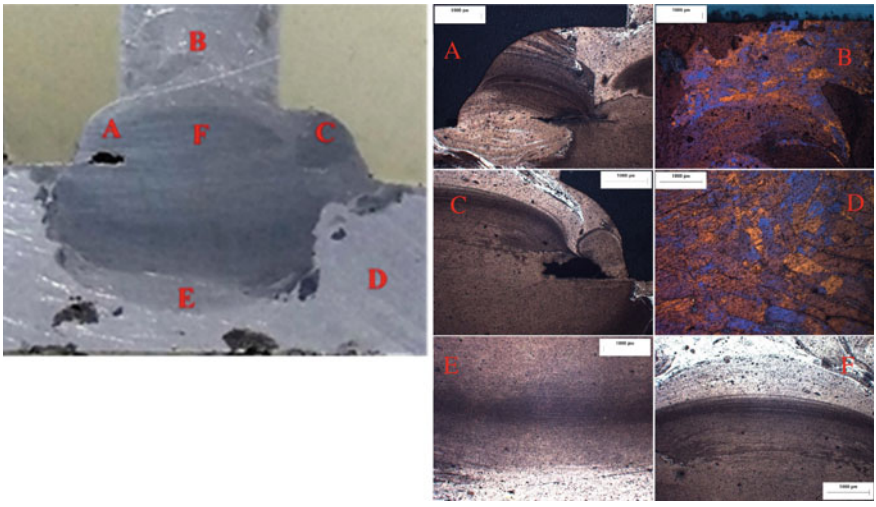

Fig. 13 Section of the residual tablet and metallography at different locations

surface and therefore perfectly framed by optical microscopy). All this is obviously linked to the lack of compaction of the plastic material during extrusion, caused by many factors already analyzed, such as the centrifugal effect due to the high rotation speeds and the not perfect adaptation of the head channels to the processing conditions. However, it is possible to identify the flow of the material quite easily, leaving an indelible trace in its movement from the outside towards the inside of the tablet, conditioned by the rotation of the head on the upper surface.

Moreover, it is possible to observe in Fig. 6, a substantial difference in the morphology of the material remained "trapped" inside the residual tablet between the center and the sides; in the center, as also confirmed by the metallography, the aluminum chips were completely bonded with a very fine microstructure. Whereas, the chips boundary is still visible in the stirred zone far from the center extrusion hole (Fig. 6d).

2.3 Properties of Ti-Based Light Alloys Produced by PBF

Given the intrinsic differences between electron- and laser-based PBF processes, the same as-built (namely with no further post-processing treatment) sample of Ti-6Al-4V will be characterized by a higher surface roughness and a lower fatigue strength if produced by electron beam melting [34]. In terms of comparison between traditional manufacturing techniques and metal additive manufacturing, the performance of samples after post-processing treatments for stress relieve and machining, show a fatigue strength that is comparable or even better than traditional ones [35].

Strong efforts are currently performed by the scientific community to improve parts quality (i.e. density, finishing), and also to optimize the PBF parameters in order to control the microstructure. Moreover, to improve the performance of PBF parts and to widen the range of materials that can be manufactured by PBF techniques, Ti-based light alloys with new formulation tailored for additive manufacturing are under development. Results show that the epitaxial growth typical of additively manufactured titanium alloys can be hindered adding boron to powder blends of Ti-6Al-4V, Ti-12Mo, Ti-20V, due to the grain refinement effect linked to the TiB needles formation [36]. The iron addition to a β-Ti alloy in order to get the Ti-1Al-8V-5Fe formulation (also known as Ti-185), has been investigated by Azizi et al. [37] as feedstock material for selective laser melting. The final AM part produced with the Ti-185 powder show a fine microstructure characterized by the presence of nano-scale α phase inside the β matrix, coupled with high dislocation density. As a result, these peculiar features are responsible for remarkable mechanical properties in terms of strength and plasticity.

New formulations of peritectic titanium alloys with the addition of rare earth elements (i.e., La) have been recently proposed by Barriobero-Vila et al. [38], namely Ti + 2 wt.% La and Ti-1.4Fe-1La (wt.%). The microstructural characterization shows that the resulting orientation of the alpha phase is not always related to that of the beta phase, which reflects in a reduction of texture and equiaxed microstructure.

3 General Considerations and Outlook

Two novel approaches and methodologies of friction stir welding on aluminum alloys were presented. The first approach consists in a double-side FSW (DS-FSW). The second approach is represented by a radial deviation of the rotating pin from its centerline, during FSW (RT-FSW). With respect to conventional FSW, DS-FSW shows more uniform elastic modulus across the sheet section, with respect to the FSW, better formability and higher FLC response. On the other hand, the RT-FSW in post-weld annealing (PWA) condition showed the best mechanical response respect to the un-welded annealed AA5754 sheet.

The feasibility of solid-state recycling of pure aluminum AA1099 chips was investigated using the innovative FSE process to produce defect-free wires. A finite element simulation was initially carried out in order to optimize both the design of the main and secondary components used in the experimental tests. The main results obtained can be summarized as follows: i. excluding the initial transient phase, the temperature greatly influences the extrusion load during the process; as the temperature increases, the machine load progressively decreases until a steady state value. ii. FSE process applied to recycle AA1099 chips allows to obtain wires manufactured with good surface quality, but with non-homogeneous microstructure and with presence of small internal voids.

Titanium based light alloys produced by electron or laser powder bed fusion, are now widely known in the field of metal additive manufacturing. The powerful option of a design which is free from the limitations typical of traditional manufacturing techniques, is strengthened by microstructural and mechanical properties which can be properly customized to be competitive with cast, forged or wrought alloys. The fast growth of the AM technology coupled with the development of new alloys formulations tailored for specific applications or to overcome microstructural weaknesses typical of AM, enlighten the new era of metallurgy.

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50 Years of Chemistry in the Engineering Faculty: From Free Radicals to Nanosystems

Pierluigi Stipa, Simona Sabbatini, Michela Pisani and Liberato Cardellini

Abstract The history of the Chemistry within the Engineering Faculty will be described, and the evolution of the research topics will be shown till the actual main research lines. The explanation of these topics will also take into account the direction of their possible development in the next future.

1 The Beginning

As the Engineering Faculty started, the Chemistry group was organized by Paolo Bruni, moving from Bologna University (*Istituto Chimico*), and included, in the following years, Barbara Cardillo, Giorgio Tosi and Liberato Cardellini. The research topics were mainly centered on Electron Transfer Reactions, including Charge Transfer Complexes [12, 17, 69] and Organic Free Radicals, and for this reason the first Electron Paramagnetic Resonance (EPR) spectrometer (the election equipment for the detection of Free Radical Species) of Ancona University was achieved, directly from Japan [10]. The group was later reached by Pierluigi Stipa (1983, post-doc position) and Lucedio Greci (1985, full professor position), both moving from the same *Istituto Chimico* of Bologna University, with expertise in that research field, in particular the synthesis and reactivity of heterocyclic Nitroxide Radicals, a class of stable organic free radicals.

After 1990, the number of the researcher joining the group increases, allowing the formation of different teams, each of them directed toward the development of

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a specific research topic: Organic Free Radical Chemistry, Applications of Infrared Spectroscopy, Gene and Drug Delivery, Innovative Teaching.

2 Organic Free Radical Chemistry

2.1 Synthesis and Applications of Nitroxide Radicals

This research line represents an implementation of the starting research group topic, as developed by Lucedio Greci first, and then by Pierluigi Stipa. Within such a field, a large number of Heterocyclic Nitroxides Radicals, belonging to the indolinonic, quinolinic and benzoxazinic series, has been synthesized and studied [3, 21].

Nitroxides constitute a class of very stable Organic Free Radicals, whose stability is mainly due to the localization of the unpaired electron in their N-O function [29, 65]. A delocalization is however possible, as revealed by their EPR signals, and more recently confirmed by means of Density Functional Theory (DFT) calculations [9, 62]. Some characteristic features of one of these derivatives, taken as a typical example, are shown in Fig. 1. The electronic structure there reported explains their peculiar chemical behavior: in fact, together with the typical Nitroxide reactivity toward Carbon centered radicals, these derivatives are able to react very rapidly also with O-centered [28, 61] and N-centered radicals, [1] the so-called ROS (Reactive Oxygen Species) and RNS (Reactive Nitrogen Species) respectively, both considered as the main species responsible of autoxidative processes [27]. For this reason, many of these derivatives have been successfully tested as antioxidants in polymers [22, 40] as well as in biological systems, [5, 39] while others resulted of interest in the field of Controlled Radical Polymerization, and some of them have been object of International Patents [45]. In particular, many of these Nitroxides, and their corresponding alkoxyamines, [66] have been successfully employed in the Nitroxide Mediated Polymerization (NMP), [7] and recently used also for the synthesis of

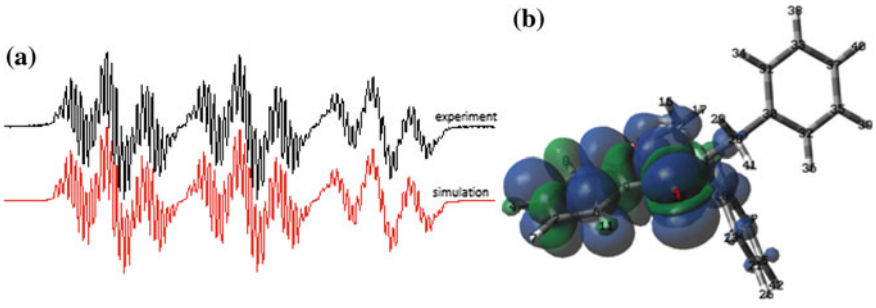

Fig. 1 **a** Experimental (black) and simulated (red) EPR spectra; **b** spin density distribution (α–β) computed at the B3LYP/EPR-III level (positive values in blue and negative in green)

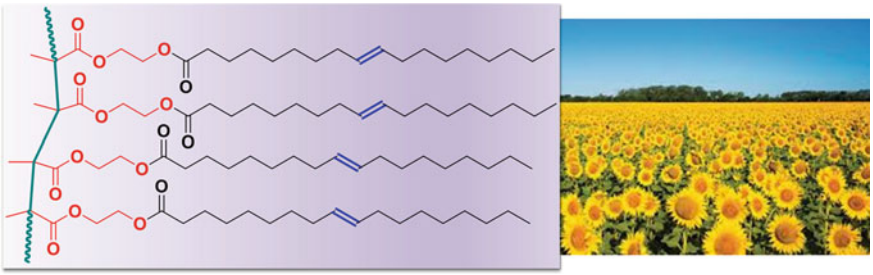

Fig. 2 A possible structure of the synthesized biodegradable copolymer: the methacrylic chain in red and the oleic oil residue from sunflower oil in black

biodegradable polymers. Our team is in fact very sensitive to problems involving the environment, as well as those arising from the use of petroleum derived plastics, such as the presence of microplastics in seawater, as well as their replacement with biodegradable materials from renewable resources in view of a *Circular Economy*. In particular, considering the large availability of sunflowers in the region, we are implementing the synthesis of these materials as acrylic copolymers of sunflower oil (Fig. 2), by means of NMP, which in turn is actually considered as the most eco-friendly polymerization technique.

This last study is still in progress and is carried out with the collaboration of researchers from Bologna University (DICAM) and Marseilles University (France, Institut de Chemie Radicalaire).

2.2 Nitrones and EPR-Spin Trapping

The preparation of our Nitroxides is usually achieved starting from the corresponding Nitrones (N-Oxides) which, in turn, result as very interesting candidates in EPR Spin Trapping. This technique is based upon the fast reaction between a suitable diamagnetic molecule (a spin trap) and short-lived free radicals, initially formed in the reaction system, yielding relatively long-lived radicals (spin adducts), whose EPR signals are persistent enough to be recorded and analyzed, leading to the identification of the initial short-lived radical (Fig. 3).

In this field, our derivatives from the Benzoxazine series showed very interesting features [63, 64]. In fact, besides their fast reactions with many kinds of Free Radicals, the EPR signals of the corresponding spin adducts are very specific of the radical trapped, overcoming in this way the main drawbacks typical of their commercially available homologues [8]. Moreover, their reactivity toward ROS is mainly responsible of their efficacy as antioxidants in biological systems, also more pronounced of that showed by commercial Nitrones. These last results attracted the interest of a research group from Buenos Aires University (Departamento de Quimica Organica), with which we are continuously collaborating in the development of

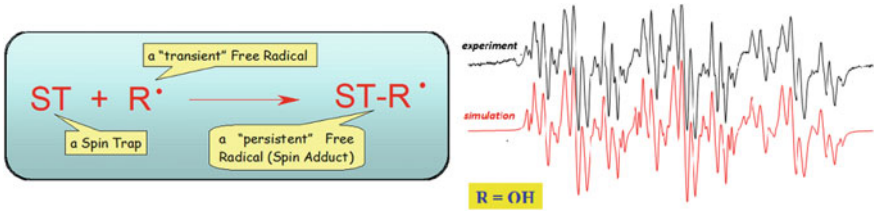

Fig. 3 The mechanism of the Spin Trapping technique (left) and EPR signal of a Benzoxazine-OH spin adduct

new heterocyclic nitrones, also through hosting several times their Ph.D. students in our laboratories [41].

2.3 Future Perspectives

In the context of the research topics previously described, our future goal is to improve our knowledge and skills in the polymeric materials field, by designing new derivatives acting as efficient antioxidants as well as valuable controllers in the synthesis of biodegradable polymers from renewable sources. At the same time, a deeper study on the identification of the pollutant microplastics will be carried out, in view of reducing their presence in the environment, as well as their possible reuse. Such a study will mainly take advantage of the Infrared (FTIR) and EPR facilities available in our Department, which showed to represent very *diagnostic* techniques also in the field of polymeric materials.

Concerning the biological implications of our derivatives, new Heterocyclic Nitrones will be designed, with the scope to modulate their water/lipid distribution in order to differentiate their specificity in fighting against in vivo free radical induced damages. These studies will also take advantage of DFT and MD (Molecular Dynamics) calculations, made possible by the availability of the corresponding hardware and software at CINECA Supercomputing Center (Casalecchio di Reno, Italy).

3 Infrared Spectroscopy

Fourier Transform Infrared (FTIR) spectroscopy is a well-known technique widely applied in basic and industrial researches. It studies the interactions of matter (organic and inorganic compounds) with the electromagnetic radiation and offers the possibility to correlate the morphological features of a sample with its vibrational patterns.

This technique was introduced at the Polytechnic University of Marche more than 35 years ago by Professor Tosi in order to study the synthesis and reactivity of charge transfer complexes among organic molecules [11] and to detect defects in polyethylene acetabular cups for hip prothesis [47]. Beginning from 2000, a new Infrared spectrometer equipped with a microscope, made it possible to expand the type of samples to be analyzed and especially the methods of analysis. The coupling of IR spectrometers with visible microscopes has led to perform imaging analysis, in which biochemical and spatial information of biological samples, such as tissues and cells, are combined. In this way, it was possible to map very restricted regions of non-homogeneous samples, and to detect the vibrational motions of the most relevant macromolecules, such as proteins, lipids, carbohydrates and nucleic acids.

3.1 Micro-Imaging of Biological Samples

Biological samples have characteristic and well-defined IR vibrational modes that can be used as markers for their biochemical response to different treatments and pathologies [33, 36]. In this light, the research team of IR spectroscopy has exploited Infrared Microspectroscopy (FTIRM) on cells and tissues, providing a huge amount of structural informations on specific metabolic processes, the occurrence of oxidative stress and the presence of phlogosis, in addition to an evaluation of cancer grading [34, 36, 38, 58]. FTIR microspectroscopy has been successfully applied also to analyze biological samples from patients affected by several tumoral pathologies, such as breast cancer, [2] colon cancer, [24] benign and malignant skin lesions [37, 68]. The first and main objective of these researches was the detection of specific spectral markers for the most relevant biocomponents, which could be unequivocally related to the specific tumoral pathologies. Particular attention was reserved to head and neck tumors which have clinical behavior sometimes difficult to predict with classical histopathology. In the past decade, various epithelial pathologies of the oral compartment have been studied [34, 38, 57, 58]. In most cases, the IR imaging approach played a key role in detecting early stages of inflammatory, benign, and malignant diseases, helping to gain a deeper understanding of different pathologies nature.

Specimens from salivary gland tumors, odontogenic cystic lesions and neoplastic sinonasal lesions have been explored [23, 67]. In all cases, visible and infrared images of each section were acquired, and the biomolecular features of tissue components were evaluated. To discriminate the spectra corresponding to different components, for each IR map, unsupervised hierarchical cluster analysis (UHCA) and the principal component analysis (PCA) were applied [35]. The whole methodological process is sketched in Fig. 4.

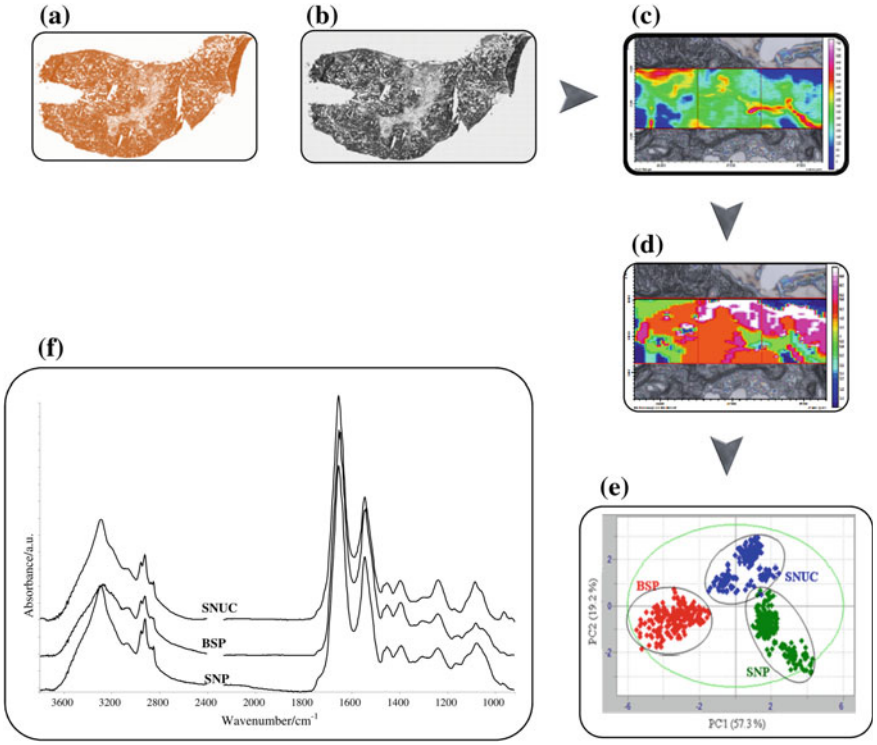

Fig. 4 Each sample was submitted both to **a** histological and **b** FTIR Imaging analysis. On specific areas, the **c** IR maps were acquired. IR data were then submitted to multivariate analysis, **d** UHCA and **e** PCA, from which **f** absorbance average spectra were achieved

3.2 Infrared Spectroscopy of Biomaterials, Biopolymers, Microplastics

FTIR microspectroscopy can be considered one of the most versatile analytical techniques for different applications. It was used to evaluate the effect of different polishing and finishing procedures on restorative material [44] and to map the topographic distribution of a biomimetic collagen fibrils/HA nanocrystals composite on titanium substrate [43]. Recently, FTIR spectroscopy was used to detect and characterize biopolymers involved in oxidative processes and radical reactions, together with microplastics derived by seabed and wastewater treatment plants. Considering the extreme relevance of these topics, the application of FTIR spectroscopy could be very useful as well as leading to interesting future implications.

4 Gene and Drug Delivery

Beginning from 2000 a new research line concerning the synthesis, preparation and structural characterization of neutral liposomes as carries of DNA for gene therapy was developed. The development of vectors able to transport genetic materials inside the cells efficiently, selectively and safe for patients is still part of human gene therapy (HGT) which plays a very important role in medicine. Synthetic vectors with respect to viruses show many potential advantages, such as lack of immunogenicity, no limits to the size of nucleic acids to be loaded and finally preparation procedures cheap and easy to perform. Within this framework, we started studying neutral liposomes (NLs) and their interactions with DNA in the presence of bivalent cations as potential DNA vectors. The use of divalent metal cations was proposed to promote the formation of complexes NLs/DNA stable in water solution. The formation of these systems was the result of a self-assembling process in which the driving force was represented by the release of the counter-ion entropy upon neutralization of DNA phosphate groups by metal cations. The preferred equilibrium geometry is dictated by a critical interplay between the surface charge density and the elastic properties of the constituent lipid bilayers.

The supramolecular structure of the lamellar phase loaded with DNA (L_α^c) consists of an ordered multilamellar assembly where the DNA helices are sandwiched between the lipid bilayers and metal cations bind the phosphate group of DNA to the lipid heads, while in the complexed hexagonal structure (H_{II}^c) the DNA strands are collocated in the water rods arranged on a hexagonal lattice (Fig. 5). From these studies a series of papers on structural and physicochemical properties of neutral carriers for the DNA delivery and an in vitro transfection attempt was produced [14–16, 18, 31, 48–54].

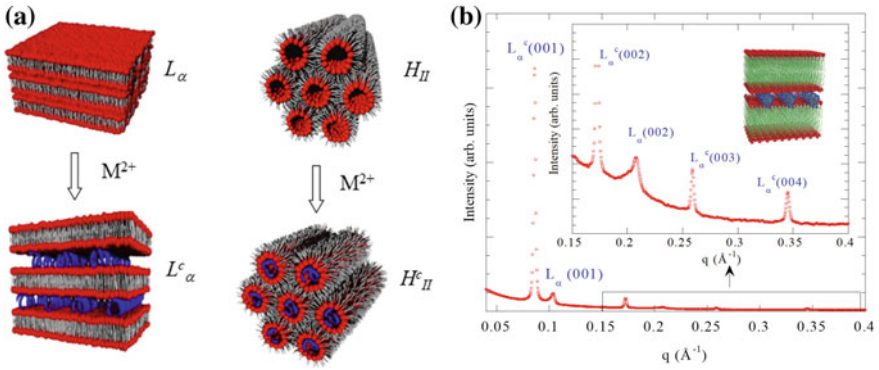

Fig. 5 **a** An example of uncomplexed (L_α) and complexed lamellar phase (L_α^c); uncomplexed (H_{II}) and complexed hexagonal phase (H_{II}^c). The lipids are in red (headgroup) and grey (chain) and the DNA rods are in blue. This figure was redrawn by ref. [70]; **b** Synchrotron SAXS pattern of complexes NLs/DNA

From 2009 to 2015, additional developments of the research in this field concerning the synthesis of new phospholipids for the gene delivery systems were carried out. These lipid molecules were functionalized with chelating agents in the head portion becoming cationic after the inclusion of a bivalent metal cation on the crown: in such a way, non-toxic cationic liposomes were obtained. In particular, crown ether lipids were synthesized to prepare liposomes to promote the interactions between DNA with lipid membranes in the presence of metal cations and the efficiency of these liposomes as potential delivery systems has been studied [4, 13, 32]. Moreover, the liposomes are interesting delivery systems due to their amphiphilic nature and they are capable of transporting both water-soluble and water-insoluble drugs inside the cells. Within the frame our research group proposed novel liposomal nanocarrier containing mannose 6-phosphate(M6P)-cholesteryl conjugates. By virtue of its affinity for the CI-M6PR receptor, M6P group enables liposomes to carry bioactive molecules along the route leading to lysosomes [26, 46]. In this work we showed the capability of M6P functionalized liposomes to be internalized by M6P-receptor expressing cells through intracellular tracing experiments in NIH-3T3 cells by means of confocal microscopy measurement.

In recent years, nanomedicine—the use of nanotechnology for medical purposes—has received wider attention among the scientific community. The main idea behind drug carriers developed in nanomedicine is to load the drug into a nanoparticle and inject it into the body. Within this framework, from 2016 we are currently developing soft-systems based on lyotropic liquid crystals (LLCs) dispersed in a continuous aqueous medium to be used as vectors for anticancer drugs. The lyotropic liquid crystalline phases represent an interesting drug delivery matrix due to high solubilization capacities for hydrophilic, lipophilic and amphiphilic guest molecules. The most investigated lyotropic nanostructural carriers are cubosomes and hexosomes. In particular, we prepared and characterized nanoparticles from phytantriol (PHYT), alone or in combination with another cationic lipid (DOTAP), unloaded and loaded with the antineoplastic agent 5-fluorouracil is one of the major drugs for the treatment of stomach, head and neck, and breast cancers. After evaluating the entrapment efficiency of 5-FU in PHYT cubosomes, their in vitro antitumor activity in human breast cancer cells was assessed. 5-FU-loaded cubosomes significantly enhanced the cytotoxic activity of the drug in cells, making them promising carriers for the efficient delivery of 5-FU [6]. Therefore, these results are a promising first step towards the development of new chemotherapy systems.

5 Improving Autonomous and Creative Thinking in All Students

Students who arrive at university differ in many aspects, especially for motivation and cognitive development [60]. Given the features of higher education, to better serve gifted students, we must provide them with transformative learning opportunities [25, 59].

In a chemistry course for students of the Engineering Faculty, stoichiometric calculation provides the opportunity to propose challenges of various difficulties in order to involve all students. The students are actively involved in the learning process and teaching is partly done using the cooperative learning method [20]. Students are empowered and encouraged to solve problems in a meaningful way. It is asked to explain, illustrating and argue the solution process in order to make the reasoning visible [42, 56]. Problems solved by the students are corrected, feedback is given, and the students are encouraged to find original solutions. These solutions are rewarded with bonus. In a school environment that wants to favor creativity, mistakes should not be judged in a negative way. The hallmark of successful individuals is that they love learning, they seek challenges, they value effort, and they persist in the face of obstacles [30].

The acquired professional experience and the evidences found in literature show that this way of teaching allows to establish supportive psychological environments that motivate students to improve their cognitive abilities [55]. After each lesson all students receive the list of concepts and exercises to be solved, to acquire the necessary skills in problem solving. Problems concerning new topics are solved at the blackboard, analyzing, representing, and explaining the steps and underlining the strategies used by experts to solve these problems. Given the importance of knowledge of chemical concepts in problem solving, students are encouraged to draw concept maps and make summaries.

Differentiated instruction and the proposition of problems of different difficulty allows each student to work according to their own pace and to increase self-esteem. This way of teaching is very productive and stimulates students' cognitive growth. In more than twenty years of use, this teaching method has allowed to collect hundreds of creative solutions to selected problems particularly demanding, many of which are original [19]. Most students positively accept this way of teaching and learning because it allows to significantly improve their problem-solving skills, useful in other university courses and in their professional life. In a study conducted on graduate students (N = 407) it results that 93.6% of students who passed the chemistry exam with a score of at least 27/30 graduate with the highest marks: 110/110 or 110 and praise.

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Physics of Matter: From the Nanoscale Structure to the Macroscopic Properties of Materials

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Abstract The physicists of the Polytechnic University of Marche (UNIVPM) have been conducting research in the physics of matter since the early seventies. Here we report a number of topics of the research activities carried out by the physicists working at the Department of Materials, Environmental Sciences and Urban Planning (SIMAU) of the Engineering Faculty, limiting our review to arguments and methods that are currently subject of investigation. The main scientific achievements and the most promising future developments are highlighted. The main purpose of this activity is the study of the macroscopic properties of matter in connection with its atomic structure for a variety of materials of technological interest in physics, chemistry, engineering, biology and medicine. These investigations require experimental tools capable of accessing the materials structure at the nanoscale. X-ray

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diffraction (XRD) and scattering techniques have represented the primary tool used to probe the structure of matter with atomic resolution, whereas electron microscopy techniques have provided complementary information on the structure and morphology of materials from the microscale down to the nanoscale. XRD studies have been performed using the X-ray instrumentation available at the departmental laboratories and, more recently, with the high-performance machines of the European synchrotron radiation facilities. Electron microscopy techniques have been implemented in an inter-departmental laboratory aimed at the structural and morphological characterization of soft and hard materials. The more recent set-up of laser optics laboratories has allowed an extended investigation of the properties of soft materials with focus on nonlinear optics of liquid crystalline and polymeric compounds.

1 Introduction

All the macroscopic properties of materials, such as mechanical, electrical and optical properties, are inherently connected with their atomic structure. Therefore, probing the structure of matter at the nanoscale is the best way to find the relationships between nanostructure and macroscopic behavior of the materials. X-ray diffraction (XRD) is one of the most powerful tools to study the structure of materials and living matter with atomic resolution. On the other hand, electron microscopy techniques provide complementary information on the structure and morphology of materials from the microscale down to the nanoscale. The physicists of the Polytechnic University of Marche (UNIVPM) have been involved in structural studies of materials by means of XRD since the early seventies. XRD studies have been traditionally performed using the conventional X-ray diffractometers of the departmental laboratories and, more recently, with the high-performance machines of the European synchrotron radiation facilities. Electron microscopy techniques have been implemented in an inter-departmental laboratory starting from the early eighties, aimed at the structural and morphological characterization of soft and hard materials. The more recent set-up of laser optics laboratories, started in mid-nineties, has allowed an extended investigation of the properties of soft materials with focus on nonlinear optics of liquid crystalline and polymeric compounds, holographic materials for optical processing and storage, optical manipulation and development of novel optofluidic devices. The above techniques have been applied to investigate a variety of materials for innovative applications in the fields of engineering, life and environmental sciences and medicine. In the following sections we report a number of results of the research activity carried out over the past fifty years in the laboratories of XRD, electron microscopy and optics of the UNIVPM.

2 X-Ray Diffraction Studies of Soft Materials

The interest in the structure of matter at the nanoscale in the Polytechnic University of Marche dates back to the mid-seventies, when a small group of physicists started pioneering studies of the structure of liquid crystals (LCs) by means of XRD, neutron diffraction and calorimetry. At that time, the novelty of the LC science and the discovery of a variety of new LC phases motivated scientists worldwide to investigate their nanoscale structure and its link with the macroscopic properties. XRD [1] was the primary experimental technique used in these studies, performed with the conventional diffractometers originally installed at the UNIVPM laboratories. LC molecules with a variety of chemical structures were investigated in those years, not only for fundamental reasons but also for the potential technological applications spanning from physics and engineering to biology and medicine: among these, rod-like mesogens based on a rigid aromatic core linked with fluid aliphatic tails of various chemical structure and length [2], metallo-mesogens consisting of LCs incorporating metal atoms in various molecular architectures [3, 4], thermotropic main-chain and side-chain LC polymers [5–10] and polymeric composites [11]. In those years, interest was mainly addressed to the identification of new mesophases [2], the study of pre-transitional critical effects [1], the mesogenic behavior of the recently discovered polymeric and organometallic LCs [3–10].

A turning point in this research field occurred with the advent of the large-scale facilities for synchrotron light, in particular the European Synchrotron Radiation Facility (ESRF, Grenoble) in 1994 and ELETTRA (Trieste) in 1995. The extremely high brilliance and coherence of these powerful X-ray radiation sources has made it possible to access the structure and dynamics of matter on increasingly smaller space and time scales with very high resolution. Since then, the scientists of the UNIVPM soft matter group have become regular users of these facilities, performing challenging experiments not achievable in a home XRD laboratory. The variety of materials investigated is quite large but essentially belongs to the category of soft materials, in particular LCs, polymers and polymeric composites for applications in photonics, opto-electronics, information and communications technology, renewable energies, biosensors and biomedicine. To summarize the most recent activity of the group, here we focus on a few representative examples of this research, which stand out for the international resonance of the obtained results and the future perspectives.

At the beginning of 2000s, a series of pioneering studies were conducted on the physical properties of LCs in confined geometries. Interest was focused on polymer-dispersed LCs (PDLCs), a family of composite materials consisting of spherical droplets of LCs randomly dispersed in a polymeric matrix [12]. Because of the composite nature and the large surface-to-volume ratio, these materials exhibit unique optical properties for practical applications and a variety of unusual physical effects that are strictly connected with the space configuration of the average orientational order of the LC molecules within the droplets. Whereas conventional experimental techniques allow to access only areas involving a large number of droplets, for the first time we used a micron(μ)-sized synchrotron X-ray beam to probe the nematic

ordering in a single droplet of LC [13]. We thus demonstrated the effectiveness of μ-XRD as a unique tool to characterize LC ordering in single droplets, opening the way to the possibility of studying LC ordering in dispersed mesophases with space resolution of 1 μm [13].

A few years later, we started an extensive investigation of the structure and function of self-assembled liposome-DNA complexes for gene-therapy applications. Liposomes are self-closed structures composed of curved lipid bilayers that form the basic matrix of the cellular membranes. Recent completion of the working draft of the human genome has convinced scientists about the reliable possibility of using gene medicines to combat genetic diseases. The goal is to achieve the transfer of extracellular genetic material into somatic cells (transfection) and thereby provide therapeutic effects. Realization of the full potential of gene therapy depends in a major way on the development of safe and efficient nonviral gene delivery agents. Complexes composed of neutral lipids and DNA offer a promising alternative to conventional viral delivery agents with much lower inherent cytotoxicity. Within a large collaboration including physicists, chemists and biologists we have studied the nanostructure of a variety of liposome-DNA complexes, discovered new supramolecular architectures and found correlation with their biological function and transfection efficiency [14, 15]. In particular, we have demonstrated the self-assembled formation of the lamellar L_α phase in dioleoylphosphatetidylcholine (DOPC)-DNA(plasmid)-Metal^{2+} complexes (Fig. 1a). In vivo transfection tests on mouse fibroblast cell lines (NIH 3T3), using DOPC-DNA(pGreenLantern1plasmid)-Metal^{2+} as DNA vectors,

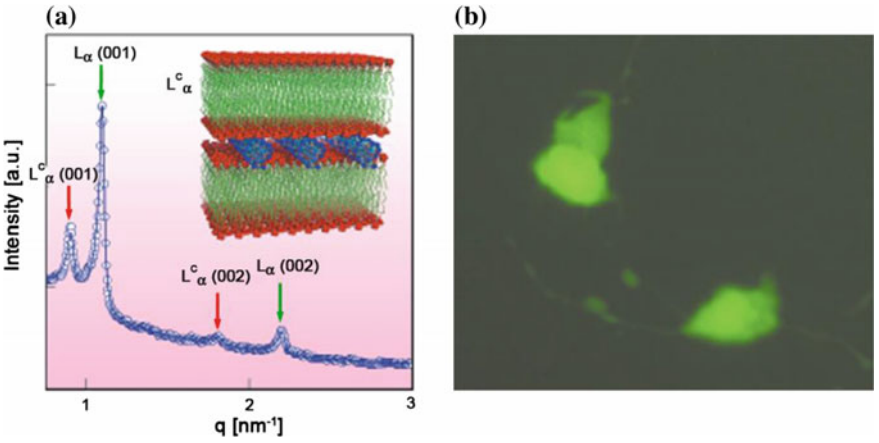

Fig. 1 **a** The XRD pattern of the DOPC-DNA-Mn^{2+} (4:3:12) solution mixture. L_α^c and L_α refer to the lamellar structure of the ternary complex and of the coexisting unbound liposome, respectively. The structure of the L_α^c phase consists of smectic-like arrays of stacked lipid bilayers with monolayers of DNA molecules intercalated within the water gaps (inset of figure); the metal cations bind the polar headgroups of DOPC with the negatively charged phosphate groups of DNA. The lamellar repeat distance is $d = 7$ nm. **b** Fluorescence micrograph of mouse fibroblast NIH 3T3 cell lines transfected with pGreenLantern1 DNA. The DNA was complexed to DOPC liposomes in presence of Ca^{2+}

demonstrated the transfection capacity of these systems (Fig. 1b). Our results have represented a first but fundamental step in the development of new biological materials and in the refinement of procedures to achieve efficient and tissue-specific transfection for gene therapy applications [16], a research area still very active in the group with great future perspectives [17].

A final example, probably the most representative for importance of the topic, experimental effort and international resonance of the results, concerns the extensive study of the nematic (N) phase of a new class of LCs, the bent-core mesogens, featuring a nonlinear molecular structure [18, 19]. The N phase of conventional LCs is characterized by the uniaxial nonpolar orientational order of the molecules, which in principle makes inherently impossible the existence of biaxial or polar/ferroelectric fluid N mesophases. On the other hand, starting from the seventies a number of theoretical studies and molecular simulations have predicted the existence of the biaxial N phase and, in parallel, the possibility of a polar N order, although their experimental demonstration in thermotropic LCs has proved quite challenging and elusive. For this reason, biaxiality and polar order in nematics have long been considered as the *Holy Grail* of the LC science. Our group has greatly contributed to this hot and widely debated issue, starting from the beginning of the 2000s with the discovery of the cybotactic N mesophase of bent-core nematics (BCNs). With a series of fundamental XRD experiments covering a fifteen years period [18–25], we have demonstrated the ferroelectric N switching in bent-core nematics (BCNs) and their potential to exhibit macroscopic biaxial N ordering. Both properties are due to the peculiar nanostructure of the cybotactic phase, which is constituted of biaxial and polar clusters of smectic-like ordered molecules (Fig. 2). These results represent an outstanding step in the LC science for both fundamental reasons, as they unveil the existence of a new state of matter, and from the technological point of view,

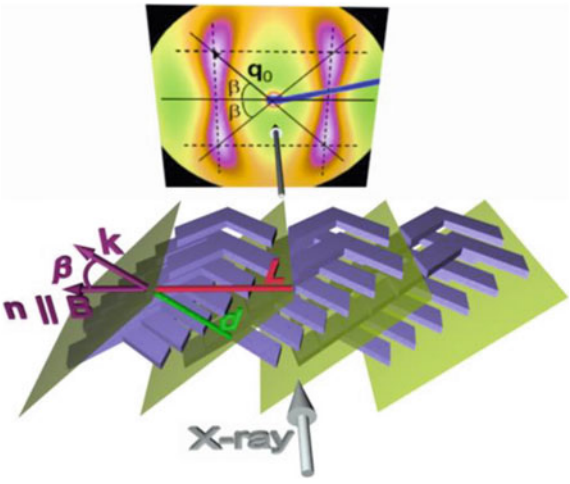

Fig. 2 Schematic drawing of the molecular arrangement of bent-core molecules within a skewed cybotactic cluster (aligned under a horizontal magnetic field **B)** together with the corresponding small-angle XRD pattern (After ref. [23] Reproduced by permission of The Royal Society of Chemistry)

because these materials have great potential in the development of a new generation of electro-optical devices for a variety of applications in different fields.

In parallel with the above mentioned studies, the current scientific activity of the soft matter group is focused on a new long-term research project, in collaboration with scientists of the ESRF, aimed at studying the mechanisms of anchoring, self-assembling, space arrangement and molecular orientation of ultra-thin films of LCs deposited on solid substrates with different techniques. This represents a research field with great potential and still essentially unexplored.

3 Electron Microscopy and Microanalysis of Materials

Electron microscopy and X-ray analysis are perhaps the two most frequently used modern tools for studying the materials structure down to the nanoscale. They each have many variants for addressing many materials types and properties and very often, they are used concurrently due to complementary information.

Modern electron microscopy techniques play essential roles in the characterization of material structures and properties. Electron microscopes utilize electrons of a pre-set energy, usually from tens of electronvolts to 200 keV. The electron beam is used to generate secondary signals from interaction with the investigated specimen. The signals arising from the beam–specimen interaction include secondary electrons (SE), backscattered electrons (BSE), transmitted electrons elastically and inelastically scattered, characteristic X-rays, Auger electrons, cathodoluminescence (CL), and electron-beam-induced current (EBIC). Each type or combination of signals can provide imaging or mapping contrast at its corresponding resolution. The wide variety of signals/information available in the electron microscope contributed to the widespread of the technique in almost all scientific field.

Electron microscopy characterization at the Faculty of Engineering of the Polytechnic University of Marche have initiated in the early eighties when the first scanning electron microscope (SEM) was installed for studies on materials for engineering applications. From those years the increasing demand of materials characterization at the micro- and nano-scale was the driving force for the implementation of laboratory equipment. A new laboratory for sample preparation was established. In the middle nineties an analytical transmission electron microscope (TEM) equipped with diffraction facilities and energy dispersive X-ray (EDX) microanalysis was acquired. Consequently, the laboratory for sample preparation was further implemented with the most advanced techniques, including electrochemical and ion beam thinning. Since then, every specimen from hard and soft materials can be successfully prepared for SEM and TEM observations. Recently, a field emission high resolution SEM, capable of investigating materials at the nanoscale even at low voltage operation, was added as a new facility available to researchers. Since 2006 all electron microscopy facilities at the Faculty of Engineering are organized in a Centre for

electron microscopy (CISMIN), which administrates instrumentation and offers scientific and technical support on issues concerning electron microscopy techniques and sample preparation.

Over the years, electron microscopy techniques have been used in the characterization of a wide variety of materials and devices such as p-n junctions and semiconductor devices [26], thin films and multilayers [27–31], light metal alloys (based on Al, Mg and Ti) [32–35], nanostructured materials for magnetic and energetic applications [36–41], scintillating crystals [42, 43], biomaterials and materials for additive manufacturing [44–46].

At the end of eighties strong collaborations with national and international research groups involved in production and characterization of thin films and multilayers by unconventional deposition techniques have been established. Pulsed laser deposition (PLD), pulsed laser reactive deposition (PLRD) and electron beam deposition (EBD) techniques have been used to produce thin films and multilayers or induce surface modifications of bulk materials. In particular, attention was focused on nitrides, silicides and carbides for applications in electronics or as hard material coatings [27–29]. Furthermore, the potentialities of laser and electron beam energy pulses in the production of metastable and non-stoichiometric compounds as well as in the modification of surfaces or in the interfaces intermixing have been also investigated [30, 31].

One of the most promising topic developed over the years have pertained the structural characterization of light metal alloys (Al, Mg, Ti). Outstanding results have been obtained by using electron microscopy in conjunction with positron annihilation techniques, small angle X-ray scattering (SAXS) and differential scanning calorimetry (DSC). Attention was focused on the atomic mechanisms in the early precipitation stage that lead to the formation of atomic clusters and ordered crystalline zones. The results obtained on different materials have clarified the nature and the extent of the physical processes active in the early stage of precipitation and the role of interaction between lattice vacancies and precipitates in the formation of the hardening nanophases (Fig. 3). Based on the results obtained, new material treat-

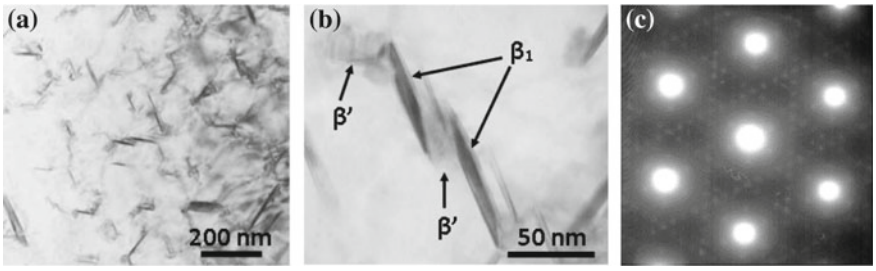

Fig. 3 TEM micrographs of the WE 43 Mg alloy in the T6 state: **a** bright field general view, **b** details of the phases present, the globular precipitate is β' while platelets are β_1, **c** selected area diffraction pattern showing the extra spots due to the secondary phases. Zone axis <0001> $_{Mg}$ (Copyright (2008), with permission from Elsevier, ref. [34])

ments capable of improving the mechanical properties of alloys used in aerospace, automotive and biomedical fields have been proposed [32–35].

Mg-based alloys other than structural applications have been also investigated as solid-state hydrogen storage material for energy production in fuel cells. The mechanisms of formation and decomposition of hydrides in systems based on Mg and the catalytic properties of Nb have been deeply studied. The results obtained allowed clarifying the mechanisms responsible of the hydride (MgH_2) decomposition, the role of the lattice vacancies in such mechanisms and the processes of hydrogen diffusion and release out of the material [36–39].

Currently, the ongoing activity concerns the characterization of nanostructures responsible of the mechanical properties of materials produced by additive manufacturing (AM). The most investigated materials for structural mechanical applications are Ti6Al4 V, maraging steels and Al10SiMg. Outstanding results have been obtained in the characterization of pure and contaminated metal powders used in the AM process. Furthermore, in Co–Cr biomedical alloys produced by AM, for the first time, alternated lamellar nanostructures of the ε-Co (hcp) and γ-Co (fcc) phases have been identified in the as sintered condition as well as after thermal treatments (Fig. 4).

This peculiar microstructure developed in the layer-by-layer production process is responsible of the improved mechanical properties of the material [44–46].

All the results reported here have clearly evidenced how the macroscopic properties of materials depend on the nanostructure. Therefore, to understand and improve the macroscopic performances of materials, it is essential to investigate and control the material structure down to the nano-scale.

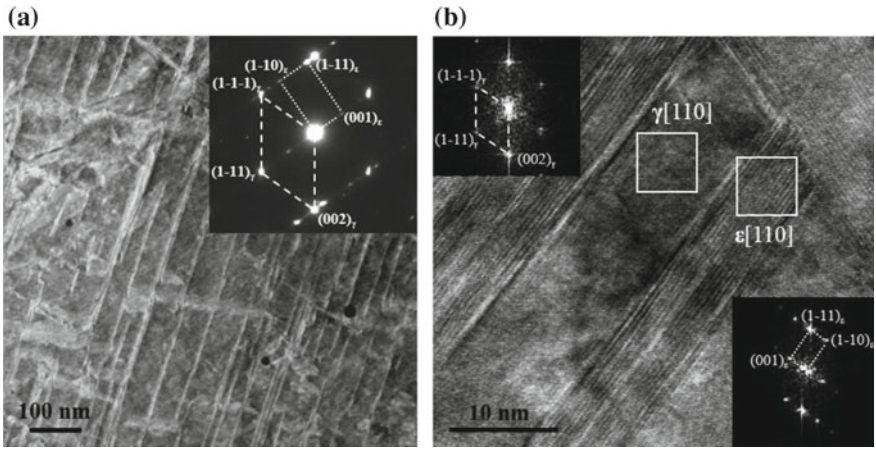

Fig. 4 High resolution TEM images taken in <110>$_\gamma$ zone axis orientation showing the lamellar structure of the Co-Cr biomedical alloy: **a** as sintered condition—inset: SAED pattern, **b** heat treated condition—insets: Fourier analysis of the squared regions (Copyright (2016), with permission from Elsevier, ref. [45])

4 Photonic Materials and Devices

Starting from the year 1995 new laser optic laboratories have been equipped to be devoted to the investigation of liquid crystalline and polymeric materials and to the development of demonstrators of novel optical devices. The main stream of researches has been the one concerned with photo-induced effects in these materials leading either to transient nonlinear phenomena or to permanent modification of the structures. In this context many original results have been obtained and several scientific collaborations at international level have been established.

Concerning nonlinear optics of liquid crystals, the most important achievement has been the discovery of the "Colossal Optical Nonlinearity" [47], still subject of several investigations around the world, concerning both fundamental aspects and possible applications. It has been observed that nematic liquid crystals doped by a specific dye known as Methyl Red at low concentration (0.1% in weight), under proper conditions, exhibit a nonlinear refractive index n_2 up to 10^3 cm^2/W, that is 8 order of magnitude higher than the conventional value characterizing the optical nonlinear response of liquid crystals, the well-known Giant Optical Nonlinearity observed for the first time in 1980.

This effect consists in the onset of a Kerr-type intensity dependent refractive index in the material that can be written as: $n = n_0 + n_2 I$, being n_0 the low intensity value. Such colossal response allows realizing a strong coupling between light beams at the same frequency and different wavevector leading to the generation of nonlinear phase grating producing beam diffraction with efficiency close to the theoretical limit in thin liquid crystal samples. This effect is shown in Fig. 5 that reports the pattern of the light induced diffraction of a probing He–Ne laser beam. The high number of diffracted beams originated by the nonlinear effect is a visual evidence of the high nonlinear response given the small sample thickness (1 μm) and the low power density of the interacting beams (100 μW/mm^2) [48].

The origin of this phenomenon has been explained as a light-induced modification of the surface conditions at the substrate-liquid crystal interface that in turn gives rise to bulk reorientation [49]. The basic role of space charge in this process has been

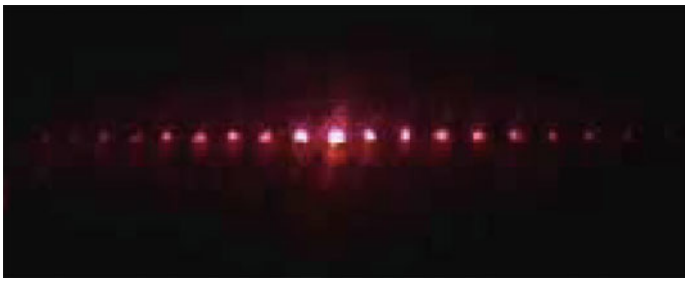

Fig. 5 Transient grating diffraction pattern due to colossal nonlinearity of dye-doped nematic liquid crystals (Reprinted with permission from ref. [48], Optical Society of America)

recently demonstrated [50]. This strong nonlinearity has been exploited to get wave front correction of aberrated beams at low power level (microwatts range) using a standard wave conjugation geometry and for the all-optical control of the trajectory of solitons created in liquid crystal cells.

The same compound when irradiated at higher intensities or using higher dye concentration (1%) shows permanent reorientation of the liquid crystal molecules, leading to permanent modifications of the optical properties that allow recording high resolution holograms [51] using both c.w. and pulsed [52] laser beams.

Driven by these results, investigation on holographic recording was extended to other polymeric and composite materials, with the aim of finding materials suitable for high resolution holographic storage. In the frame of a large European Network and an European project focused on optical holographic disks, technologies for 1D and 2D holographic lithography were built and high sensitivity polymeric materials suitable for micro-holography were developed [53].

This optical patterning approach allowed demonstrations of a number of optical devices. Among them it is worth to recall the achievement of phase-only modulation in a Polymer Dispersed Liquid Crystal were nano-size liquid crystal droplets are obtained by UV photo-polymerizzation leading to samples transparent to visible light but exhibiting a change of the refractive index when submitted to electric field [54]. Besides that, the technology of holographic lithography allowed to develop plastic microlaser using different designs to fabricate DBR (Distributed Bragg Reflector) [55] and DFB (Distributed Feed-Back) optical resonators [56].

Based on the mentioned activity the group achieved international leadership in:

(i) study of nonlinear optical properties of liquid crystalline materials;
(ii) holographic optical patterning of soft matter;
(iii) demonstration of optical active and passive devices based on the above phenomena and methods.

The applications driven activity led to getting 3 patents and the establishment of a spin-off company for development of optical sensors.

Starting from the described expertise new research directions have been undertaken to be further developed in the future.

Nonlinear optical reorientation of liquid crystals has been demonstrated to be the basic mechanism to get optical trapping of microsize beads dispersed in a nematic liquid crystal. This phenomenon leads to an optical tweezing effect with peculiar features with respect to the conventional one based on high intensity gradient. In this case the trapping range can be a few orders of magnitude larger, easily overcoming the distance of 100 μm distance between optical trap and the particle. Moreover, such trapping range and the associated force can be tuned by an applied electric field enhancing or quenching the effect in dependence on the dielectric anisotropy of the liquid crystal [57–59]. These studies have to be considered as preliminary ones to the further development of the optical tweezers apparatus to investigate DNA exhibiting liquid crystalline order and other biosystems of interest for biomedical application.

Active and passive optical devices are currently developed in the frame of Optofluidics in view of possible development of novel platforms for the Lab-on-Chip (LOC)

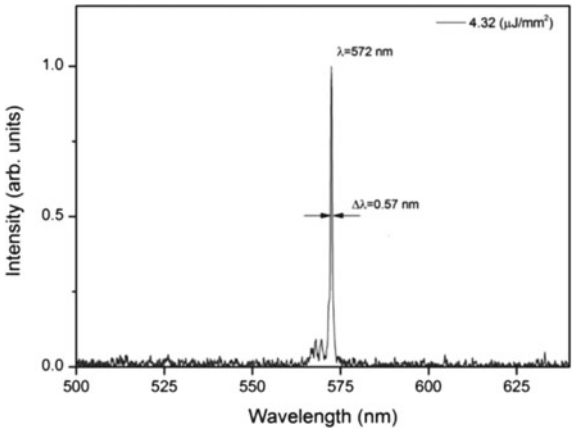

Fig. 6 Laser spectral output of a glass embedded optofluidic laser based on Fabry-Perot cavity (Reprinted with permission from ref. [60], Optical Society of America)

technology. In collaboration with the Italian Institute of Technology (IIT), a new optofluidic laser based on a Fabry-Perot cavity fully embedded in a glass chip has been realized and optically tested. It represents a record result for what concerns low threshold (2 $\mu J/mm^2$) and high-quality factor Q (~10^3) for optofluidic lasers based on Fabry-Perot cavity [60] (Fig. 6).

Further investigations are under way testing different configurations of the optical cavity for a further reduction of the pumping threshold in view of development of portable biosensors. Under a wider international collaboration, the investigation of photo-induced phenomena in liquid crystal cells based on substrates made by iron-doped Lithium Niobate (LN) crystals allowed realizing all-optical phase modulators [61] and getting LC reorientation in microfluidic channels [62].

Another research direction is the light-induced actuation of object at a macro scale. Along this research direction one recent achievement was the realization of a novel photo-mobile polymeric compound based on composite structure allowing photo-induced caterpillar-miming robot [63]. At the same time the Marangoni effect was exploited to get translational [64] and rotational [65] motion of objects floating on common liquids. All these results go towards the direction of light-controlled robotics.

5 Conclusions

We have reported a number of topics of the research activity carried out by the physicists working at the SIMAU Department of the UNIVPM. We have highlighted relevant scientific achievements and most promising future developments in the study of the relationships between structure of matter at the nanoscale and macroscopic properties of materials. Regarding the future perspectives of this research, a great boost is expected from the upgrade of the scientific instrumentation currently underway at

the XRD and electron microscopy laboratories, as a part of a strategic project aimed at the creation of a large inter-departmental facility to support innovative research in the fields on nano-science and nano-technology. The scientific results obtained so far, together with the excellent growth prospects, are expected to open new avenues for the next fifty years of the physics and materials science research at the UNIVPM.

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Energy Scenarios for the Future of Mankind

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Abstract The current scenarios for the future of energy seem to suffer a kind of schizophrenia. Some experts do not venture into an uncertain future and prefer to stick to a business-as-usual scenario focused on fossil fuels like they are going to be used in the future with no limitations at all. According to this scenario fossil fuels are not a commodity bound for depletion in the next decades, but they are going to be used forever, and no "energy transition" is in sight for the foreseeable future. Some other experts depict a completely different scenario, where solar energy and electric vehicle are "disruptive" technologies that in a matter of few years will send out of the market both the power utilities like we intend them nowadays and internal combustion engine cars, determining the end of oil-age and nuclear-age. In our opinion both scenarios have some strengths but suffer of many weaknesses, and at the end of the day the "energy transition" from oil-age to renewable-age will happen during this century but probably it will not be so fast as some predict. The paper describes the strengths and weaknesses of the two scenarios and presents a feasible vision for the foreseeable future of world energy. Eventually, current research efforts under way at DIISM-UNIVPM will be presented, starting from the reasons why the topics are substantial for the energy transition to continue with the results expected from these researches.

1 Introduction

On October 8, 2018 the Intergovernmental Panel on Climate Change (IPCC) released their "Special report on the impacts of global warming of 1.5°C above the pre-industrial levels" [1] where they present four "illustrative model pathways" (here shown as Fig. 1) for CO_2 emission reductions that limit global warming to 1.5°C with "*no or limited overshoot*".

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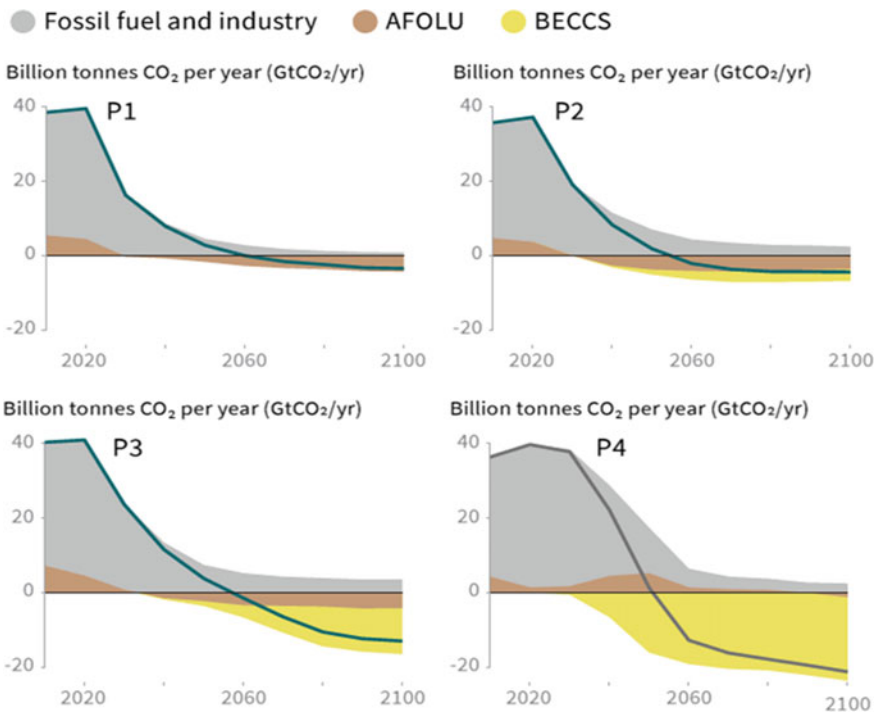

Fig. 1 Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways [1] (AFOLU: Agricolture, Forestry and Other Land Use; BECCS: BioEnergy with Carbon Capture and Storage)

According to the report and from an energy-planning point of view the most important mitigation measures for the short-medium term are the reduction in final use demand (32% reduction in 2050 for scenario P1) and the dramatic reduction of coal and oil uses. In other words, a strong decarbonisation.

Pope Francis came almost to the same conclusions in his Encyclical "LaudatoSì" [2] and the recent Club of Rome report on the limits of growth, entitled "Come on!" [3], proposes to completely abandon fossil fuels by 2050 as the only way to limit to 1.5°C the increase of the earth temperature.

All these alarming voices contain the same solution to the problem of climate change: phase out the fossil fuels and move towards renewables energies and a better efficiency in final uses, the so called "energy transition".

This solution is now feasible, both in technical and in economic terms, and some observers believe that it will be implemented much faster than expected, due to some "technology disruptions" that are already happening. We will describe this scenario as "Disruptive scenario".

On the other hand, in a kind of schizophrenic syndrome, so many observers think that the current energy scenario, based on fossil fuels, is here to stay as if no other future could be imagined.

Even if the situation is rapidly changing due to the abovementioned climate emergency, there is so much at stake that it is reasonable to think that the oil & gas industry will do whatever it takes to resist any quick change that could send them out of the market. While trying to adapt to the new situation oil & gas companies will try and convince public opinion that they are "too big to fail", renewables are a just a toy for some "tree huggers" without feet on the ground and there is no way out of fossil fuels; therefore coal (maybe in its "clean" version), oil and natural gas will continue to play the most important roles for years to come. We will describe this scenario as "Business-as-usual scenario".

As usual, things lie somewhere in between and an important "energy transition" will happen during the next decades. The reasons why the transition will not be so fast like some imagine and will take quite a lot of time are explained in the "Feasible scenario".

Sideways to the scenarios description, research efforts currently carried out at DIISM-UNIVPM will be briefly described, namely Demand Side Management, Micro-Grids and Energy Storage, Wind Energy and Biofuels from Algae. All these research lines are meant for accompanying the "energy transition" by taking into account, studying in detail and giving feasible solutions to different aspects of energy conversion, transportation and final uses.

2 Disruptive Scenario

It is well known that in one single hour of any given day the Sun radiates to the Earth more energy than mankind can consume in one year.

Going into more detail, the shortwave radiation annually absorbed by the atmosphere and the planet's surface, after considering that 30% of incoming radiation is reflected by clouds and surfaces, is about 4.10^{24} J. Energy consumed globally during the first decades of 21st century is of the order of 5.10^{21} J per annum. So, the energy consumed annually is something less than 0,015% of the solar irradiance [4].

Given these figures, it is immediately evident that exploiting solar energy is not a matter of energy balance but purely a matter of engineering and economics (and policies!).

As a matter of facts, a recent paper developed roadmaps to transform the energy infrastructure of 139 countries to 100% renewables by 2050 creating more than 24 million new jobs worldwide [5].

Putting together a number of considerations about the trends of some industries relevant to energy production, distribution and utilization, Tony Seba elaborated a revolutionary scenario [6, 7] that we will present here as "disruptive" because it is based upon the fast disruption of some consolidated industries, namely the internal-combustion-engine automotive industry, the oil & gas industry and the energy utilities industry, due to some emerging technologies able to present the consumer with more convenient and affordable services (something like what happened in the recent

past with digital photography "disrupting" film photography and mobile telephone "disrupting" landline telephone).

Quoting Tony Seba [6], "*the Stone Age did not end because humankind run out of stones. It ended because rocks were disrupted by a superior technology: bronze. Stones did not just disappear. They just became obsolete for tool-making purposes in the Bronze age. The horse and carriage era did not end because we ran out of horses. It ended because horse transportation was disrupted by a superior technology, the internal combustion engine.*

The idea is not new: Sheikh Ahmed Zaki Yamani, minister of oil and mineral resources of the Kingdom of Saudi Arabia and influential personality within OPEC (Organization of the Petroleum Exporting Countries) during the 1973 oil crisis, used to say the same thing about Stone-age and Oil-age endings. The difference is that, according to this scenario, we are now on the verge of seeing the Oil-age actually end.

Tony Seba continues [6]: "*The age of centralized, command-and-control, extraction-resource-based energy sources (oil, gas, coal and uranium) will not end because we run out of petroleum, natural gas, coal or uranium. It will end because these energy sources, the business models they employ, and the products that sustain them will be disrupted by superior technologies, product architectures and business models. Compelling new technologies such as solar, wind, electric vehicles and autonomous (self-driving) cars will disrupt and sweep away the energy industry as we know it*".

The reason why conventional energy framework is inevitably bound for disruption is that distributed solar generation, electric vehicle and autonomous vehicle are information products, subject to Moore's law, like personal computer and tablets, and governed by information economics and "increasing returns". Conventional energy resource economics, on the contrary, are governed by "decreasing returns". They cannot compete with technologies based on increasing returns and their fate is written.

To explain the concept, we quote again Tony Seba [6]: "*take the new darling of conventional energy: fracking. To "frack" a single oil or gas well requires hundreds of trucks, millions of gallons of water, and tons of sand with hundreds of chemicals blasted through the ground. You also need thousands of miles of pipelines, massive factories to liquefy or compress the gas before it can be shipped or stored, and massive ports with massive plants to decompress the gas and pipe it again to the power plant. Power generation can start only after all this process is complete.*

The return on these wells start decreasing as soon as you start pumping the oil or gas. Despite all the talk of abundance and a "golden age of energy", fracked wells may deplete by 60–70% the first year alone.

Also production from traditional wells declines by half in about two years, after which the wells drip on for a few more years.

Extraction economics is about decreasing returns:

- *The more you pump, the less each well produces;*
- *The more you pump, the less the neighboring well gets;*
- *The more you pump, the more each unit of energy will cost in the future.*

Solar, electric vehicle and the clean disruption are about increasing returns.

Solar PhotoVoltaic (PV) panels have a "learning curve" of 22%. PV production costs have dropped by 22% with every doubling of the infrastructure (Fig. 2).

The more demand there is in the market, the less your neighbor pays for her panels, and the more your neighbor benefits. Every time a solar panel is built in Germany, Californians benefit from lower costs when the next solar power plant is built. Every solar panel sold in Australia cuts the cost of the next solar panel in South Africa. Lower costs benefit all new solar customers.

Every large solar power plant in the desert benefits not only the people who buy its power, but everyone who buys solar power in the future.

The higher the demand for solar PV, the lower the cost of solar for everyone, everywhere. Your neighbor benefits, the warehouse owner in Australia benefits, and future buyers of solar benefit from lower costs. All this enables more growth in the solar marketplace, which, because of the solar learning curve, further pushes down costs.

This mutually beneficial arrangement is the opposite of extraction industries like oil & gas. When China's demand for oil surged in the last decade, world prices for oil went up by a factor of ten. The higher the demand for oil in Beijing, the higher gasoline prices are in Palo Alto and Sydney.

This is not just a theoretical framework. Solar PV has improved its cost basis by more than five thousand times relative to oil since 1970. By 2020, as the market for solar expands, solar will improve its cost basis relative to oil by twelve thousand times.

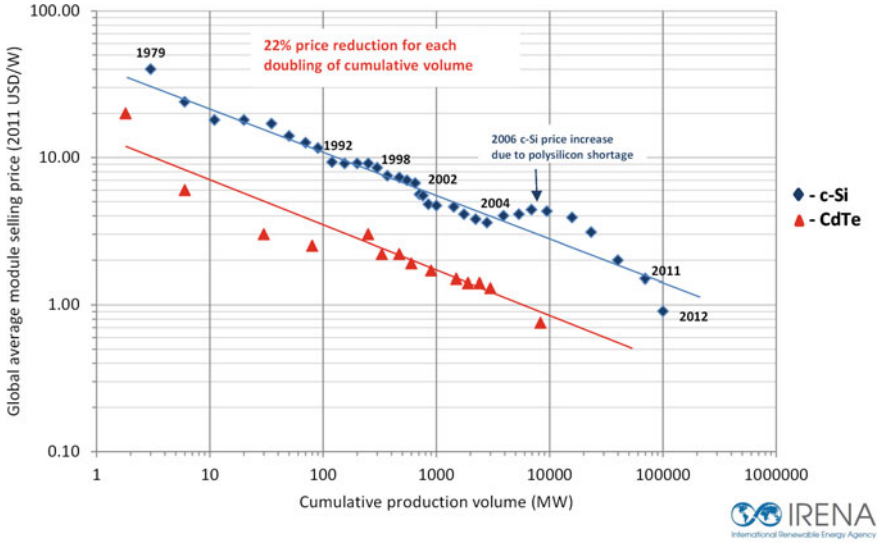

Fig. 2 Learning curve of PV technology [source: IRENA] (http://www.irena.org/-/media/Images/IRENA/Costs/Chart/Solar-photovoltaic/fig-62.png)

The economics of energy resource extraction, based on decreasing returns, just cannot compete with the economics of technology industries and its increasing returns.

The fossil fuels industry is pushed not just to extract more wells but to dig deeper, use harsher chemicals and create more wastelands. The fuel industry has to do this just to stay afloat. The BP Gulf Oil disaster and the monstrosity of Alberta Oil sands are not exceptions; they are the inevitable routine."

"*The century-old energy and transportation industries are on the cusp of disruption. The transition has already started and the disruption will be swift. Conventional energy sources are already obsolete or soon to be obsolete. The business model that enables them cannot compete with the disruptive force of technologies like solar, electric vehicles and self-driving cars.*"

3 Business-as-Usual Scenario

Going back to the figures given at the beginning of the previous Section it is possible to say that the total resources of fossil fuels are maybe as large as 200.10^{21} J [4] and it means that, at the current rate of consumption, fossil fuels could satisfy the needs for the next 400 years.

It is quite common among some of the observers the position that renewable energies would never be able to completely replace fossil or nuclear energies [8], while others are issuing warnings on how difficult would be for the renewable energies to cover the needs of modern world [9]. In many cases the solution of the energy problem had been envisioned in nuclear energy, but that was before the Fukushima disaster, which silenced most of pro-nuclear choir. And it was before the "unconventional" oil & gas reserves had started to be exploited.

That leaves the sole fossil fuels to lead the current scenario of energy. Actually, the mutual role of coal, oil and natural gas has changed during the years but in 2017 they, as a whole, still represented almost 85% of global share of primary energy [10] and getting rid of them is easily said but not easily done. Moreover, the crude oil consumption rate does not show any signal of crisis whatsoever: from 2014 the global consumption has increased by 8 million barrels per day, topping at about 100 million barrels per day [11].

The oil & gas industry are aware that fossil fuels are heavily contributing to the global warming but their recipes for contrasting the phenomenon are quite naïve, such as a massive reforestation of the size of Amazon rainforest, or pro-domo-sua, such as the promotion of a continued investment in oil & gas resources which are "*essential to meeting the dual challenge of providing billions of people with more energy while drastically lowering carbon emissions*" [12].

In the following we will try and give a role to different fossil fuels in a Business-as-usual environment.

3.1 The Role of Coal

Contrary to common belief, coal's role has accelerated since year 2000, notwithstanding its well known contribute to climate change and many others bad effects on the environment, doubling to 1.5 billion tonnes per year its penetration in the energy markets [13]. This is mostly due to the rising demand within Asia, met by supplies from Indonesia and Australia.

Developed countries are trying and push the decommissioning of as much coal plants as possible: in 2017, UK saw the first "coal-free" day since the start of Industrial Revolution and 2018 saw 42 days powered without coal, expediting the path towards a coal-free economy, that should be reached, according to plans, in 2025. Similar commitment is shared across the OECD (Organisation for Economic Co-operation and Development), also due to the fact that "*over half of Europe's coal fired power stations are now loss-making, and almost all will be by 2030*" [13].

China and India, facing very heavy pollution problems, are committed in phasing down coal plants growth as well, but this seems effective only within the respective borders, because the economic support for coal continues for plants to be built abroad, mostly in order to sustain mining industry which, in China alone, occupy three million workers.

As a result, up to 500 million tonnes of new coal capacity is currently under consideration, with an estimated investment in new coal projects of 24 billion USD, more than 90% of which coming from China, Japan, South Korea and India [13].

In this environment, the Trump administration support to coal sector, even if it employs only 50,000 workers in the US, is a new variable whose outcome is unknown.

Adding to the picture the scarce results from research efforts aimed at obtaining a "clean coal" and effective CCS (Carbon Capture and Sequestration) technologies does not call for optimism on environmental terms.

3.2 The Role of Oil

Since the second half of last century crude oil has surpassed coal to become the "*world's leading source of primary energy, with its share of the global energy supply peaking during the late 1970s at about 44%*" [10].

The oil share has decreased since then, down to 32% in 2010; nevertheless, during the last fifty years, oil has played the role of "*largest component of the global primary energy supply, and its consumption rose from about 1.6 to 4.3 Gtonnes per year* (the last figure is referred to 2015, and it means about 31.5 billion barrels per year)*, nearly a 2.7-fold increase*" [10].

"*In the last decades liquid fuels have retreated from electricity generation (less than 7% of all refined fuels were burned in power plants in 2015) and residential uses such as heating and cooking (now also less than 7% of global demand for liquids). The consumption of refined oil products has become even more concentrated in the*

transportation sector: all major forms of moving goods and people—be it shipping, railroads, trucking, automobiles and flying—rely overwhelmingly on refined oils" [10].

"*And it must be repeated that this importance goes beyond the reliance on high-performance fuels in all forms of transportation:*

- *Oil-derived lubricants are indispensable for countless industrial tasks;*
- *Modern transportation infrastructures are unthinkable without oil-derived paving materials; and*
- *Syntheses of scores of plastics begin with oil-derived feedstocks*" [10].

Given the importance of oil in modern societies and the awareness that it is present in this planet Earth as a finite quantity, many worried about how long its supply will last for the benefits of mankind.

The "oil peak" theory, due to Marion King Hubbert [14], is the most renowned theory about the fate of oil (and also of other fossil fuels). Even though Hubbert's production curve shapes have had to be changed after the discoveries of "unconventional" sources, some observers believe that the principles behind Hubbert's theory still hold [15], while others [10] base their criticism on the incorrectness of such predictions.

The exploitation of "unconventional" resources have changed the terms of the debate about the "oil peak", and also the recent developments about renewables and electric mobility have contributed to this change of paradigm. In this context, the Hubbert's theory has somewhat lost part of its importance, and this is why we won't go here into any details about it.

The "unconventional" resources, on the other hand, deserve some focus, because they have actually changed the role of oil and gas in energy scenarios. Oil sands, tight oil, shale oil and also shale gas have changed the fossil fuels paradigm because since when they have started to be exploited, mainly in Canada and US at the end of the first decade of this century, the world framework of energy markets has profoundly changed, making, for example, the US an exporter after that they had acted as importer for decades.

But, even though in quantitative terms the future of "unconventional" resources seems bright, many shadows haunt them. Environmental impacts associated with the extraction processes, the use of chemicals, the heavy consumption of fresh water, the greenhouse gases (GHG) emissions are very concerning.

And the economics of the industry are somewhat concerning too. A recent report from the Institute of Energy Economics and Financial Analysis (IEEFA) [16] wonders "*if the industry is still not profitable—after a decade of drilling, after major efficiency improvements since 2014, and after a sharp rebound in oil prices—when will it ever be profitable? Is there something fundamentally problematic about the nature of shale drilling, which suffers from steep decline rates over relatively short periods of time and requires constant spending and drilling to maintain?*" [17]. The law of "diminishing returns" definitely applies here.

Liquid fuels are peculiar for some applications, for example marine and air transportation and road heavy transportation, and there is no fully available substitute to

fossil fuels at present. LNG (Liquefied Natural Gas) and biomass may play a role, but it is difficult to say how big.

When thinking also at other applications where it does not exist a feasible substitute (petrochemistry) it is easy to predict to crude oil a life that goes well beyond the end of this century.

3.3 The Role of Natural Gas

Natural gas is the last-comer among the fossil fuels and also the most promising, raising from 10% of the global primary energy supply in 1950 to approach 25% in 2013 [18].

Its success depends upon many factors, one of them being that it is considered "the bridge fuel" to a low carbon energy system, due to the fact that its combustion emits less carbon dioxide than coal [19]. As a matter of fact "*the European Union's 2050 energy strategy aims to reduce greenhouse gases emissions by between 80 and 95% when compared to 1990 and in its Energy Roadmap 2050* [20, 21]. *The European Commission says it views natural gas as a key factor in achieving this reduction, at least in the medium term.*"

The EU document states that "*gas will be critical for the transformation of the energy system. Substitution of coal (and oil) with gas in the short to medium term could help to reduce emissions with existing technologies until at least 2030 or 2035*" [20].

What will be the fate of natural gas on the long term, i.e. after 2035, is a matter for debate. Some consider the huge quantities made available by shale formations through fracking technologies and the flexibility guaranteed by LNG the reasons for a long term success, notwithstanding the problems haunting the shale gas (similar to those affecting unconventional oil as explained in the previous Section) and the LNG (energy and environmental costs associated with the liquefaction process) [18]. The huge infrastructure already in place for gas distribution is another reason in favor of natural gas in a decarbonisation context, at least until 2050 [22].

Some others, concerned with the environmental impact that natural gas brings (being anyway a fossil fuel) foresee as its long-term role that of a simple "*flexible back-up and capacity balance where renewable energy supplies are variable*" [20]. This line of thought questions the role of natural gas as "bridge fuel", especially as an alternative to oil in the transportation sector [23]. The positive figures in terms of greenhouse gases emissions derived from the analysis of combustion are penalized when the whole life cycle is taken into account, due to the natural gas leaks in the supply chain, amounting up to 3.2% of global production. Any leak of natural gas before combustion is a great boost in GHG emissions, because it has a Global Warming Potential (GWP) which is 72 times higher than carbon dioxide over a 20 years time horizon (and 25 times higher over 100 years), and a leak of 3% can bring down its climate benefit over other fossil fuels [6, 24].

4 Energy Transition: A Feasible Scenario

After describing, as extremes, a scenario as revolutionary as possible and a scenario relying on the status quo as much as possible, it is time to take into account all the strengths and weaknesses of the two extremes and design the path forward. We will do that by listing the variables to be taken into account, leaving the reader with the choice of his best solution.

When talking about energy alternatives, we have taken into account just renewables and fossil fuels. Nuclear fission (even if unconventional fuels such as thorium are used) and nuclear fusion (even in the LENR, Low Energy Nuclear Reaction, version, also known as cold fusion) are now marginal voices in the debate on energy because they suffer a series of problems [15], among them being safety and how to dispose of nuclear wastes, that have prevented so far their introduction into markets and do not let foresee any important development in the near future. This is the reason why we have left them out of the picture.

The same can be said about hydrogen and everything revolving around it, the so called "hydrogen economy" [25]. The peculiar properties of the substance and the need for a dedicated infrastructure, too difficult and expensive to be built from scratch, have cancelled also this option, at least for the time being.

The main weaknesses ascribed to renewable energies(in particular to solar, wind and biomasses, because the hydroelectric source is considered to have reached its plateau), that make them unable to cover the whole load and render them a "big illusion", are well known and can be summarized as follows [8]:

- They are diluted in time and space and require huge surfaces to catch the needed quantities;
- They are irregular and unreliable and cannot be easily stored;
- Deriving from solar radiation, they are thermal energies and the efficiency of the conversion into mechanical or electric energy is limited by the 2nd law of thermodynamics.

There are many arguments that demonstrate that such weaknesses are not anymore able to obstacle renewables growth and success, both in technical and economic terms. We will list some of them in the following.

On the technical side the first argument in favor of renewables is EROEI, or Energy Return On Energy Invested. EROEI is defined as the ratio between the amount of energy delivered from a specific energy resource and the energy used to obtain that amount of energy resource. The minimum EROEI value that an energy resource must possess to be considered viable is 3. If EROEI ≤ 1 then we have an energy sink. Table 1 presents the EROI of currently used energy resources [15].

As far as the efficiency of the renewables is concerned, the recent report "Global renewable energy trends" [26, 27], released by Deloitte Insights, describes the advancements in terms of efficiency reached by innovative materials. It is very interesting the notation about perovskite, which "*has been the fastest-developing solar technology since its introduction, making efficiency gains that took silicon over half a*

Table 1 EROEI of some energy resources [15]

Renewables	EROEI	Not-renewables	EROEI
PhotoVoltaic (CdTe)	30–40	Crude oil (1930)	50–100
Hydropower (large scale)	30–40	Crude oil (today)	15–20
Wind power (large scale)	20–30	Coal	50
PhotoVoltaic (Si)	12–15	Natural gas	20
Wind power (small scale)	5–15	Nuclear power	7–20

century to achieve in less than a decade. In June 2018, a British and German startup demonstrated a record 27.3 percent conversion efficiency on perovskite-on-silicon tandem cells in laboratory settings, beating the laboratory record of standalone silicon cells. Belgian researchers achieved similar efficiency the following month, and both claim that over 30 percent efficiency is within reach. Perovskite has a simpler chemistry, the ability to capture a greater light spectrum, and higher efficiency potential than silicon. Perovskite can also be sprayed onto surfaces and printed in rolls, enabling lower production costs and more applications. Perovskite modules may be commercialized as early as 2019".

To complete the argument about materials, Fig. 3 shows the trend, over the years, of PV cell efficiencies. It is evident the dramatic growth in efficiency that the PV technology has undergone in the last 40 years.

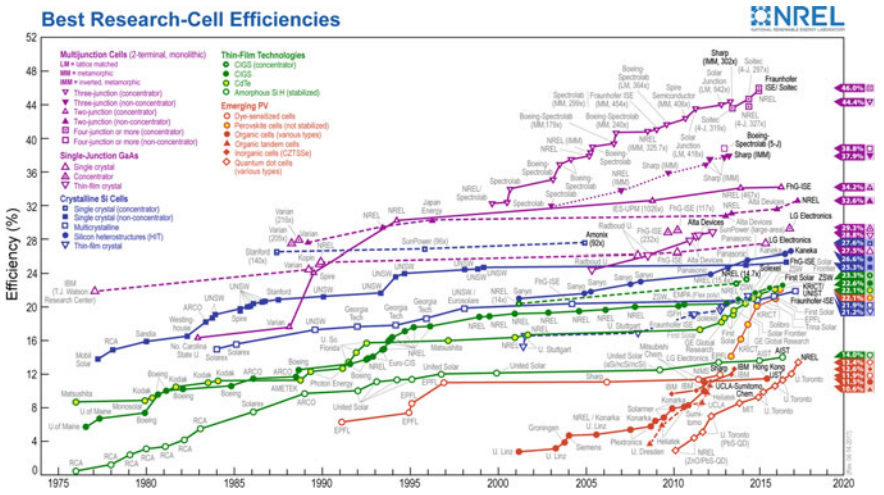

Fig. 3 Trend of PV research-cell efficiencies over the years [source: NREL] (https://www.nrel.gov/pv/assets/pdfs/pv-efficiencies-07-17-2018.pdf)

One last word on technology is about the energy storage. The presence of unreliable energy sources, such as wind and PV, coupled with the path towards EoE (Electrification of Everything) requires the large availability of means of energy storage, in particular electric storage. The huge market penetration of electric vehicle expected within the disruptive scenario depicted in Sect. 2 can itself represent an important way to store electric energy. Apart from that, several R&D efforts are under way as reported in the literature [28, 29]. Figure 4 shows the status of the different technologies under investigation in terms of readiness level.

One important signal about the importance of storage in the whole energy context is the news released by Bloomberg [30] about the huge investment opportunities presented by this technology. Bloomberg forecasts 620 billion USD in investment on energy storage from now to 2040. And this brings us to the economic side of the frame.

The already mentioned Deloitte Insights report on "Global renewable energy trends" [26, 27], states that "*three key enablers—price and performance parity, grid integration, and technology—allow solar and wind power to compete with conventional sources on price, while matching their performance*." In addition, "*as technologies such as blockchain, artificial intelligence (AI), and 3-D printing continue to advance the deployment of renewables, prices will likely continue to fall, and accessibility will improve*."

Deloitte notes that "*Longstanding obstacles to greater deployment of renewables have receded as a result of three key enablers*:

- ***Reaching price and performance parity***: *The unsubsidized cost of solar and wind power has become comparable or cheaper than traditional sources in much of the world. New storage options are now making renewables more dispatchable—once an advantage of conventional sources.*

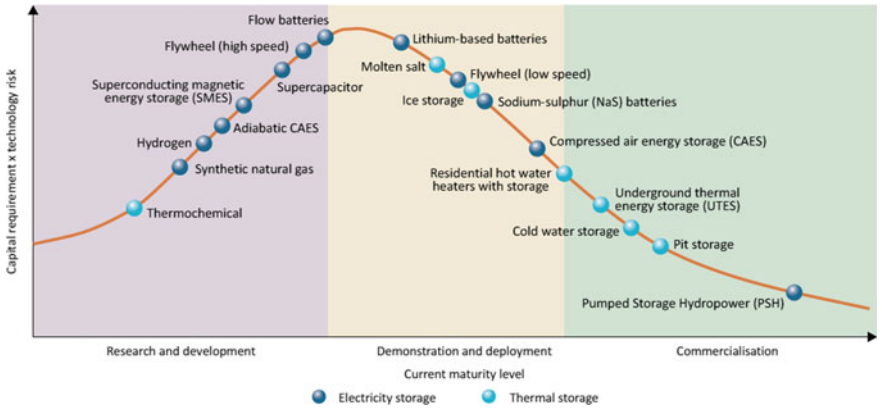

Fig. 4 Readiness level of energy storage technologies [29]

- ***Cost-effective and reliable grid integration***: *Once seen as an obstacle, wind and solar power are now viewed as a solution to grid balancing. They have demonstrated an ability to strengthen grid resilience and reliability and provide essential grid services. Smart inverters and advanced controls have enabled wind and solar to provide grid reliability services related to frequency, voltage, and ramping as well or better than other generation sources. When combined with smarter inverters, wind and solar can ramp up much faster than conventional plants, help stabilize the grid even after the sun sets and the wind stops, and, for solar PV, show much higher response accuracy than any other source.*
- ***The impact of technology***: *Technology is accelerating the deployment of renewables: automation and advanced manufacturing are improving the production and operation of renewables by reducing the costs and time of implementing renewable energy systems; AI can finetune weather forecasting, optimizing the use of renewable resources; blockchain can enable energy attribute certificate (EAC) markets to help resolve trust and bureaucratic hurdles; and advanced materials are transforming the materials of solar panels and wind turbines.*"

The endorsement of renewables from Deloitte does not come alone. Several signals from the financial community inform that many investors are shifting from oil & gas to more environmentally sustainable initiatives: the path towards renewables is irreversible, as demonstrated by the number of such investments [31]. The announcement that the World Bank Group [32] will end financing oil & gas extraction is an important signal in this direction, like it is the news from the Financial Times [33] that Blackstone, one of the world's leading investment firms, will launch an investment fund worth hundreds of millions, named Zarou, in renewable electricity generation assets in Africa and like it is the establishment of a task force on climate-related financial disclosures [34].

The Deloitte report [27] points out the importance that a tool like corporate Power Purchase Agreements (PPAs) may have for the development of a market devoid of incentives. According to many renewable energies operators corporate PPAs are the right tool for such a market where energy produced is not supported anymore by incentives.

As a matter of fact, analyses on the Levelized Cost Of Energy (LCOE) performed by Lazard [35] demonstrate that, even without any subsidy, the cost of energy produced by renewable technologies is fully comparable with the LCOE of energy produced with conventional sources, as shown in Fig. 5. As already mentioned, this is also due to the dramatic decrease in the cost of renewables, like, for example, the 99% reduction in the cost of PV modules in the last 40 years [36].

In summary, energy transition is already a fact, and this is demonstrated by so many signals. What it is uncertain is the speed at which it will move and it is unlikely that it will accelerate like the scenario presented in Sect. 2 predicts. It will not be a matter of one or two decades and probably it will span throughout the whole present century.

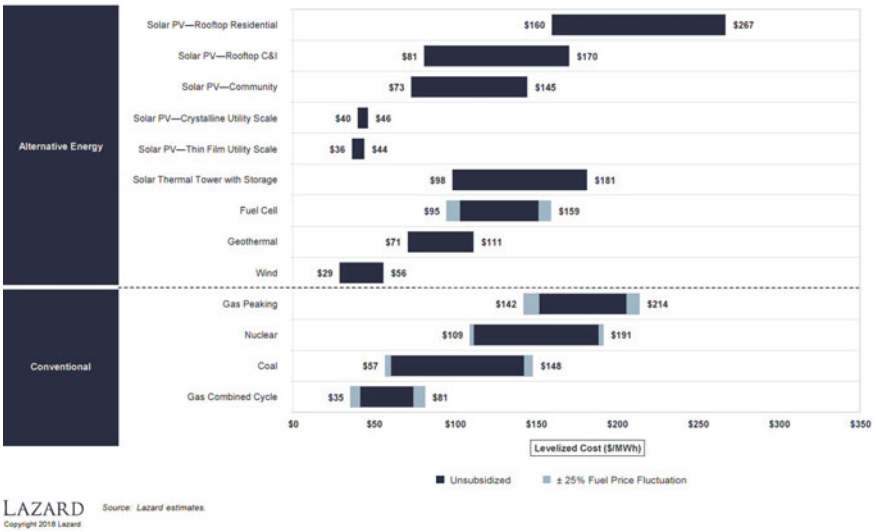

Fig. 5 Levelized cost of energy comparison-sensitivity to fuel prices [35]

5 Current Research on Energy at DIISM-UNIVPM

Several research groups at the Dipartimento di Ingegneria Industriale e Scienze Matematiche (DIISM) of Università Politecnica delle Marche are involved in activities aimed at accompanying the energy transition [37].

Topics are substantial to such goal and are studied in order to investigate feasible solutions to different aspects of energy conversion, transportation and final uses. In the following the lines of research are described in details, giving the reasons why they are addressed and the results sought.

5.1 Wind Energy

Wind energy is one of the main players in the scenario depicted in Sect. 2 and it is predicted to become the largest power source in the European Union in a 2040 horizon, according to World Energy Outlook 2018 by the International Energy Agency (IEA) [38] (see Fig. 6).

Research on wind energy at DIISM-UNIVPM is carried out along different lines, which are described in the following.

Low Noise Wind Turbine Blade project: new wind farms are frequently sited near inhabited places so the noise emissions control is a very important challenge for the blade designers. Our research is focused on the design and test of aerodynamic devices able to reduce acoustic mid frequency emissions from wind blade.

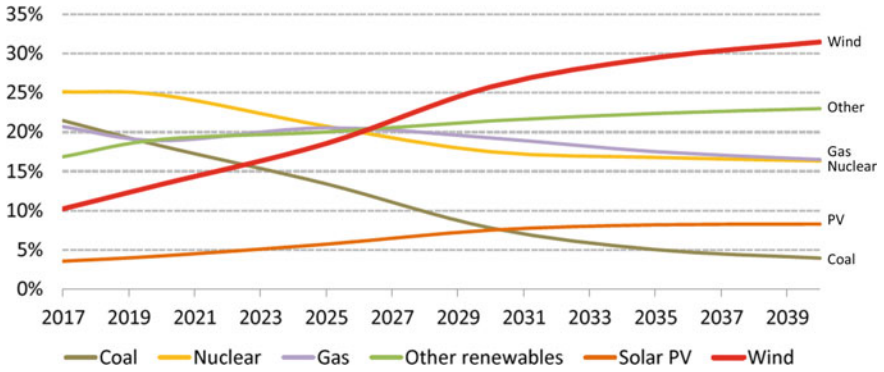

Fig. 6 Share of electricity generation by source in European Union, 2017–40 [38]

An extensive campaign of measurements in semi anechoic room is occurring on an instrumented small scale wind blade. At the same time the understanding of noise generation mechanisms of wind turbine blades is very complex due to its aerodynamic nature. For this reason its prediction demands the access to sophisticated numerical tools. Thermofluids group of the UNIVPM is active on the development of innovative models and solution algorithms to simulate the aeroacoustic sound produced by wind turbine blades. More in depth non-reflective boundary treatment was considered in our numerical code as well as accurate approximation schemes able to avoid artificial acoustic waves dissipation. The subject of the ongoing work is related to simulation of wind turbine airfoils self-noise which is a hot topic in wind energy community. Future work will address the numerical design of control devices of the aerodynamic sound produced by the blades.

Morphing Wing project: the pitch controlled wind turbine is the main technology today used to control the power produced. In order to improve the aerodynamic performance of the blades, in this project a flexible airfoil geometry is developed. Numerical and experimental tests are planned on new airfoil shapes equipped with smart materials. The results of the research will allow to develop a new integrated control system in order to increase the aerodynamic efficiency of the blades rotor.

CFD studies on wind turbines performances: currently available software packages used by wind energy analysts suffer of the lack of availability of accurate wake models. Well established tools, such as FAST of NREL [39], adopt the dynamic wake modeling which underestimates the power produced by downstream waked turbines. This is a critical issue for wind energy community. Thermofluids research group of the UNIVPM is active on the development of several innovative fluid flow models and solution algorithms [40–42]. The long term goal of this research is to merge the software modules to produce a high-fidelity simulation tool of wind farms overcoming the current limitations.

In situ measurements of power produced by wind turbines: The UNIVPM research centre WEST-lab, operates in this research area realizing tests and simulations on small and large wind turbines.

ADELE (Aerial Drone for Environment and Energy) project: wind turbine drone inspection and evaluation will help to identify and prevent root causes of cascading events that contribute to failure modes. This will significantly reduce downtime of turbines. More detailed information on wind turbine performances will allow operators to develop more site-specific lifetime management strategies. Better knowledge of the properties, degradation and failure mechanisms of materials provides new opportunities for weight and cost reductions, higher reliability and improved manufacture of components and structures. Increased accuracy and robustness of the remote sensors measuring the performance and health of turbines and their components will form the basis of high quality and low cost data collection. The aerial fleet of ADELE is designed to operate at hostile ambient conditions in order to perform visible and infrared inspections of the main wind turbines components.

5.2 Smart Grid and Energy Storage

The increasing penetration of intermittent Renewable Energy Sources (RES) may introduce uncertainty in the available production capacity and require backup power and energy storage systems to ensure a reliable power supply.

The example of such behavior is the famous "duck curve". The duck curve is the graphic representation of higher levels of wind and solar on the grid during the day resulting in a high peak load in mid to late evening. The difference in the duck curve and a regular load chart is that the duck curve shows two high points of demand and one very low point of demand, with the ramp up in between being extremely sharp. It looks like a duck! (Fig. 7) [43].

This behavior introduces uncertainties that challenges the traditional paradigm of the electric energy system based on a "demand following" generation. In the traditional paradigm, the aggregated demand curve of electricity was quite easy to predict since it was variable during the day but almost non-elastic with the season and the typology of day (working day, weekend or holiday).

On the contrary, with the increasing penetration of renewables the uncertainty related to their energy production reflects in the energy system, both on supply and on demand side. For this reason, "the generation following" paradigm is making its way in the energy system. The idea is to provide flexibility to the energy system by compensating the uncertainty of production from renewables by modifying the energy demand so that the centralized power plant could efficiently work without following the sudden changes that happens on both supply and demand side due to the variability of not predictable renewable sources. In this context, micro grids and energy storage are key technologies for providing flexibility to the energy systems. According to the Microgrid Exchange Group (MEG), "A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid" [44, 45]. Within a microgrid it is possible to test and consequently envisage at smaller

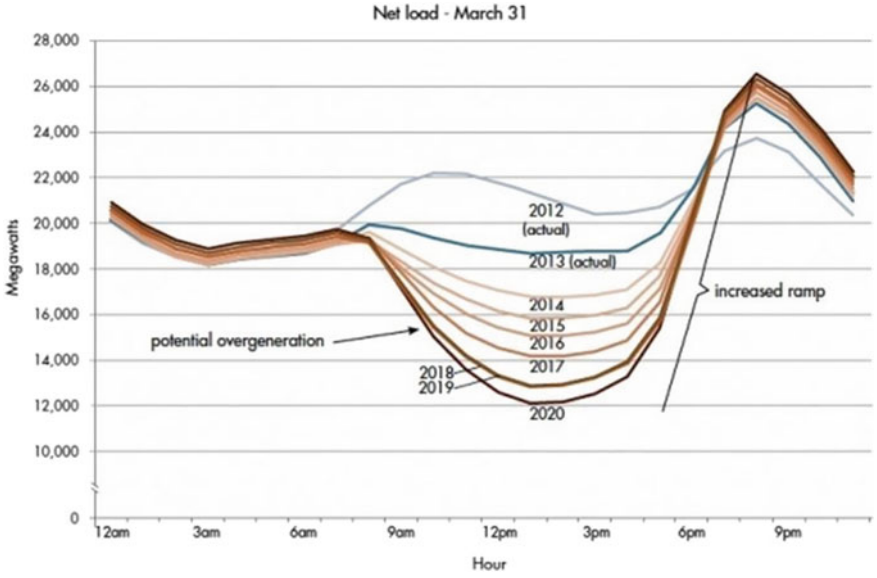

Fig. 7 The "duck curve" predicted for the California electric system [43]

scale what could be the future large scale "smart grids" by optimally managing distributed energy systems, energy storage and active loads in order to fully exploit the potential of renewable energy without giving back electricity to the grid.

However, in recent years, in the context of the energy transition, the scientific literature introduced the concept of smart multi energy systems [46] in order to go beyond the only electric sector and to include all the potential synergies between different energy networks (natural gas, district heating and cooling) and all the "connecting technologies" such as cogeneration and trigeneration (connecting gas, electric, thermal and/or cooling networks), heat pumps (connecting electric and thermal networks); energy storages (thermal and electric).

Ongoing research activities at DIISM-UNIVPM are focused on optimal design and management of microgrid and smart multi energy systems at different scale: residential [47] and industrial [48] microgrids equipped with renewables, energy storage and heat pumps; urban scale multi energy systems [49]. Also, energy storage plays an important role in the research activity [50]. In particular, thanks to the cooperation with the Nanyang Technological University of Singapore, the use of thermal energy storage in tropical climates [51] and liquid air energy storage are investigated [52, 53]. A recent research activity on energy storage relates to electric mobility in urban systems; indeed, electric vehicles batteries could be seen as distributed energy storages for the electric system in vehicle-to-grid (V2G) and vehicle-to-building (V2B) applications [54].

5.3 Demand Side Management (DSM)

In the same context of large RES penetration it is paramount the availability of energy flexibility at the demand side. Demand Side Management (DSM) is defined as all those actions aimed at modifying the electricity demand to increase customer's satisfaction and simultaneously produce the desired changes in the electric utilities load in magnitude and shape [55]. DSM can be beneficial to the power system thanks to: (i) reduced electric power peak demands; (ii) higher operational efficiency in production, transmission and distribution of electric power; (iii) lower investments for new power capacity; (iv) lower price volatility; (v) lower electricity costs and (vi) a more cost-effective integration of highly intermittent renewables [56–58]. In the literature, three broad categories of DSM are identified: energy efficiency and conservation, on-site back up through local generation or storage and demand response [57]. In particular, given also the relevance of the energy demand in buildings [59], the management of thermostatically controllable loads in the built environment has a central role.

Focus of our research was indeed the investigation of the DSM potential of thermal energy storage systems and heat pumps [60, 61]. Buildings can provide flexibility through the passive storage inherent in their envelope or by means of external active storage systems. An example of inherent storage is represented by Thermally Activated Building Systems (TABS), which require properly designed control systems in order to implement DSM strategies and maintain the internal comfort, given their high thermal inertia [62]. On the other hand, heat pumps are efficient devices, electrically driven, which are easily coupled with building thermal mass, energy storage or RES [48]. They allow to implement DSM strategies in the built environment, both residential and industrial, and to exploit, more generally, the flexibility of the refrigeration sector [63].

Through a comparative study, the different effects produced on the energy demand by the three different DSM categories highlighted in literature (energy efficiency, energy storage and demand response, (DR)) were investigated [64]. It was possible to conclude that: (i) Energy efficiency actions can produce mainly peak shaving and energy conservation; (ii) Energy storage systems allow load shifting; (iii) DR operates an active load shifting to off-peak hours (valley filling) and peak shaving.

Eventually, an integrated environment, where the demand side and the supply side can interact and mutually affect each other is necessary in order to properly quantify the benefits produced by DSM actions on the overall power system (in terms of operational costs reduction, avoided RES curtailment, peak shaving…) [65, 66]. Furthermore the final users participation share into demand side management programs has a high relevance [67]. Results show that increasing the number of consumers participating into DSM programs increases the flexibility of the system and, therefore, reduces the overall operational costs, while decreasing the benefit per individual participant, since a reduced effort from each consumer is needed.

Further investigations are necessary to define optimal strategies to use the available flexibility provided by heat pumps and thermal energy storage systems. This is particularly true with the advent of integrated energy systems, which consist of multi-carrier energy systems characterized by a mutual dependence among the infrastructures of the different systems. Heat pumps and energy storage systems can indeed affect positively the operation of the overall energy system and especially its reliability [68–70].

5.4 Biofuel from Algae

In Sect. 3 it was already pointed out that some applications, namely marine and air transportation, will hardly be able to get rid of liquid fuels, mostly due to the energy intensity that they can carry in their unit of volume. This leaves way to only two solutions for the long-term: either we keep on relying on fossil fuels or we switch to liquid biofuels.

Biofuels are a fascinating alternative to fossil fuels, but, if they are produced from superior plants grown in temperate climates, they can dangerously conflict with food agriculture and their EROI easily approaches the lower limit of convenience of 3 [15].

A feasible alternative seemed to be biofuel extracted from algae and microalgae, which guarantee a higher lipids content with respect to superior plants [71]. This is why a research line was started at DIISM-UNIVPM aimed at investigating the feasibility of producing biodiesel from microalgae.

Initially the research dealt with the biodiesel production methods [72–74] but when realizing that fuel derived from algae was far more expensive than fossil fuels and even than biodiesel from superior plants, the activity was put in stand by [75].

6 Conclusions

The speed at which energy transition will proceed during the 21st century, floating between the two extreme scenarios described in Sects. 2 and 3 of the present paper, will be dictated by many variables. Technology innovations and economics will drive the transition but policies will play a fundamental role as well [76].

In this sense reports from International Energy Agency (IEA) could help governments to establish such policies, especially those more innovative, courageous and, let's say, disruptive.

The last IEA World Energy Outlook was released on November 13, 2018 [38] and was not fully appreciated by those [77] who want an acceleration of the transition process, also in order to keep pace with the goal of maintaining the global warming below the 1.5 °C limit.

The IEA Sustainable Development Scenario (SDS) pursue the limit of 1.7–1.8 °C global warming and recognizes that "*continued investment in oil & gas supply, however, remains essential even in the Sustainable Development Scenario to 2040, as decline rates at existing fields leave a substantial gap that needs to be filled with new upstream projects*".

Is this a too conservative scenario? Only time will tell.

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Integrating Advanced CAE Tools and Testing Environments for the Design of Complex Mechanical Systems

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Abstract Computer-Aided Engineering (CAE) software are widely used to simulate the behaviour of complex mechanical systems, aiming at predicting at the early stages of design their performance and possibly preventing the occurrence of flaws or malfunctions during prototyping. The recent technological advances in hardware and software make possible a full integration of methods and tools that were developed to deal with different application fields, magnifying the power of such instruments. The designer can now use virtual prototyping environments able to drive the whole design process; they not only allow to check his/her concepts but indeed enable the optimization of the design and even of the whole manufacturing process. In this scenario, many recent research projects at the Polytechnic University of Marche exploited the integration of various CAE tools, nominally built to analyze phenomena

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very different to each other; in many cases they have been also interfaced with the software tools used for the final prototyping and testing phases. The paper shows three case studies, which were developed for different fields of industrial engineering, where the concurrent use of different CAE simulators helped the study of complex multi-physical mechanical systems.

1 Introduction

The scientific research and technical developments in the field of new design processes are presently driven by the requirement of time compression and the need to manage complex mechatronic systems. It has been since many years now that powerful CAE tools have been made available to the designer for the assessment of specific aspects like e.g. mechanical properties, fluid dynamic behaviour, motion simulation, etc. Single parts, mechanisms or machines were validated against their specific requirements but testing and validation of the complete system often came later, resulting in risky and expensive reworking and modifications.

The present availability of commercial tools that can be integrated in a single design framework makes possible the realization of virtual prototyping environments where the designer can simulate the whole mechatronic system from the conceptualization phase up to the physical protoyping and testing phase, with a drastic reduction of the processing times. In past years, such tools have been exploited by the researchers of the Polytechnic University of Marche in different engineering fields. As an example, the paper reports three case studies: first, a comprehensive experimental analysis was performed on timing belt transmissions by means of Laser Doppler Vibrometry for vibration measurement, Digital Image Correlation for deformation maps assessment and acoustic intensimetry for noise emission; second, a computational fluid dynamics code was integrated with a multi-body dynamics software for the study of a swimming robot; third, CAD, FEM and image generation were combined to develop a test simulator able to optimize the shape of specimens used for material characterization.

2 Current Features and Open Issues of CAE Software

In the last years, the use of Computer Aided Engineering (CAE) tools has significantly increased in both industrial and academic environments. In fact, they allow the reduction of the design costs and shorten the time to market and, furthermore, they are employed by researchers as verification, troubleshooting and analysis tools. Nowadays, the predictive capability of CAE software is so advanced that often much of the design verification is performed by means of computer simulation rather than by direct physical prototype testing, which is deferred to the very last design phases.

The dynamics of multibody systems is managed by many computer codes which differ one from the other under several points of view: model description, choice of basic principles of mechanics and topological structure [23]. The research on novel simulation tools is nowadays focusing on phenomena characterized by a challenging level of mathematical complexity. Among others, the problems of systems with non-holonomic constraints [16], systems with close to singular dynamic behaviour [24], and the effect of lubrication on mechanisms surfaces [17] have been recently investigated. Due to the growing relevance of mechatronic systems working under closed-loop control, many techniques are being tested for the development of simplified gray- or black-box models aimed at implementation in governors or controllers [8], especially in the fields of robotics.

Another topic which has been arousing a particular interest in the last years is the interaction of mechanical structures with fluids. This class of problems represents still today a real challenge for both the involved mathematical complexity and the computational burden required by numerical computations. The problem of fluid-structure interaction was firstly tackled at the beginning of the space age, when the behaviour of liquids in moving tanks was a novel topics; however the subject is far from being definitely filed and much research is still on-going [25]. For example, in the field of ultra-deep waters installations of submarine pipelines efficient simulations tools for the planning and on-line management of the deployment process are greatly needed: both the simplification of models and the numerical aspects are nowadays matter of research [18].

A particular kind of interaction between fluids and multibody systems is found in aerodynamics. The current trend is that of developing tools and models for aeroelastic phenomena. This kind of simulations received a boost in the latest years due to the greater and greater computational power presently available. The results are obviously of great impact on many fields, such as the dynamic analysis of wind turbines [20] and of incompressible flows in turbomachineries [6].

Moreover, in real-world environments multiple types of coupled physical phenomena interact: the continuously increasing computational capabilities of the simulation hardware makes now possible in many situations to relax the assumptions of systems decoupling, leading to effective multiphysics simulations. New powerful analyses can now be performed in new application fields like thermal management, MEMS, electrical motors, mechanical vibrations, etc. However, coupling individual simulations may introduce limitations on stability, accuracy, or robustness that are more severe than the limitations imposed by the individual components.

Material testing is another field where CAE systems and finite element models (FEM) have been increasingly and systematically used in the last year. The testing procedures to identify the properties of materials are rapidly evolving. One of the main reasons of this change is the availability of reliable and accurate full-field techniques which allow to obtain the deformation field on specimens of any shape during a test. Full-field measurement provides indeed a lot of information on the mechanical behaviour from a single test and inverse methods can be exploited to identify the constitutive parameters [3].

Nowadays, Digital Image Correlation (DIC) [2] represents probably the most widespread full-field technique for strain measurement, thanks to its simple set-up arrangement and relatively low-cost equipment. Among the inverse methods, the most used are the Finite Element Updating Method (FEMU) and the Virtual Fields Method (VFM). Several applications on inverse methods can be found in linear elasticity, plasticity, visco-elasticity [21], etc. For each application, however, the performance of the identification procedure is strongly influenced by the accuracy of the DIC measurement and by the shape of the specimen. Simulated experiments generated through advanced CAE tools can be used to assess the error of the testing environment [4] and optimize the specimen shape and the test set-up.

3 Use Cases at the Polytechnic University of Marche

3.1 Vibro-Acoustic Simulation of Timing Belt Transmissions

The issue of the periodic noise generated by timing belts in automotive engines is relevant, therefore designers aim to reduce the arising acoustic emission; vibrations are also related to fatigue failures, therefore they affect transmissions reliability too [1]. All these facts motivated the researchers at the Dept. Industrial Engineering and Mathematical Sciences to investigate across several years the vibroacoustic behaviour of timing belts transmissions.

The main challenges of this research at the time it was developed were related to the complexity of the numerical simulation which required the integration of several numerical tools taking into account different physical phenomena. Multiphysics simulation was at its early developments and computational power was constantly increasing, but still limited. Furthermore, knowledge of composite materials behavior was not comprehensive and accurate. Similar difficulties were present on the experimental side; some vibration tests were performed with contact sensors, adding important masses to the belts and without the possibility to measure in operative conditions, with the belt running.

The problem was approached by a continuous iteration between numerical modelling and experimental validation, realized by test benches of increasing complexity. From the numerical point of view, a timing belt is a very complex system, made up of very heterogeneous and anisotropic materials (e.g. rubber, textile fibers, metal fibers), whose numerical modeling is very difficult and computationally demanding.

From the experimental point of view, it is necessary to identify measurement instruments capable of measuring deformation and vibrations under operating conditions, i.e. on a moving belt running on a set of pulleys. Since it is not possible to place sensors on the running belt, the development of the Laser Tracking Doppler Vibrometer (TLDV) offered an interesting solution to such a problem [9]. In fact, TLDV allows to track a moving point of the belt and to measure its vibration in time. This fact, by eliminating the relative motion of the measuring beam on the surface,

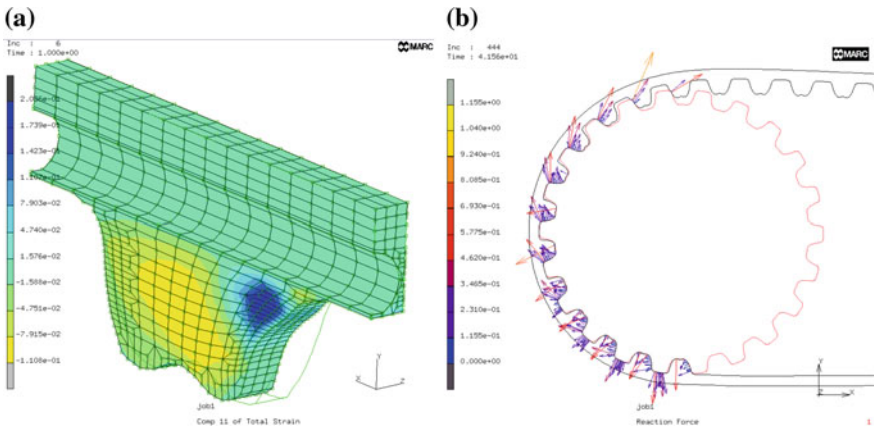

Fig. 1 Numerical model: **a** deformation maps in a 3D model of a single tooth; **b** contact forces in the complete arc of the pulley

also eliminates the source of speckle noise which always affects LDV measurements on moving surfaces.

Image processing was also a very interesting technique applied for a complete analysis of displacement and deformation of soft materials like rubber. The study of the local behavior of the belt was focused on the single tooth and on its contact with the pulley by finite element analysis, and then on the global behavior of the belt, through the development of a lumped parameter model, whose parameters are those obtained from the local analysis. The main steps of the research are shown below.

Figure 1a shows the numerical model of the single tooth. In particular, the map of displacements obtained with a simplified 2D FEM model is shown and compared to the deformation map obtained in a 3D FEM model that takes into account the complex structure of the tooth and the presence of the different layers of material and reinforcing fibers. With an even more important computational effort, it was also possible to simulate the entire arc of engagement on a single pulley by means of FEM: in this way it was possible to evaluate the trend of the contact forces along the curvilinear coordinate that follows the belt trend, Fig. 1b. For a qualitative validation of the simulation, the results are compared with the sequence of images of the tooth acquired at increasing levels of deformation.

To obtain a quantitative evaluation of the displacement and deformation field of the tooth, an image analysis of the deformation of a grid of points, drawn on the tooth lateral surface, was performed, see Fig. 2. As the stress level varies, the displacement of each individual target point is evaluated by processing the image Fig. 2b to obtain the displacement map Fig. 2c, which provides insight on tooth deformation. The parameters of the tooth model [13] defined in this way can be used in a lumped model composed by a system of masses, springs and dampers, in order to represent the entire arc of the belt with a lower computational weight with respect to a full FEM of the belt. The dynamic behavior obtained by this lumped parameter model

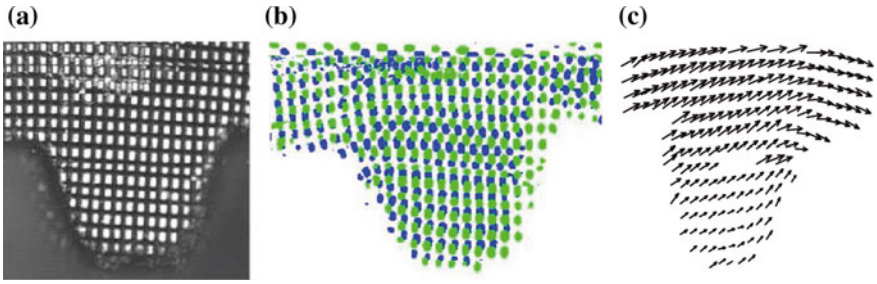

Fig. 2 Sequence of images of the tooth at increasing levels of deformation

can be compared with the results measured by Laser Doppler Vibrometer. Then, starting from the operational deflection shapes it is possible to calculate the emitted sound field [14]. This continuous interaction of modeling and experimental validation provided a set of tools [7, 15] that allowed a comprehensive and detailed analysis of timing belt dynamics, which triggers design optimization aimed to management of vibroacoustic emission.

3.2 Integration of CFD and Multi-body Software to Study the Dynamics of a Swimming Robot

The attempts to design machines capable of moving like marine mammals and fish are inspired by the superior performance of biological swimmers in terms of both efficiency and manoeuvrability [22]. The possibility to replicate successfully the swimming modes evolved by fish in thousands of years depends on the understanding of the fluid mechanics principles of marine locomotion. By using computational fluid dynamics simulation techniques, engineers are trying to quantify the propulsive performance of biological thrusters, i.e. tails and fins, in terms of forces and torques. However, in order to obtain the resulting motion, the aforementioned quantities must be integrated in a multi-body model, which accounts both for the mass distribution and for the hydrodynamic effects, like added mass and viscous damping, applied to the swimmer fore body. As a matter of fact, multi-body techniques can be used to evaluate the propulsive capability under different kinematic conditions, e.g. thrusters undulating frequency, and the obtained data can be exploited to improve the vehicle design in terms of mass distribution. At the same time, the dynamic equations of the model can be coupled with trajectory planners and advanced control techniques in order to compute the effort required by the robot guidance system in order to perform a given mission.

A multi-body approach has been used by authors to model an ostraciiform swimming robot they designed and manufactured in previous works [10, 11], in order to predict its motion. The vehicle, shown in Fig. 3a, consists of a rigid cylindrical hull

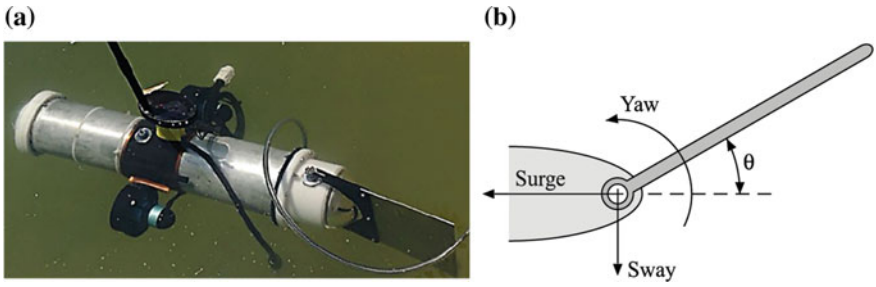

Fig. 3 **a** prototype of the swimming robot; **b** propulsive forces and torque decomposition

and a bio-inspired thruster, namely an oscillating plate shaped like a caudal fin and connected to the fore body through a revolute joint. The main novelty here is the integration of the propulsive forces and torque due to the fluid-thruster interaction in the dynamic model of the whole robot.

Fluid dynamic analysis has been performed by means of computational techniques using MIGALE, an in-house developed research code based on the Discontinous Galerkin (DG) space discretization [5, 12]. The incompressible and two-dimensional version of the DG code has been used, suitably extended to deal with a moving reference frame to account for the fin oscillation. The numerical simulations provided a complete dynamic characterization of the bio-inspired thruster as a function of the Strouhal number[1] St.

The numerical analysis provided the range of the hydrodynamic forces and torque (surge and sway force components and yaw moment, according to Fig. 3b) within an oscillation period, as a function of the foil angular position θ. In order to characterize the propulsive performance of the bio-inspired thruster, the numerical analysis has been repeated for Strouhal numbers in the range $[0.2 \div 1.1]$, where the lowest value corresponds to a negative thrust generation and the largest to approximately a half of the maximum propulsive efficiency, as shown in Fig. 4a. In other words, the range identifies two opposite swimming conditions: minimum and maximum thrust generation, while the most efficient condition stands among them.

The multi-body analysis has been performed by using MSC Adams. Since most vehicle mass is due to its hull, the robotic fish has been approximated with its rigid fore body, subject to the hydrodynamic forces due to the thruster-fluid interaction. Two separate contributions have been considered to compute the vehicle inertia moments: a steady component due to the hull, the onboard electronics, the actuators and the payload; a variable component due to the ballast rod fixed to bottom of the vehicle. Although this component has a constant mass value, it can be split in two identical parts and then fixed to the hull in two specular positions with respect to the vertical plane of symmetry, i.e. the $y - z$ plane, of the robot. In this way it is possible to

[1]The Strouhal number is a dimensionless parameter traditionally used to characterize oscillating flows phenomena. It is defined as $St = fA/U$ where f is the foil oscillation frequency, U is the modulus of the robotic fish swimming velocity and A is the wake width.

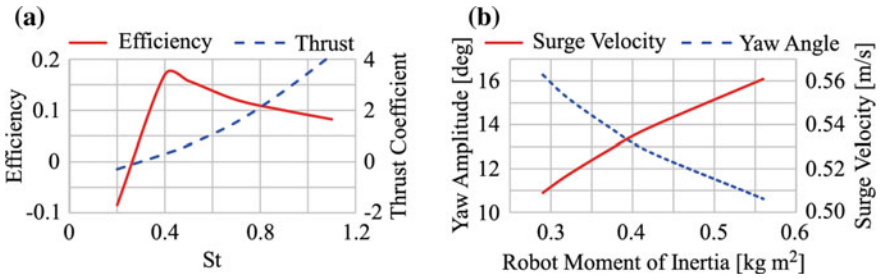

Fig. 4 **a** thrust and efficiency as a function of Strouhal number; **b** effect of mass distribution on maximum surge velocity and yaw oscillation amplitude (frequency $f = 2$ Hz)

modify the moments of inertia I_y and I_z according to the ballast configuration, while the position of the center of mass remains unchanged.

Simulation results provide useful hints for an effective navigation: Fig. 4b shows the effect of the mass distribution on the swim dynamics: the dashed line represents the robot oscillation amplitude about the z axis (yaw) due to the resulting moment of the propulsive forces, an effect known in literature as *recoil*; the diagram shows that the amplitude is reduced by one third as the moment of inertia increases. On the other hand, the continuous line shows that the ballast configuration has a minor influence on the maximum speed reached by the vehicle.

In the end, the multi-body analysis has proved its adaptability as a framework where the off-line fluid dynamics predictions can be integrated to study the dynamic behaviour of the vehicle and to test the real-time control techniques required to manage autonomous navigation.

3.3 Application of Advanced CAE Tools to Optimize the Specimen Geometry in Inverse Identification Methods

The use of inverse methods coupled with full-field measurements to identify the mechanical properties of materials has remarkably increased in the last decades, as already illustrated in Sect. 1. Nonetheless, the error assessment and the uncertainty quantification of such techniques still represent an open issue. The reason is that the identification chain includes several error sources that interact in a highly non-linear and unpredictable way. For instance, there are experimental uncertainties, errors caused by the image acquisition and the measurement technique, numerical errors due to the minimization algorithm used in the inverse method and so on. The only possibility for having a reliable error quantification is simulating the whole chain using advanced CAE tools.

One of the first contributions in this field was provided by Rossi and Pierron [19], who highlighted the importance of using simulated experiments to assess the accuracy

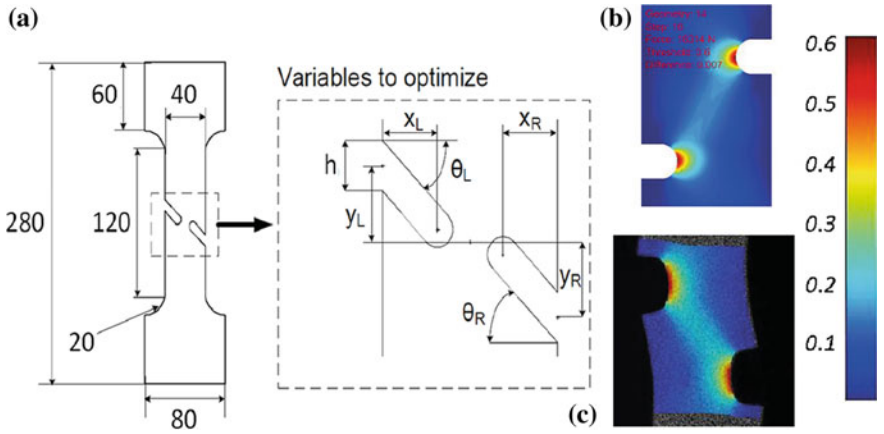

Fig. 5 Different steps in the simulation process: **a** definition of a parametric geometry with CAD **b** FE model of the simulated test **c** DIC analysis of synthetic images generated from FEM data to reproduce a real experiment with actual uncertainties (noise, illumination, speckle pattern, etc.)

of an inverse method and to choose the optimal experimental set-up. A simulator has been developed to virtually reproduce an experimental test: the simulator is able to disentangle with a reasonable accuracy the different error sources that come from the identification chain, i.e. experimental errors (noise, illumination, in-plane and out-of-plane movements, specimen orientation, lens distortion, etc.), DIC settings (subset size, step size, smoothing functions, etc.), errors due to the identification procedure (choice of the first guess, non-uniqueness of the solution, etc.) [4].

In this article an example is illustrated where the simulator is used to optimize the geometry of specimens used to identify the non-linear hardening behaviour of metals. The different steps of the simulation process are depicted in Fig. 5. First, a parametric CAD model of the specimen is developed as a function of the geometrical variables to be investigated (Fig. 5a). Second, for a given set of geometrical variables, a complete FE model of the experiment is generated (Fig. 5b). Third, the displacement map obtained by FEM is used to deform a colormap image of the real specimen that will be analysed with DIC afterwards (Fig. 5c). The synthetic image generation has to be performed carefully to avoid the occurrence of numerical artifacts [19]. The experimental uncertainties (camera noise, illumination, rigid body movement) are introduced using suitable routines during the image generation [4]. Finally, the parameter identification is performed applying to the synthetic images the same procedure used for actual experiments, i.e., in the present example, DIC analysis to extract the strain map and VFM to identify the non-linear hardening curve. The parameters identified from the synthetic images generated with the simulator are compared with the reference parameters introduced in the FE model in order to assess the accuracy of the identification procedure.

In the case study described here, the simulator was used to reproduce a virtual experimental set-up equipped with a CMOS camera having 1280 × 1024 resolution

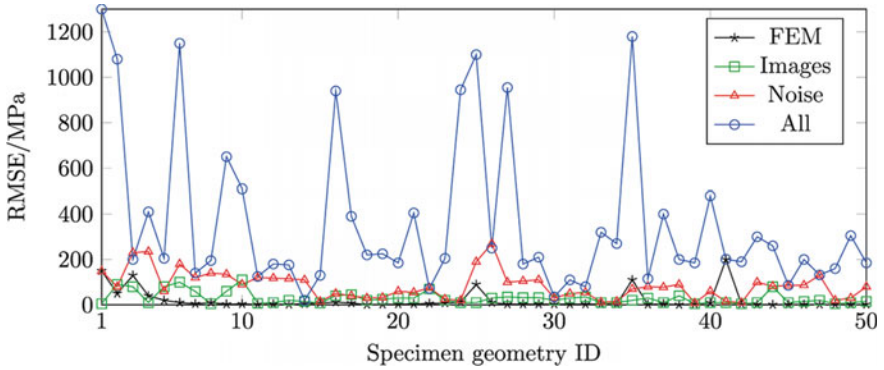

Fig. 6 Comparison of 50 specimen geometry using the simulator, different scenarios were investigated: no error (FEM), synthetic images with no noise (Image), synthetic images with noise (Noise), synthetic images with all error sources (All)

with 8-bit sensor, mounting a lens of 50 mm. The camera was supposed to be placed at 560 mm with respect to the specimen surface. Moreover, experimental uncertainties were included in the simulated images, i.e. camera noise applying an Extreme Value distribution, out-of-plane and in-plane motions, illumination variation using a simulated light spot.

The reference hardening curve is a Swift law—$\bar{\sigma}_{REF} = k(\varepsilon_0 + \bar{\varepsilon})^N$—that reproduces the behaviour of a steel-like material, with $K = 1000$ MPa, $\varepsilon_0 = 0.02$, $N = 0.5$. The global error was calculated as the root-mean-square error (RMSE) of the reference and the identified hardening curve.

Figure 6 shows the RMSE for 50 different specimen geometries, evaluated introducing gradually the error sources, i.e. (i) FE results—no error, (ii) synthetic images without noise, (iii) synthetic images with noise, (iv) synthetic images with all error sources. If only the FEM model were used to compare geometries, each of them would be able to identify correctly the curve. As the different error sources are introduced in the simulator, instead, a large scatter is observed and only few geometries are able to correctly identify the hardening curve. Such geometries represents the optimal solution.

4 Conclusions

The article outlines the present technological level of CAE packages and highlights the advantages that can be exploited by researchers and professionals from the integration of different software tools. As a matter of fact, it is expected that such trend will bring even more benefits when new fields of research will bring effective results in commercial implementations: just to quote some examples, they may come from the impact of web, cloud and mobile devices, from the capturing and reuse of knowl-

edge, from the assessment of negative knowledge, from the proper management of new and smart materials, etc. The paper showed by means of three different case studies how the researchers at the Dept. of Industrial Engineering and Mathematical Sciences of the Polytechnic University of Marche exploited such issues in the past years: they are ready to take the opportunities offered by such technological developments to face the coming challenges too.

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Environmental Sustainability of Engineering Works: Geological and Geotechnical Aspects

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Abstract The design and construction of engineering works such as road infrastructures, port facilities and waste disposal plants require that important environmental issues be addressed, in order to guarantee sustainability and facilitate acceptability by the population. With these objectives, much of the scientific work produced by the geological and geotechnical research group of the Università Politecnica delle Marche in the past 50 years has involved aspects such as understanding the effects of

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human activities on the environment in order to prevent or minimize the risks of permanent damage, exploration of solutions that optimize the use of natural resources, implementation of technologies that promote the use of improved natural materials for construction, application of design procedures that are based on high quality geological, geotechnical and geo-environmental models of the construction sites. This paper will present, via the illustration of some practical examples, the contribution that such research activities have provided on the solution of some important engineering problems in the past decades.

1 Introduction

The contribution of the scientific research in the area of Geological and Geotechnical Engineering has been traditionally directed towards the search of new solutions to reduce the impact of engineering works on the environment, to preserve the integrity of natural resources, and to protect historically valuable sites and existing constructions from the impact of ever-more demanding human activities.

Sustainability is therefore the word that may join an apparently very diverse assortment of research subjects. Sustainability implies that the risk associated with engineering works is minimized, which requires the correct evaluation of the geological and geotechnical models of the site and environment affected by the works.

The geological model represents the geometrical model of the environment to be assessed on the basis of a well-recognized depositional history; it is assembled specifying each individual geological unit together with the presence of discontinuities with their bedding and frequency. The geological model must be supplemented with detailed information about groundwater, coherent with the knowledge of the hydrogeology of the area.

The geotechnical model is a schematic representation of the ground directly influenced by the construction with the specification of the physical and mechanical properties of each soil, to be selected on the basis of field and laboratory investigations and for any considered limit state required for the ground and the specific construction.

The geo-environmental model is the identification of possible sources of contamination and the representation of the pollutant migration mechanisms and paths, due to construction activities or in case of ascertained contaminations. The geo-environmental modelling requires the site hydro-geological, geotechnical and geochemical characterization by specific laboratory and in situ testing.

The correct interplay between these models is a critical issue for any design, either for modest or very complex constructions, and it is a measure of the role given to the understanding of the environment to prevent accidents and to reduce the risk of faults. In the following, some examples will be presented to show how the research

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work of this unit has been driven in seeking the correct balance between the very different disciplines dealing with environment. In particular:

- the research work to keep and preserve the aquifers providing best quality water to our Region, with the use of advanced tools together with more traditional hydrogeological surveys to ensure water resources sustainability;
- the analysis of linear infrastructures in landslide-prone areas;
- the wide use of new technologies to improve mechanical and physical properties of natural soils, in order to allow their reuse as barrier materials or as stabilization means for unstable slopes, such as those along the Ancona landslide;
- the safe design and construction of waste disposals and the geo-environmental characterization, risk assessment and encapsulation of polluted sites.

2 Sustainable Use of Water Resources

In this section, past and ongoing research activities of the geological group are presented. The research work primarily regards the study of hydrogeological features of aquifers to support the design of engineering works for water supply and for protecting groundwater resources. The pattern of groundwater circulation (i.e. the flow directions), the setting of the hydraulic contacts among different aquifers, the hydrogeological structures and finally the volume of aquifers are the most important issues addressed in most of the past and present studies. More specifically, the research work of this unit has contributed to the enhancement of the knowledge of the hydrogeological setting of the central Italy concerning the fissured and karstic aquifers and, to a less extent, the porous aquifers of the alluvial plains [1].

2.1 Methods, Geological and Hydrogeological Framework

In the following, results and methodology used during the last decade (and still ongoing) to determine the hydrogeological setting of several areas in the limestone domain of the Marche region are presented.

Such settings are pictured as single hydro-structure (complex, or group of aquifers characterized by different lithological composition, different permeability but groundwater circulation representable as single flowpath), verified and validated by using tracer and isotope hydrology techniques joined with results from traditional hydrological analysis. Measurements made in hydrogeological investigations encompass tracer tests, discharge measures in springs and rivers, chemical-physical quick determinations, isotope and chemical analyses. It can be referred to scientific literature to consult the applied methodologies [2–4].

The main lithological and geo-structural characters of the Umbria-Marche zone derived from geological surveys carried out last decades can be described as folds

and thrusts style with Apennine and anti-Apennine faults, which cut and release the sedimentary carbonatic sequence (from Jurassic to Eocene) covered by Miocene-Pliocene and Pleistocene sediments towards the sea line [1, 5–9].

In the Apennines and minor ridges, the Meso-Cenozoic limestone sequence outcrops (Fig. 1), with the Jurassic-infra Cretaceous and Cretaceous-Paleogene groups characterised by the complete, condensed, reduced and lacunose series. In the foothills and sometimes in the coastal ridges, the Miocene sequence is present, composed of different marly limestone lithotypes.

In this area two main ridges, derived from detachment tectonics of layers of sedimentary cover bordered by thrusts having Adriatic vergence. The leading detachment level corresponds to layers of the Scaglia cinerea, Marne a Fucoidi and Rosso Ammonitico Formations.

Asymmetrical folds associated with reverse faults border the Umbria-Marche ridge in the east side allowing the outcropping of the Massiccio sequence; these folds

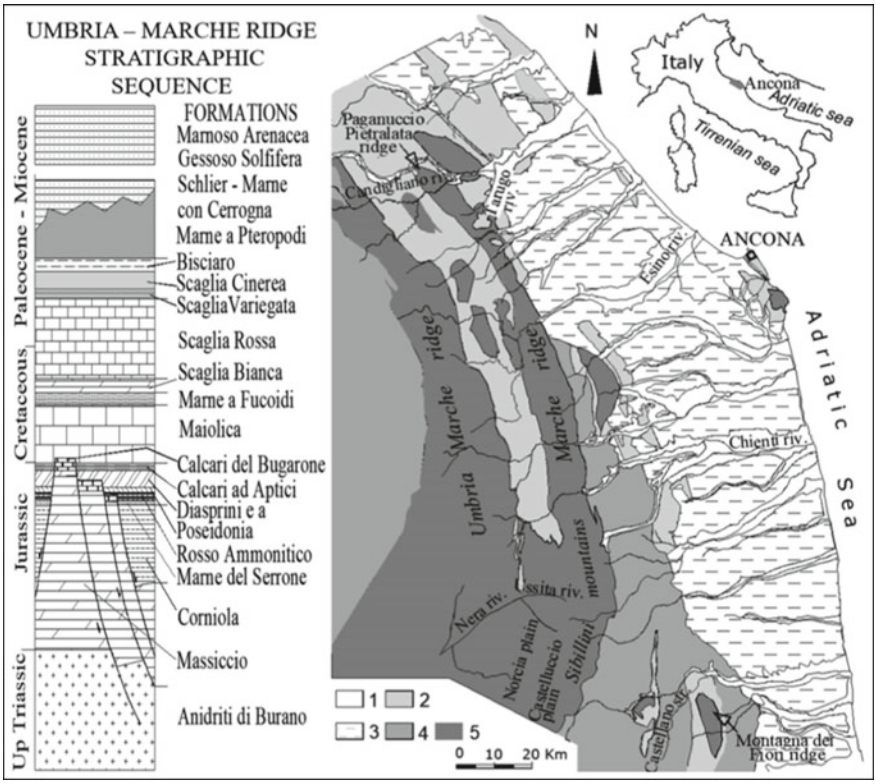

Fig. 1 Schematic geological map of the Marche region with location of the studied areas. Legend: 1: Alluvial deposits, 2: Plio-Pleistocene terrigenous deposits, 3: Miocene marls and terrigenous deposits, 4: Marnoso Arenacea Formation (Miocene); 5: Meso-Cenozoic limestone sequence. On the left: stratigraphic sequence with the different series. From [8] modified

are partly overlapped and translated to north-east. The Marche ridge is conversely characterised by an anticline structure, identifiable in the southern area (Mt. Sibillini complex). In the inner Marche Basin, which divides the two ridges, minor limestone ridges outcrop in tectonic contact with Miocene deposits on the eastern side (Fig. 1).

The foothill area is also interested by fold structures, bordered by thrusts on the eastern side [1, 9].

The hydrogeology of the Umbria-Marche region, object of the research activity of this unit, highlights that most of the springs in the Apennines zone, often used for water supply, emerge from the three main hydrogeological complexes of Calcare Massiccio, Maiolica and Scaglia (Meso-Cenozoic sequence) with discharge sometimes above 500 l/s (springs emerging from the basal aquifer) and usually lower than 50 l/s. Basal flow of groundwater occurs in the Massiccio complex [10, 11]. In many cases the basal aquifer is recharged by Scaglia and Maiolica. The permeability of the complexes is basically due to fissures and karst.

2.2 Focus on Limestone Hydrostructures

Some results of studies of the geological group are presented. They concern some of the investigated hydrostructures, referring, for the others, to the bibliography.

Sibillini ridge

The Umbria-Marche sequence occurs in the Mt Sibillini. The main limestone aquifers are the complexes of Calcare Massiccio, Maiolica and Scaglia [1, 9]. Linear springs fed by basal flow usually arise along rivers, whereas single springs are less frequent but with high discharge.

The hydrogeological boundary is the prolonged overthrust with a displacement up to ten kms [12] in the southern and eastern area, where the marls of the upper part of the limestone sequence are the aquiclude of the Sibillini complex in the Adriatic front. On the western side the hydrogeological boundary is represented by a fault line (Notturia—Norcia—Preci). On the northern area the hydrogeological boundary is not well-defined owing to the likely presence of hydraulic contacts. Anyway, towards north we can observe the main drainage zone of the hydro-structure, localized in the Nera springs, Nera river and Ussita river (Fig. 1).

The importance of hydrogeology (i.e. the identification of hydrogeological complexes, aquicludes and other limits to flow) for water supply studies is stressed by observing the distribution of the main springs in this area: they are spread especially close to the hydrogeological boundaries and emerge along the watercourses with linear springs showing an overall discharge of about 10 m^3/s in the northern area, 3 m^3/s in the western area and about 4 m^3/s in the southern and eastern area. These values have been extremely changed by the earthquakes' occurrence in the last years [13].

An example of the importance of isotopic analyses performed on groundwater and rainwater is reported in Fig. 2, where an almost constant behavior of oxygen-18, compared with spring discharge and salinity, allows to obtain the main recharge area of the aquifer recharging the spring.

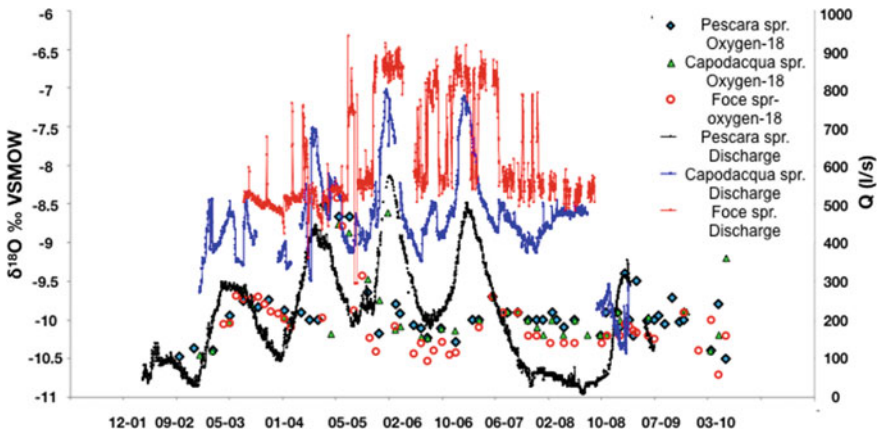

Fig. 2 Discharge and isotopic content in the Pescara, Capodacqua and Foce springs (Mt. Sibillini)

Tracer tests performed in the last years allowed for the identification of a connection between the Castelluccio plain and the east-southern aquifers (Fig. 3).

Montagna dei Fiori ridge

The Montagna dei Fiori ridge is an anticline verging towards NNO-SSE and reversed towards east where the Umbria-Marche sequence outcrops.

This hydro-structure is sealed by the Marne con Cerrogna and Scaglia cinerea Formations (Fig. 1) owing to stratigraphic and tectonics factors to the North, West and South, whereas the eastern front is bordered with a thick debris cover [1, 7].

No significative spring emerges in the area and this is related to the peculiar geo-structural setting and very developed deep karst phenomena that force the infiltrationwater to a rapid percolation until the basal flow.

The deep flowpath is drained by the Castellano stream. In this sector several discharge measurements in the recession period were made to give an indirect evaluation

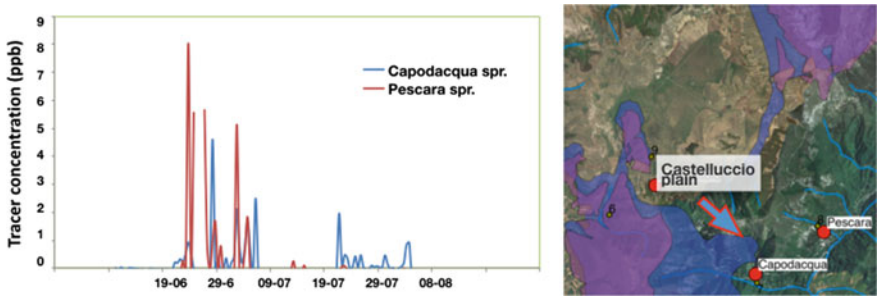

Fig. 3 Tracer breakthrough curve in the Capodacqua and Pescara springs and estimated flow direction (Mt. Sibillini ridge). Tracer injected on June, 9th

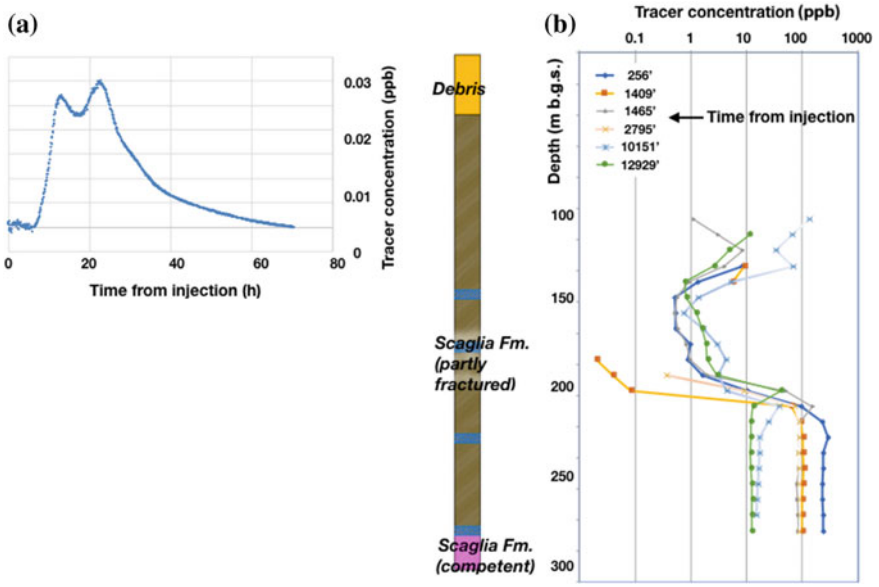

Fig. 4 Tracer tests in deep wells (Montagna dei Fiori ridge) **a** Tracer breakthrough curve of a two-wells test, **b** Results of a single well test with vertical flow occurrence

of the actual infiltration of the complex and estimate the aquifer potentiality for water supply.

Other tests were made in some pilot deep wells (about 300 m) to evaluate the aquifer parameters and velocity and direction of groundwater by using artificial tracers (Fig. 4).

Mt Paganuccio-Pietralata ridge

The hydro-structure of Mt Paganuccio-Pietralata is an anticline sealed by low permeability deposits, comprising the aquifers of the Calcare Massiccio, Maiolica and Scaglia [1]. Baseflow drainage line is the Candigliano river; on the south, the Scaglia aquifer is drained by the Tarugo river (Fig. 1).

Discharge measurements and river hydrographs can give indication about the water potentiality of the hydro-structure; in the Tarugo river, for example, a mean discharge increase of 40 l/s in the recession period brings to a flow volume increase of at least 1.2×10^6 m^3/year (Fig. 5).

These data lead to the project of deep wells for water supply in the studied area.

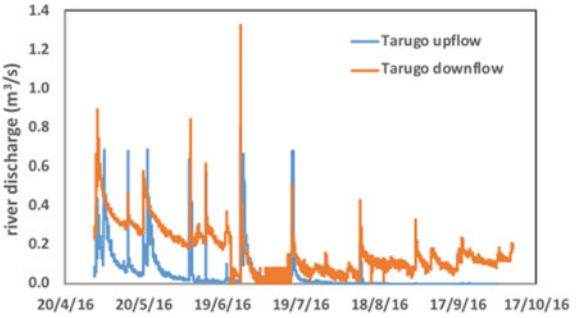

Fig. 5 Hydrograph of two gauging stations in the Tarugo river (upflow and downflow). It is apparent the discharge increase in the downflow station (Mt. Paganuccio—Pietralata ridge)

2.3 Final Remarks on the Hydrogeological Researches

In conclusion, detailed geo-structural and hydrogeological surveys in the investigated areas gave as result the lithological properties of aquifers and aquicludes, schematic tectonics, in some cases even fault displacement and the outline of surface water network and springs position.

The ensuing hydrogeological model was then compared to the results of tracer tests, isotope analyses and river discharge measurement used to evaluate groundwater circulation, the recharge area of aquifers and water resources. Final results are primary represented by the identification of zones in which wells and other works for water supply have been built and, secondly, the location of safeguard and protection areas around springs, tunnels and wells.

3 Sustainable Design in Landslide-Prone Areas

In this section, work of the Unit more specifically oriented towards the analysis of large infrastructures will be briefly presented, focusing in particular on the greater problems that arise when a large, potentially unstable area must be crossed.

This research Unit has been involved in the study, design, and follow-up monitoring of large structures and infrastructures for over 20 years, and has acquired considerable experience in the typical difficulties of such works. They are invariably works of inherent complexity and require careful planning.

Such works would comprise most large-scale engineering works, such as road infrastructures (tunnels, bridges, embankments, etc.), pipelines, etc. They pose a series of issues to be addressed, which can be grouped into two main categories, regarding respectively:

- structural efficiency, which requires primary engineering calculations, in order to guarantee safety, stability and adequate serviceability performance;
- sustainability requirements in order that the structure as designed can actually be constructed without excessive costs and put to use without unnecessary damage

to the environment, which requires preliminary planning and prediction of costs; this is particularly important for such large works, which involve public funding and monitoring of expenses.

When planning to insert a structure in a specific environment, the design of the structure itself may strongly depend on the environment in which it will be operating. This is quite obvious when there exist past expressed problems at the site which it may not be possible to avoid (for example, vicinity of known landslides), but it may be even more significant in cases where problems may be present which have not yet expressed, and are therefore not known, but could emerge as a result of construction processes (for example existing slip surfaces or faults which could be reactivated by the construction, giving rise to slope movements). In such cases, even with top quality structural design and technology and following construction procedures which may have been successfully approved and applied in other situations, instabilities or even catastrophic damage could ensue.

As a result, a halt of construction would become necessary, in search of adequate remedial measures or, in the worst cases, a more radical variation of the overall design. Such procedures could prove very costly and cumbersome, especially for large infrastructures where the funding and financial plan depend on public administrations and are overly difficult to change.

In order to work within a framework which considers sustainability from the start, a series of additional issues must be taken into account. Though structural efficiency and guaranteeing safety and stability remain the primary design requirements, it is imperative to add sustainability requirements from the outset, and not as an extension to be carried out after critical design decisions, such as the selection of the path of the infrastructure, have been taken and the costs of the works have been fixed.

In recent years there has been strong motivation to modernize the infrastructural network in Italy including rail, roads and pipelines. This class of infrastructures, which are typically linear, have a large impact on the environment, especially when they cross hilly or mountainous regions requiring the construction of several bridges and tunnels. Such impact can be very large if the geology of the area is complex, as is the case of southern Italy, where soil deposits have been involved in quite recent tectonic activity which caused the formation of soil discontinuities and strong non-homogeneities. In such formations landslides can easily develop, so that routine design approaches are not appropriate for modelling the interaction with the new infrastructure. Moreover, lack of a correct diagnosis of the landslide phenomena during the design process may greatly reduce the efficiency of any possible stabilization measure.

These themes represent the focus of the research activity addressing engineering solutions which minimize the impact of infrastructures in difficult soils on the environment. This work largely benefits of the long-lasting collaboration with public administrations and contractors involved with the construction, design and monitoring of such works.

3.1 Meaningful Experiences

The work of this Unit, which goes back to pioneer research studies of 1991, spans over a large spectrum of cases and classes of geotechnical and structural design.

In the EPOCH (European Programme On Climatology and natural Hazard) research project, involving several research teams coordinated by the University of Ancona, the slow movements of the superficial layers involved in slope instabilities were investigated, with an attempt to establish possible connections with rainfall data and the groundwater hydraulic regime [14].

Within the EPOCH project, a separate study was initiated concerning the behaviour of soils containing discontinuity surfaces, which can play an important role in slope instability phenomena. In this research, rather than investigating the aspects concerning the behaviour of the discontinuity itself, as in Fracture Mechanics, the surrounding volume of soil is modelled as a continuous medium containing discontinuity surfaces. An original numerical model was formulated, which is still today being developed and implemented [15, 16]. The model is also being expanded to interact with specific research into extended finite element strong discontinuity formulations, and collaboration with research teams from other Universities is envisaged for the future.

Several studies have been carried out on the behaviour of structurally complex soils. Results have been achieved particularly in understanding the influence of dilatancy on the shear strength of overconsolidated clay [17–19] and in geotechnical characterization of natural heterogeneous soils using the binary mixture framework [20, 21].

Regarding the theme of assessing the geotechnical model for infrastructure design, research activities have dealt with the subject of pipeline positioning and interaction over vast unstable areas [22, 23].

More recently, a great number of research activities have been developed regarding the sustainable design of road infrastructures, and specifically of tunnels, located mainly in structurally complex formations outcropping in the Umbria-Marche Region and in southern Italy. One of the first case studies regarded the opening of the tunnel of San Martino in the city of Ancona, in which the main problem was the interaction with a densely constructed urban area, and the impact on the surrounding habitat had to be monitored and contained [24, 25].

As confirmed by a number of subsequent studies, the prevention of possible failures largely depends upon formulating a correct interpretation of the soil deformation pattern, which in turn depends upon adequate and sufficiently extensive monitoring during the works and detection of existing discontinuities. The evidence and experience acquired during the years of the Unit's research studies (PRIN 2015, PRIN 2010–2011, PRIN2008) suggest that, in order to minimize instability processes and avoid acceleration of existing deep-seated landslides, interventions should be oriented towards minimizing stress release, reducing pore pressure and improving ground strength [26–34].

3.2 Focus on Landslides in Structurally Complex Formations

The presence of structurally complex formations is a common feature in most of the landslides analyzed. The complexity is related to the heterogeneous and discontinuous nature of deposits at the scale of the laboratory samples (mesostructure) and at the scale of the engineering problems (macro and megastructure). This means that structurally complex formations cannot be confidently studied and modelled with classical approaches of Soil Mechanics or Rock Mechanics. The presence of structures, such as joints and slickensides, suggests the influence of tectonic-induced shear surfaces in the kinematics of failure and indicates that a hybrid soil-rock-mechanics approach should be followed to address their geometrical and mechanical characterization [35, 36].

The case studies of this Unit refer to complex soil formations of prevailing pelitic composition. In some of the cases the landslide occurs in deposits of jointed siltstone or claystone. In other cases, instabilities appear in flysch deposits, often characterized by the presence of layers of strongly degraded material; these layers consist of hard lithorelics surrounded by a clayey matrix, which has softened as a consequence of the prolonged action of circulating water and the intrinsic weakness of the microstructural bonds.

In the first case the behaviour of the slope is conditioned by the so called "macrostructures" (joints, bedding planes and faults), and the geotechnical characterization of the surrounding soil (typically stiff, overconsolidated and fragile) is different from that of the material within the discontinuity. In the second case, the behaviour of the slope depends on the mechanical behaviour of the soft soil matrix; this explains the frequently observed ductile response at failure of samples taken from the flysh deposits, becoming slightly fragile at low confining stresses.

As an example, the case of a deep-seated instability phenomenon observed when excavating the south portal of the Piscopio I tunnel along the Jonica highway in the vicinity of the town of Catanzaro (Fig. 6) is briefly illustrated.

From a geological point of view the infrastructure is located in the southern extremity of the Catanzaro Palaeo-strait, not far from the "Copanello fault" regional tectonic system. The proximity to this important geological structure induced a structural complexity of the deposits in which the tunnel was excavated that is the main cause of the instability phenomena observed at the southern tunnel entrance. The other big fault, close to the slope crest, caused the lowering of the Miocene chalks and the generation of a secondary discontinuity system, giving the slope a "domino structure", as confirmed by seismic refraction.

The monitoring system implemented in this case (topographic measurements, inclinometers, piezometers) was particularly useful to detect the kinematics and the evolution of the observed phenomenon in relation to the tunnel construction works, to review the geotechnical model for the soil and to drive the geotechnical survey towards the characteristics of the Plio-Pleistocene deposit (which at the beginning had not been identified as critical for the considered slope), and specifically to assess the values of the pore water pressures along the well-defined failure surface.

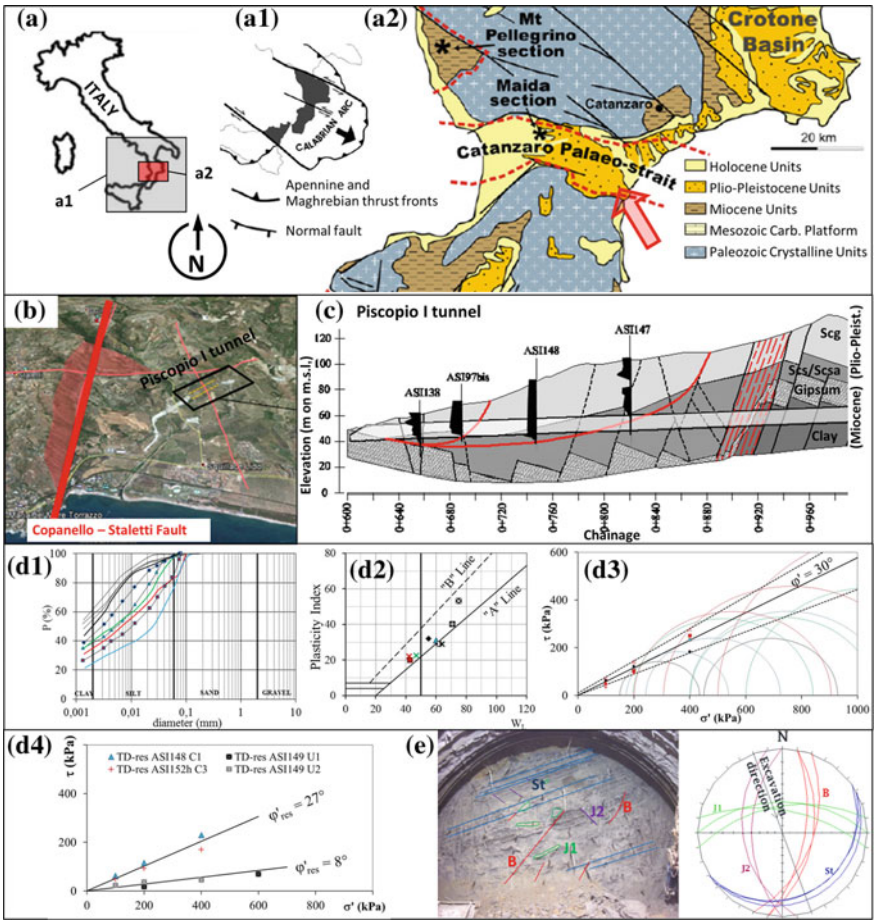

Fig. 6 **a** Location of the Piscopio I tunnel (**a1** Geotectonic framework map of the Calabrian Arc, **a2** Simplified geological map of Catanzaro basin [from 37]), **b** Aerial view of the area with indication of the main faults, **c** Schematic geological setting along the tunnel, **d** Test results on Scs/Scsa **d1** Granular curve distribution, **d2** Casagrande Plasticity Chart, **d3** Effective stress failure envelope from drained triaxial tests and direct shear tests, **d4** Residual stress failure envelope from direct shear tests, **e** Typical survey of the excavation face: chainage 0 + 779, Southern tube from the Northern entrance

The reproduction of the geo-structural settings and of the groundwater pressure regime allowed the definition of appropriate stabilizing measures. These consisted mainly in the implementation of deep drainage systems, in particular two large-diameter wells equipped with long radial drainage pipes, aiming at lowering the pore-water pressures at critical depth of the unstable mass. The effectiveness of these mitigation works was immediately confirmed, since a reduction of the displacement rate was observed, allowing the completion of the tunneling works and the safe opening of the road.

4 Sustainable Use of Natural Resources

In this section, the fields of activity and the main practical experiences of the environmental geotechnics Unit will be presented, focusing in particular on the application of ground improvement techniques for the reuse of excavated materials and on sustainable landfill design and remediation approaches for polluted sites.

4.1 Improvement and Reuse of Excavated Soils and Dredged Sediments

One of the contributions of geotechnical engineering in optimizing the use of natural resources concerns excavated soils and dredged sediments (e.g. [38]). This research field helps in achieving the recycling and recovery goals fixed by the European Union directive 2008/98/CE (Waste Framework Directive), which comprises obtaining at least 70% of recycle rate for construction materials by the year 2020. Different soil improvement techniques can be applied to make excavated soils suitable for earthwork construction, avoiding their disposal, or to improve the mechanical characteristics of dredged sediments disposed in confined facilities, to become land reclamations.

The main research activities developed by the Unit in this field concerns the stabilization of excavated soils by addition of binders (hydrated lime, quicklime or cement) and the consolidation of dredged sediments in confined disposal facilities by means of vertical drains and pre-loading.

Physical and chemical properties of fine-grained soils can be improved by adding lime as stabilizing agent to obtain proper mechanical characteristics for earthen structures (e.g. dikes, road embankments) and for slope stabilization purposes [39]. In particular, the soil treatment by lime, through its chemical reactions with the clay fraction, allows obtaining improved workability, higher hydraulic conductivity, lower compressibility and higher shear strength compared with the properties of the untreated soil [40]. Given the great number of intrinsic and curing variables affecting the properties of lime treated soils (e.g. type and amount of lime, soil water content, curing time and temperature), the research carried out by the Unit in this field aimed at optimizing the design of soil-lime mixtures taking into account typical in situ construction procedures and curing conditions [41].

Among the practical applications coordinated by the Unit, two main works were undertaken in the Ancona city area. They concern the stabilization of the Montagnolo slope and the construction of road embankments in the Torrette district.

The former work, developed in 2001–2002, originated from the necessity to stabilize the Montagnolo slope, a section of the well-known "Ancona Big Landslide" that occurred in 1982 [42]. The stabilizing works included drainage trenches, diaphragm walls and a containing berm of about 15,000 m^3, made by compacting the in situ soil stabilised with hydrated lime. A wide laboratory mix-design phase identified

3% lime as the optimal proportion to obtain proper values of hydraulic conductivity, shear strength and stiffness parameters to assure the slope stability. A full-scale test pad confirmed the laboratory test results and allowed setting up the construction procedures (Fig. 7).

The latter work (2007) concerns the construction of road embankments (1 km total length and up to 4 m high) to improve the traffic to the Ancona Regional Hospital, where the excavated soils along the route were fully reused after stabilization with lime. In this case, high compression stiffness was also required to avoid settlements in the service life. Results from the laboratory testing, design analyses and modelling, together to the in situ test pad and careful construction quality controls ensured the desired overall performance of the lime-stabilized embankments [43].

One of the best examples of environmental application of soil stabilized with cement is given by the sidewall barriers of the Barricalla landfill for hazardous waste disposal, near Turin (built in '90 s). The very high shear strength parameters and low hydraulic conductivity obtained by adding 5% slag cement to the available soil (a clayey silt) allowed side barriers 40° slope, thus gaining significant extra volume for waste disposal [44]. The necessary laboratory experimental study, pioneering for the time, was the opportunity to set up the laboratory of environmental geotechnics of Università Politecnica delle Marche, with innovative equipment and procedures (e.g. column tests with leachates, pollutant diffusion and sorption tests), constantly updated in the following years and still in use today.

Dredged sediments are another class of materials that need specific techniques to improve their mechanical characteristics. The increasing pressure for new solutions to combine dredging needs with land reclamation for harbor development encourages the research activity to this aim. The Unit has carried out research activities in this field (by research agreements with the Ancona Port Authority) to improve the mechanical characteristics of dredged sediments once placed in confined disposal facilities. In particular, stone columns, prefabricated vertical drains and preloading [45] were designed for two confined disposal facilities at the Ancona harbor, based on specific models to predict settlements, a challenging task due to the typical large strains exhibited by dredged materials [46].

4.2 Sustainable Landfill Design and Remediation Approaches for Polluted Areas

The research devoted to environmental sustainability aims at identifying and improving the developing processes that will assure the capability of the environment to support the impact of human activity. Among these activities, the safe design and construction of waste disposals and the geo-environmental characterization, risk assessment and remediation of polluted sites are definitely included.

Static and seismic stability, taking into account the mechanical properties of subsoil, waste materials and lining systems, play a central role in the design of new

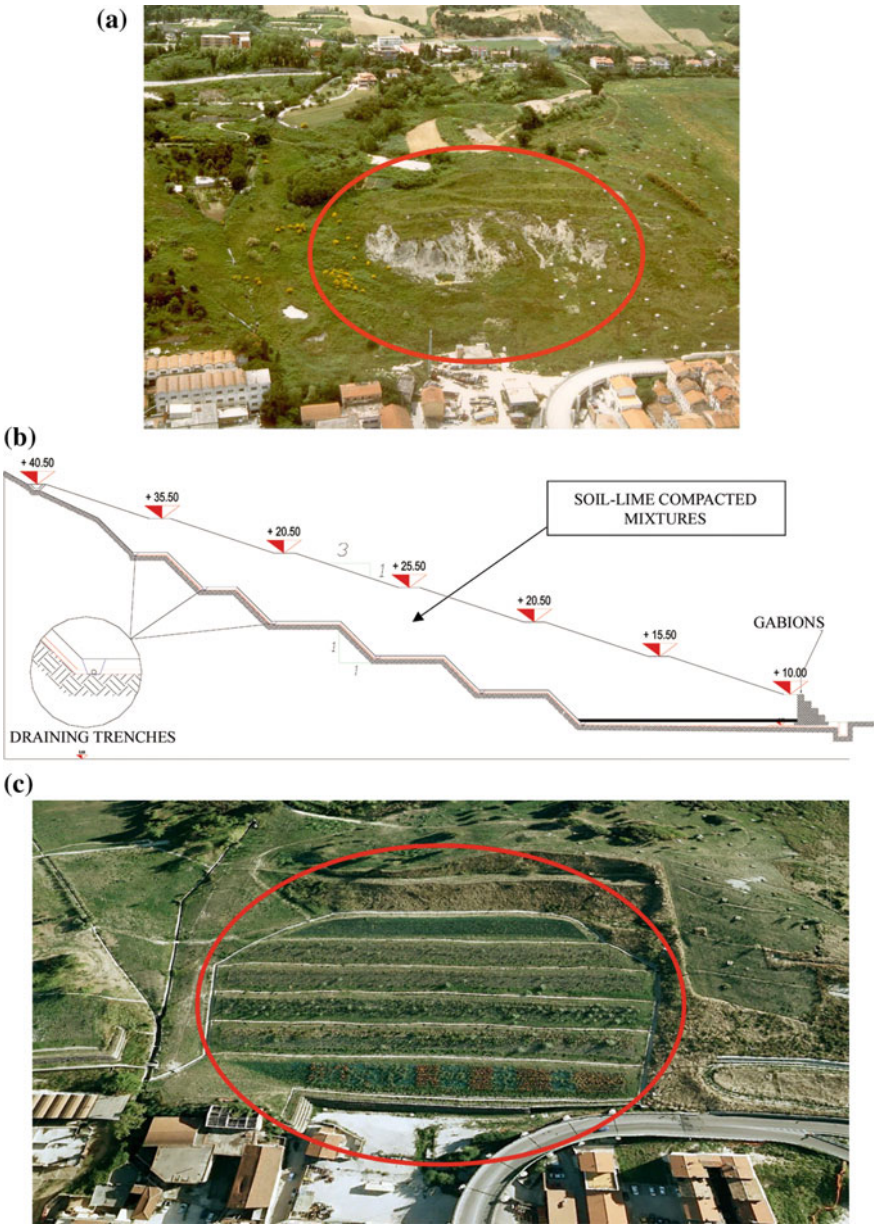

Fig. 7 **a** Montagnolo slope, **b** Typical cross sectional view of the stabilizing berm—modified from [42], **c** Current state of the slope

landfill or enlargement of existing ones. The main geotechnical issues for safe and efficient design of modern landfills include the variability of waste parameters, the shear strength at interfaces of composite liners, which significantly depends on temperature, on the type of contacted surfaces and ageing in leachate [47, 48], and the selection of proper methods for stability analysis and related assumptions. The Unit has experienced many of these challenges by supporting the design of new landfills and of stabilization measures for existing landfills with stability problems.

Among these experiences, the one related to the Belladanza landfill, in central Italy, was one of the most comprehensive [49]. The work consisted in the enlargement (400,000 m^3) of an existing plant. After an extensive geotechnical investigation, stability analyses, carried out by both LE and FE methods, highlighted that temporary and permanent stabilization measures were necessary. Passive pile rows and a soil-cement berm were designed to ensure the stability of the landfill during construction and service. The stability analyses accounted for shear strength reduction at critical interfaces of composite liners and were carried out simulating different construction stages. This case history pointed out that critical conditions can occur during construction [49].

Environmental issues concerning polluted sites were also deeply studied by the geotechnical Unit. In the last twenty years, the number of contaminated sites in Italy (more than 20 thousand) has considerably increased as a consequence of a more effective control activity due to an increased social and legislative sensitivity.

The great differences in the chemico-physical characteristics of the contaminants, their frequent presence in combination and the very different mechanisms of migration and interaction with the soil matrix make the management of contaminated land a very difficult task and research in this field can contribute to answer to many important questions [50, 51]. For this reason, a collaboration of skills ranging from geotechnical engineering to applied chemistry and hydrogeology is required. Methodological approaches must also be strictly defined according to both the specific situation and the objectives to be pursued. In this regard, an important input is provided by the D.Lgs. 152/2006, which is the law that defines the methodological approach to be followed and goes into detail on the specific procedures for the characterization of contaminated sites and on the risk assessment.

The Unit has been involved in the study of many contaminated sites in Italy and in our Region, with reference to characterization and risk assessment phases of polluted sites management. A representative example in our Region is a currently disused plant where the industrial activity ran for over 80 years, resulting in soil pollution, mainly by PAHs. An extensive geotechnical investigation (38 boreholes, 25 piezometers, 141 samples collected for chemical analyses, 6 in situ permeability tests) allowed for the definition of a particular geomorphological and hydrogeological site configuration, which suggested to subdivide the site into discrete areas, each with its own conceptual model [52]. This subdivision was a key choice that drove the risk assessment and the redevelopment scenarios of the site.

The migration of contaminants is often the core of the risk assessment procedure and, in many cases, the use of analytical migration models, as those suggested by

the Standards, may provide unrealistic predictions such as in the case of volatilization from soil [53]. The use of direct measurements of vapor emissions, as recently allowed by Environmental Agencies, can be of great help in driving realistic risk estimates. Direct measurements using flux chambers (one of the first applications in our country) of mercury vapor emissions in a contaminated site located in Marche Region, supervised by the Unit, demonstrated the possible overestimation of actual emissions if analytical volatilization models were applied [54].

The Unit has been involved also in the design of encapsulation of several polluted sites and abandoned landfills, made by side (cut-off) and cover barriers. Innovative technologies for the construction of cut-off walls has been extensively studied and evaluated with special regard to the hydraulic and mechanical behavior of CB-mixtures [55], for which original prediction methods for durability assessment have been proposed [56, 57]. With regards to barrier systems, the contributions of the Unit have concerned the hydraulic performance and pollutant containment efficiency of different barrier materials, such as conventional and enhanced bentonites [58, 59].

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Sustainability in Construction Materials: From Waste Valorization to Circular Economy

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Abstract Already from the beginning, 50 years ago, the first nucleus of researchers establishing the research group, was convinced that the construction sector was the best option for the valorization of industrial by-products as "secondary raw materials". In fact, this sector is probably the largest consumer of resources and the largest waste generator, consequently it has huge environmental impact. On the other hand,

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construction materials affect the performance of buildings with respect to safety, health, environmental performance and energy efficiency. Manufacturing of construction products using alternative raw materials; recycling to manage construction and demolition waste; durability and environmental compatibility of materials: all these were the different and challenging fields of research that the group has faced in a continuous effort of innovation and cooperation at national and international level. The focus of the group was already perfectly in line with what is now called "Circular Economy", which at present is considered a revolution in the way of human economic development. We are sure the group thus contributed to this revolution even before the term was in current use. We feel ready for the next 50.

1 The First Nucleus of Researchers

The first Department that was formed at the Engineering Faculty of the University of Ancona, today the Polytechnic University of the Marche, towards the end of the 70s of the last century was the Department of Materials and Earth Sciences.

The constitution was made possible by the aggregation of three institutes: Chemistry, Physics and Geology. The first Director was Prof. Savino Melone who organized the Department in three sections that were based on the founding institutes, coordinating the planning of organizational activities and the development through the establishment of a departmental council.

1.1 Short History: People and Structures

They were pioneering years because, being the newly founded Faculty of Engineering and the location at a converted industrial warehouse, the laboratories were lacking in equipment and they had difficulty to start also because of the precariousness of the teaching staff that for the most part was not resident, but coming from other universities.

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The research activities on which to invest began to take shape towards the second half of the 70s, when the young structured researchers had identified their areas of interest and when they were assigned the first chairs as a full professor who, coming from other universities, to transfer their research guide lines at the Department.

For the Chemistry section of the Department, are the cases of Prof. Paolo Bruni, already present at the Department since the early 70's and of Prof. Mario Collepardi who, coming from the University of Rome, remained in the Department for 25 years, giving a fundamental mark to the research on cementitious materials.

Over the years, of course, there have been significant changes, the first of all the transfer to the new headquarters of the Engineering Faculty, in 1984, which saw a consistent implementation of the research laboratories, but also the reorganization of the disciplines related to the Department. The geological section expanded its disciplines and research lines in the engineering sector of geotechnics, as well as in the Physics section the research sectors in the fields of optics and microstructure of materials were diversified with the entry of new full professors.

Also the Chemistry section, grouping different disciplinary scientific sectors, has undergone splitting and re-aggregation over time relating to staff afferents (Fig. 1) within the department, without however eliminating collaborations in research topics.

Over time the Department has changed its name several times from Materials Science and Earth, to Physics and Engineering of Materials and Territory, to Science and Engineering of the Materials of the Environment and Urban Planning, and of course there have been several Department Directors among which in addition to Prof. Savino Melone, in order of time, prof. Lucedio Greci, Prof. Giacomo Moriconi, Prof. Erio Pasqualini up to the current Prof. Oriano Francescangeli.

Fig. 1 Group photo (not to scale: the research group is bigger!)

1.2 Short History: Research Challenges and Opportunities

Already from the beginning, 50 years ago, the first nucleus of researchers establishing the research group, was convinced that the construction sector was the best option for the valorization of waste, industrial by-products and other recycled materials as "secondary raw materials".

The Department in its brief history, has assumed a peculiar configuration in which the academic community has consolidated an intense relationship with the regional territory, promoting at the same time, a strong and attractive activity both at national and international level. Its activity started enquiring on synergistic researches in the field of the interaction between the building materials and the environment, bearing in mind the specificities of the different scientific areas interconnected.

From this point of view, the department created a sort of "balancing of the skills and use of resources" through the creation of different sectors to give life to a structure in which different competences could contribute to a teaching of high level and a research of high international profile in the field of materials and environmental engineering.

At the foundation, professors came from many Italian universities and different cultural background, from those with a more fundamental vocation, such as Chemistry, Physics and Earth Sciences, to those more markedly applicative, such as materials engineering, and environment.

In this context the study of material-environment interactions, chemical-physical phenomena of interest in the industrial sector, corrosion and protection of materials, environmental defence and quality of living environments received the larger consideration, and represented the main focus of research of the STM group (Scienza e Tecnologia dei Materiali). The interest of the STM group was placed on sustainable construction materials, recycling industrial by-products or biomass ashes in mortars and concretes keeping in mind particularly the environment through the monitoring of soil, water and air quality with the assessment of chemical risk and, diagnosis and prognosis of living and working environments.

Among the most relevant applications, the use of photocatalytic materials applied in the motorway area with the creation of vertical surfaces (piers and tunnel vault, masonry surfaces) and on the road pavement with monitoring of short-term and longer-term effects on the reduction of NOx emissions and precursors of atmospheric pollution.

2 New Products from Industrial By-Products

A judicious use of natural resources, achieved by the use of by-products and recyclable materials, and a lower environmental impact, achieved through reduced carbon dioxide emission and reduced natural aggregate extraction from quarries, represent two main actions that meet the needs for sustainable construction development. It

is fundamental to discuss and define the criteria on the basis of which the use of by-products and recyclable materials in concrete can be optimized.

When using recycled materials, for instance, the fresh concrete behaviour during placing can change. Moreover, when using recycled materials appropriately, some important properties of the hardened concrete such as ductility and durability can be better engineered, as several works of the STM group explains and emphasizes.

2.1 Low CO_2 Cement from Waste

With an annual production of almost 3 Gt Ordinary Portland cement (OPC) is the dominant binder of the construction industry. The cement industry contributes about 7% of the total worldwide CO_2 emissions. The urge to reduce carbon dioxide emissions and the fact that OPC structures which have been build a few decades ago are still facing disintegration problems points out the handicaps of OPC. The early deterioration of reinforced concrete structures based on OPC is a current phenomenon with significant consequences both in terms of the cost for the rehabilitation of these structures, or even in terms of environmental impacts associated with these operations.

2.1.1 Alkali Activated Binders Products

Increased attention to the environmental impact of OPC has prompted researchers to study the optimization of alternative clinkerless construction materials [8, 9, 26].

Alkali Activated Cements (AAC) are a novel class of cement-like materials obtained by the polymerization reaction of a solid aluminosilicate with an aqueous solution of alkali hydroxide, silicate, carbonate or sulphate [32] (Fig. 2).

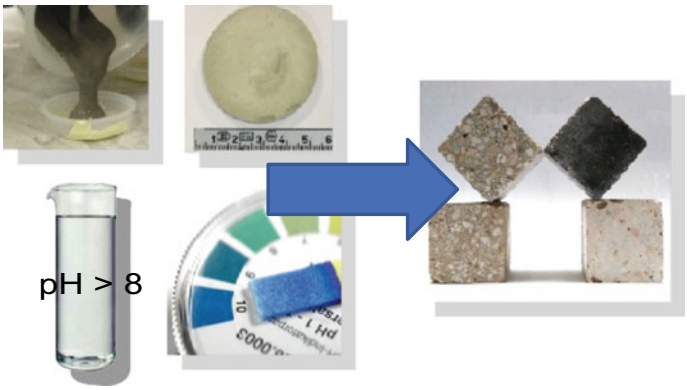

Fig. 2 Alkali activated binders

Aluminosilicate precursors are generally industrial by-products, and thanks to the absence of limestone and a general energy savings in the production of AAC, a reduction of 40–90% of greenhouse gases emissions compared to that of OPC materials with the same characteristics has been estimated [10].

The STM Group contributed further to the state of art of AAC mortars by investigating their behaviour when cured at room conditions and compared with traditional cementitious mortars at the same compressive strength class. In particular, according to UNI EN 1504-3:2006, mortars belonging to two non-structural classes (R1 $\geq$ 10 MPa and R2 $\geq$ 15 MPa) and one to structural class (R3 $\geq$ 25 MPa) were tested and compared both in the fresh and in the hardened state.

The obtained results demonstrates the possibility of manufacturing AAC mortars at room conditions which can cover three mechanical strength classes according to UNI EN 1504-3:2006 (R1 $\geq$ 10 MPa, R2 $\geq$ 15 MPa and R3 $\geq$ 25 MPa) by increasing the alkalinity of the activating solution [27–30]. In particular, the use of NaOH in alkali activated fly ash mortars caused efflorescence formation which was more pronounced with the increase of the compressive strength. The combined use of KOH instead of NaOH and calcium aluminate cement on fly ash weight removed the efflorescence phenomena [29].

Moreover, at the same mechanical strength class:

- the faster strength gaining of FA mortars prepared with KOH with respect to those prepared with NaOH is due to the faster and stronger incorporation of K^+ into the gel than the Na^+ ; in the same way, the faster strength development of MKK mortars with respect to FA ones is due to the faster polymerization of metakaolin with respect to fly ash;
- the dynamic modulus of elasticity of AAC mortars was at least 50% lower than that of traditional OPC mortars, respectively;
- AAC mortars showed lower restrained shrinkages than those of OPC mortars due to the lower modulus of elasticity;
- even if the higher alkalinity of AAC paste delayed the tendency to passivation of reinforcements, especially if galvanized, after one month of curing both bare and galvanized steel bars reached the same corrosion rates of those embedded in OPC mortars.

In addition, at the same mechanical strength class, many results depend strongly on pore distribution and total porosity of mortars since:

- the higher drying shrinkage of AAC mortars with respect to that of OPC mortars is due to the higher mesopores volume;
- the lower weight losses of FA mortars are due to the higher mesopores volume which has hindered the evaporation of water remained absorbed to the their surface;
- AAC mortars are more permeable to water vapour with respect to OPC mortars due to the higher presence of pores with large dimensions in FA mortars and the higher total porosity in MKK mortars;
- MKK mortars and FA mortars absorbed more and less water, respectively than OPC mortars since their total porosity was 60% higher and 40% lower than those of OPC mortars, respectively;

- FA mortars prepared with KOH and CAC showed an excellent resistance to sulphate attack thanks to their lowest porosities.

2.1.2 Chloride Induced Corrosion of Reinforcements in Alkali Activated Binders

In coastal zones, chlorides [39] promote the corrosion of embedded reinforcements and this phenomenon is considered one of the major cause of premature failure of reinforced concrete structures [35]. Methods proposed to mitigate reinforced concrete deterioration include the use of hydrophobic treatments, due to their ability to make concrete less susceptible to water saturation [6], corrosion inhibitors [5, 42], stainless steel rebars which are highly resistant to corrosion but very expensive, and galvanized reinforcements [2–4, 34]. In particular, galvanization of steel reinforcements is a cheaper prevention method against corrosion if compared to other anti-corrosion methods [4, 35, 41].

In the presence of $Ca(OH)_2$, as in the concrete pore solution, the protective layer is not only formed by zinc oxide and hydroxide, but mainly by a compact, protective, and highly chloride-resistant layer of calcium hydroxyzincate (CaHZn). The passivation of galvanized steel largely depends on the alkalinity of the environment and the concentration of Ca^{2+} ions. The passivation layer may be less protective due to the presence of chlorides or a high amount of soluble alkalis, whereas the formation process is favoured by oxygen availability [38].

It is well-known that steel reinforcements passivate in the alkaline environment of concrete pore solution, but in AAC, where NaOH or KOH concentrated solutions are used to activate the aluminosilicate powders, the alkalinity is much higher than in traditional OPC matrices. Alkalis are highly mobile in the pore system of AAC and this effect may significantly limit the durability of embedded reinforcements. Moreover, in AAC, the content of calcium, which contributes to the galvanized steel passivation, is much less than in OPC matrices.

The information provided by the literature on steel corrosion in AAC is limited and generally focused on simulated pore solution of alkali-activated concretes or fly ash or slag based mixtures, whereas there are no studies on metakaolin-based AAC.

Thus, the STM group investigated:

- the passivation capacity of bare and galvanized steel reinforcements in metakaolin (MK) and fly ash (FA) based AAC during the curing time [27, 43];
- the corrosion behaviour of bare and galvanized steel reinforcements in MK-and FA-based AAC in the presence of chlorides [27, 43];
- the passivation capacity and the chlorides induced corrosion behaviour of bare and galvanized steel reinforcements in FA-and MK-based AAC in comparison with that of cement based mortars, at the same strength class [27, 43].

To this aim the corrosion behaviour of both bare and galvanized steel reinforcements embedded in geopolymer and ordinary Portland cement-based mortars with

Fig. 3 Specimen for testing corrosion of reinforcing bars in AAC

three different strength classes (R1 $\geq$ 10 MPa, R2 $\geq$ 15 MPa and R3 $\geq$ 25 MPa) was investigated (Fig. 3) and compared both in the first month of curing and during 12 weekly wet-dry cycles in a 3.5% NaCl solution.

The main obtained results show that:

- during the first days after the cast, AAC prolong the active state of bare and galvanized steel reinforcements due to their initially very high alkalinity [30, 43]
- after 10 days of curing, polarization resistance increases for both bare and galvanized steel reinforcements in all types of mortars, indicating a clear tendency to-wards the passivation. This result is of particular importance for galvanized steel reinforcements in AAC mortars because the passivation process in these matrices occurs even in the absence of calcium, which is considered a fundamental element for galvanized steel passivation in common Portland cement-based materials
- during wet-dry cycles in a 3.5% NaCl solution, fly ash-based AAC ensure a higher protection to bare steel reinforcements compared to metakaolin-based AAC. Cementitious mortars protect bare steel reinforcements less than fly ash based AAC but better than metakaolin-based AAC. This is due to the higher total porosity of metakaolin-based matrix compared the other AAC matrices, which favours the ingress and thus the attack of chloride ions
- during wet-dry cycles in a 3.5% NaCl solution, galvanized steel reinforcements are strongly attacked in metakaolin-based AAC again due to the highest total porosity of metakaolin-based matrix

- for bare steel reinforcements, the higher alkalinity of the AACs matrix increases the minimum free chloride threshold necessary to induce the onset of corrosion in a chloride-rich environment compared to the cementitious matrix
- for galvanized steel reinforcements, the higher alkalinity of the fly ash based AAC matrix seems to decrease the minimum free chloride threshold necessary to induce the onset of corrosion in a chloride-rich environment compared to the cementitious matrix. However, pitting corrosion is not so penetrating to affect the Zn–Fe layer underneath pure zinc layer. Therefore, fly ash AAC are quite protective even for galvanized steel reinforcements.

2.2 Multifunctional Building Materials from Biomass Waste

Recent laws and directives are becoming stricter on energy consumption in buildings so more isolated and watertight structures are built to reduce the loss of heat. However, if adequate air changing is not guaranteed, the concentration of airborne pollutants and humidity in the indoor environment becomes a great problem. Reactive building materials offer an opportunity to provide indoor air cleaning with minimal energy use.

At this purpouse the STM group investigated the development of multifuncional building materials using as unconventional materials biomass and/or biomass wastes in order to also avoid wasting resources and raw materials supplied [22–24]. In particular, when the focus was on biomass wastes, the effect of using spruce sawdust shavings and biomass ashes as unconventional aggregates in lime-based mortar for indoor application has been investigated in terms of developed mechanical strength, permeability, capillary water absorption, moisture buffering ability and VOCs adsorption (Fig. 4) [40].

The effect of replacing sand volume with unconventional aggregates based on the different biomass wastes in lime-based mortars for indoor applications implies:

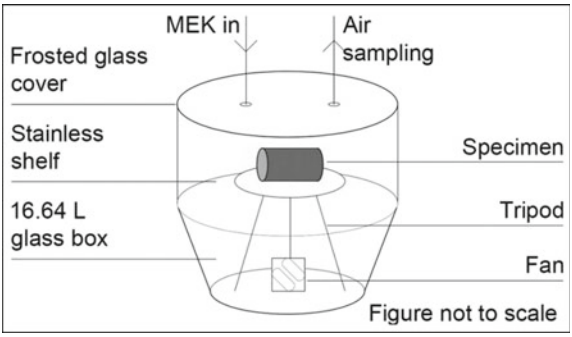

Fig. 4 Scheme of the test box for VOCs adsorption assesment

- A decrease of density of mortars: spruce saw dust and fly ash mortars can be classified as lightweight mortars
- A general decrease of compressive strength, but still acceptable for plastering/rendering applications. Instead, bottom biomass ashes increase the compressive strength of lime-based mortars of about 60%
- A general increase of capillary water absorption. However, bottom biomass ashes decrease the capillary water absorption of lime-based of about 50%, while the torrefaction process permits to 50% lower water absorption by capillarity action of mortars manufactured with spruce sawdust shavings
- An increase of water vapour permeability up to 50%
- An enhancement of indoor air quality in terms of up to three times higher MBV and up to 75% increased capacity to adsorb VOCs
- In this way, a better management of biomass waste and reduction of materials in landfill can also be achieved.

2.3 Smart Energy and Materials from Wastewater

During the last 50 years, the environmental policies and the social sensibility increased the attention to the pollutants types and concentrations in the treated wastewaters in order to obtain higher quality standard levels of the surface water.

The development of the technologies for wastewater during the time was fast and related to some specific objectives. For the nutrients reduction the traditional activated sludge treatment technique became the treatment of reference all over the world from 1930. From this technology still with full success, also several new and advanced processes based on the activated sludge principle were developed like membrane bioreactors, intermittent aeration units [33, 18, 19] and short cut via nitrite technologies. The biological unit in the time was optimized by increasing the possibility of completely reclaiming the existing structures in the full-scale plants, by introducing the feasibility of automatic control applications, by obtaining energy savings and by coupling the nutrients removals with the biological reduction of the sludge production [21, 44].

Phosphorus, essential element to life, represents the second nutrient in the wastewater with Nitrogen. Demand for rock phosphate is such that there is a global threat of phosphorus scarcity. In 2014, rock phosphate was added to the European commission list of critical raw materials. Scientific and technological options for Phosphorous removal and recovery from wastewater were already developed from 2000 years [1].

In the last 10 years, the WWTP have moved from the concept of waste treatment, to the concept of water reuse for beneficial purposes, such as agricultural and landscape irrigation, industrial processes, non-potable domestic use and groundwater replenishing [7]. On site energy recovery, particularly as biogas production, in WWTP is widely diffused as an alternative source of energy, for the recovery of thermal, electrical and mechanical energy, to be consumed either inside or outside the plant. In the

Fig. 5 Carbonera-Smartech 5-PHA and Struvite Recovery from anaerobic supernatants-years 2016 SMART-Plant Project (www.smart-plant.eu)—Coordinator Università Politecnica delle Marche; Referent Partner University of Verona

last years, two-step bioconversion comes into prominence as more value is derived to volatile fatty acid production before ending up to other end-products. Moreover, anaerobic processes offer much more than conventional wastewater treatment, recovering sustainable energy and valuable biochemical [20, 25].

Nutrient recovery and recycling takes an important role in wastewater valorisation. Recovered nutrients from the wastewater can be utilized as soil amendments or fertilizers for beneficial uses in agriculture. In particular, ammonia form is advantageous because it predominates in anaerobic reactor effluents and can be useful for fertigation purposes. Phosphorus recovery (i.e. in the form struvite or phosphorous salts) becomes essential for preventing eutrophication in the aquatic environment and for alleviating economic dependence on phosphate rocks.

The resources mentioned above are those most commonly recovered in WWTPs; in addition to them there are more innovative ones like cellulosic primary sludge [17] and polyhydroxyalkanoate.

This new approach is promoting and will recognize, probably for the next 50 years, the wastewater management as one of the main strategic economic sectors for resources valorisation and smart materials production in the effective innovative point of view of circular economy [37] (Fig. 5).

3 Closing the Loop for Construction Materials

Concrete is one of the most widely used materials in the world for manufacturing structural elements for building and infrastructures. Conventional concrete is not

considered an environmentally friendly material because of the use of non-renewable natural resources, such as sand and gravel, and its high embodied energy.

In most cases, these concrete elements are demolished at the end of their useful life, generating what is known as construction and demolition waste (CDW). Using selective demolition techniques, very pure concrete waste with a high potential for recycling can be obtained. For this, all non-mineral dry building materials, such as plasterboards, wood, metals, plastics, glass should be removed and separated before the demolition of concrete elements. All these extra materials can be recycled as well to produce eco-friendly plaster and mortars such as wood chips [14], waste glass [15], waste plastic particles [13], bricks.

The possibility of reusing concrete waste particles after suitable treatment in recycling plants has been widely studied with encouraging results. In particular, concerning structural concrete manufacture, several papers showed the suitability of reusing up to 30% coarse recycled aggregate particles for concrete strength classes up to 40 MPa [11, 16, 36]. Moreover, a correlation between elastic modulus and compressive strength of recycled-aggregate concrete (RAC) was found in (8), showing that 15% lower elastic modulus is achieved by using 30% recycled aggregates, while tensile strength is reduced by 10% if the same concrete strength class is achieved by replacing 30% virgin aggregates with recycled concrete particles [16].

In terms of drying shrinkage, particularly if finer coarse recycled-concrete aggregate is used, lower shrinkage strains are detected especially for earlier curing times. This last aspect, when considered together with a lower elastic modulus, predicts a lower tendency to crack in the RAC. Concerning time-dependent characteristics, creep behavior is more influenced by the presence of recycled aggregates than shrinkage, although its variations are rather limited compared to what occurs in traditional concrete [12, 16].

Even if 100% replacement of virgin aggregate is carried out by using particles coming from treatment of CDW, structural concrete can be prepared due to the positive effect on compressive strength achieved by adding fly ash or silica fume to the mixture as a fine aggregate replacement with the aid of an acrylic-based superplasticizer. In this way, an adequate strength class value (30 MPa), as required for a wide range of common structural uses, can be reached both through virgin aggregate concrete and recycled concrete aggregate with fly ash, by suitably decreasing water/cement with the aid of a superplasticizing admixture in order to maintain the same workability.

Moreover, if fly ash is added to RAC, the pore structure is improved, and particularly the volume of macro pores is reduced, causing benefits in terms of mechanical performances such as compressive, tensile and bond strengths. The addition of fly ash proved to be very effective in reducing carbonation and chloride ion penetration depths in concrete, even in RAC.

Finally, on the basis of the results obtained through cyclic loading tests of beam–column joints made of either ordinary or RAC concrete, evaluated by means of parameters such as cracking patterns, supplied and dissipated energy, ductility and design values, the joint made of RAC showed adequate structural behaviour.

The previous encouraging results were obtained by using the only coarse recycled aggregate fraction, while, many authors found that in RAC the fine recycled aggregate fraction is particularly detrimental to both mechanical performances and durability of concrete. In addition, the presence in the recycled aggregate of materials other than concrete (that are mainly crushed bricks and tiles) reduces concrete performance due to their higher porosity and consequently their lower density and higher water absorption. For this reason the more recent approach is to recycle for concrete production only the coarse recycled fraction.

In short, the use of materials coming from C&D waste recycling instead of sand for the production of bedding mortars proved to be profitable not only for the obvious environmental advantages but also in terms of improvement of the mortar–brick interface, which is generally recognized as the weak chain link of the masonry assemblage. A further opportunity can be the reuse of the very fine fraction (Fig. 6) coming from recycling of CDW as filler for concrete, especially self-compacting concrete mixtures. Results obtained on the basis of the rheological tests on cement pastes showed that rubble powder proved to be more promising with respect to limestone powder and fly ash as mineral addition for self-compacting concrete. This indication was confirmed by the results obtained for fresh concrete: in fact, in the case of fly ash and ground limestone as mineral addition, a certain flow-segregation could be recorded on fresh mixtures. This was confirmed by the ultrasonic pulse velocity measurements related to hardened concrete specimens with different segregation.

In conclusion, an optimization of the self-compacting concrete mixture seems to be achievable by the simultaneous use of rubble powder and coarse recycled aggregate with improved fresh concrete performance and unchanged concrete mechanical strength.

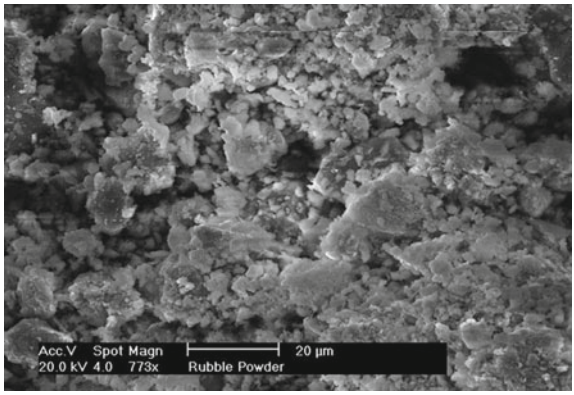

Fig. 6 SEM image of CDW powder at magnification of about 800×

4 A Tangible Vision: Beyond the Recycling Toward the Circular Economy

In recent years, the environmental and societal issues in the manufacturing, use, disposal and recycling of construction materials have been seriously considered. The demand for a more sustainable way of building and recovering the existing building stock is no longer a matter of personal choice, and actions are needed to increase knowledge and develop tools and regulations that enable maximum recovery of useful materials. This requires not only closing loops by reusing 'waste' and resources, but also slowing material loops by developing long lasting reusable products. In this way, the concept of Circular Economy (CE) can be effectively applied to the building sector, where innovation diffuses rather slowly, and where the focus has been on issues like energy use and energy efficiency more than recycling or reuse of materials at the end of life of buildings.

In this scenario, the research activities carried out by the group from the beginning of its life to date permit to laid solid foundations for creating a tangible vision concerning the future for next 50 years.

A strong link with the territory is consolidated and a wide network which ensures the global cross-fertilization is already created: now the exchange of ideas, innovation, research results, and researches themselves is a matter of fact and it is the key parameter which allows the cooperation and collaboration between academia and industry, locally and around the world.

The multidisciplinarity actually includes not only professors, but it also embraces students with different aptitudes and educations coming from different faculties who decide to approach the interaction between materials science and environment (Fig. 7).

In view of the multidisciplinarity and the network built by researchers, they are going to be increasingly included not only in the industrial context but also in the legislative one: an updated framework based on the needs of all stakeholders is

Fig. 7 New style of communication: from the group photo to the group selfie

the result of the group's research activity. The developed materials are not only sustainable but they also go beyond the simple concept of recycling:

- materials are designed to avoid the generation of waste and end-of-life products
- construction and demolition wastes are no longer treated as a minimum percentage, but they contribute to design new materials with added value
- new products are manufactured by using wastes/by-products originated from human activities and renewable natural sources to obtain smart energy and low CO_2 binders.

This perspective transforms wastes to secondary raw materials that are employed with a mindful design and used in suitable quantities, so as to reduce the impact of building materials.

Novel materials are designed with a view of multifunctionality to guarantee users' needs in a single solution. Newly developed materials are no more "passive" or "inert" with the surrounding environment, they are smart and self-sensing: they can be continually monitored in order to facilitate punctual interventions and guarantee not only the durability of structures, but also the health and safety of people that are in contact with them to live, work and play.

In this way initiatives, ideas as well as approaches are jointly related to fabricate more "circular buildings". The material intrinsic value is maintained and recovered as much as possible: today's products are resources for tomorrow.

Acknowledgements This work can not account of the most part of the scientific work of the people that in this 50 years have contributed to the activities of the research group. We have inevitably cut plenty of topics, not at all of minor interest or impact, but only because not easy ascribable under a homogeneous framework.

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Sustainable Engineering for Resilient Built and Natural Environments

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Abstract We discuss the research that is being carried out at the Department of Civil and Building Engineering and Architecture (*Dipartimento di Ingegneria Civile, Edile e Architettura, DICEA*) of the *Università Politecnica delle Marche (UNIVPM).* Over the years the DICEA has steadily focused its attention on resilient environments and buildings, making a growing know-how and skill available to the local and broad communities. Pivotal to this have been dedicated projects and funds, like the UNIVPM strategic projects and the MIUR *Dipartimenti di Eccellenza* award. In conjunction with the four companion papers, produced by researchers of the four divisions of DICEA, we illustrate the DICEA's trajectory in the analysis of sustainable engineering for resilient built and natural environments.

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1 The Research Experience at Department of Civil and Building Engineering and Architecture

The Department of Civil and Building Engineering and Architecture (*Dipartimento di Ingegneria Civile, Edile e Architettura, DICEA*) is the reference Department of UNIVPM for the disciplines of Civil Engineering and Architecture. It is made of 4 divisions, 9 laboratories and 2 research centers.

1.1 The Architecture Division

The Architecture Division includes the disciplines of Architectural Analysis, Design and Restoration, operating in the field of Digital Cultural Heritage (DCH), History of Architecture and Geomatics, as well as Architectural and Urban Design. Researches deal with recycle and reuse of historical and modern building and spaces, through digitization and programmatic and sustainable upgrade, experimenting new models towards smart cities, heritage and buildings. Robust skills in DCH, history of architecture [2], geomatics were established through survey campaigns and studies about tangible and architectural heritage, with particular regard to the improvement of relevant tools for sustainable territorial development, based on knowledge, exploitation and regeneration of Cultural Heritage (CH) as a whole. The team developed researches in 3D acquisition (point cloud and image processing), modelling and semantic segmentation, Digital Libraries (DL) and Heritage Building Information Modeling (HBIM) [25, 40], Virtual Reality (VR) and Augmented Reality (AR) solution development and so on. Significant projects (Cultural evolved district, DCE, Marche region) allowed to validate methods in order to the stimulate the potential of DCH for creative industries, developing the territorial identity and promoting cultural tourism [20]. The team is also well connected with stakeholders (local/national authorities): the CIVITAS project shows a collaboration with the Galleria Nazionale delle Marche, the main museum of the Region. In the EU framework, the Division partner of the REMEMBER project (Interreg IT-HR) and of European COST Action, CYBERPARKS - Fostering knowledge about the relationship between Information and Communication Technologies and Public Spaces, dealing with strategies to improve CH use and attractiveness [31, 36]. Very high-level collaborations in landscape management and precision farming field are moving on [37].

From an historic point of view [3], research lines in the light of urban renewal and resilience were carried out in Inland areas damaged by earthquakes (Amandola historic center, Marche region). Other research areas are: urban and territorial analyses [9], strategic visions and scenarios for the enhancement of territorial areas [8], enhancement of historical contexts both for tourists and local communities, regional branding. Furthermore, the Division offers a transversal experience in architecture, urban planning and landscaping, such as contextual analysis, strategies for the enhancement of the territory of its historical contexts [4], architectural and

urban regeneration both for the reconstruction of local communities and for development for tourism purposes. The team members developed different experiences as heads of scientific research units funded in the areas of enhancement of physical and environmental heritage both in Italy and abroad. Particularly significant are: the regeneration of the port areas along the Paranà river and the 5-year trans-disciplinary project "Regiobranding, Branding of urban-rural regions through the characteristics of the cultural landscape" [24].

1.2 The Construction Division

The Construction Division is made up of two main research groups – the Architectural Engineering group (AE) and the Design and Construction Management group (DCM) – and also includes research activities in the field of legal (collective and individual) work, occupational safety, liability and professional deontology, in the construction sector [47].

The AE group has a well-known expertise in researches dealing with the assessment, optimization and development of building envelope material and components, with improved hygrothermal, energy [22], mechanical [1], cost and durability performances, for the application in new or existing and historical buildings [33]. Results led to patents and collaborations with industrial partners. Recently, the AE group started working on the development of advanced assessment tools, especially focused on life-cycle performances and on occupants' behavior and needs [23]. This is due to the growing need for the building designer to choose among several solutions and construction technologies, having to assess their performance according to multiple, somehow conflicting, points of view. Furthermore, a recent research interest for the group deals with the relation between human behavior and built environment, leading to a "behavioral design" approach for increasing people's safety in architectural spaces [5] and improving building and components performance, e.g. from an energy point of view. The rationale behind these researches is related to the need of making future buildings and components able to more and more adapt and respond to the users' needs in terms of comfort and safety, by also considering economic and environmental issues in the building life-cycle.

The DCM research concerns the development of new digital technologies to implement lean management principles in construction. The research encompasses the overall field of Automation in Construction, including Building Information Modelling (BIM), field automation, and building intelligence. The construction management group has a long tradition of research on these themes. Field automation for real-time construction management has been largely investigated. Advanced systems for the real-time tracking of workers' and equipment for real-time safety assessment and construction progress estimation have been developed [15, 34, 35]. Facility management research concerns the implementation of intelligent technologies for multicriteria probabilistic assessment of KPIs in large real estate management surveys [16] and the application of mixed reality technologies to onsite operation support.

Building intelligence has also been largely investigated, through large-scale projects (the SEAM4US FP7 EU Project) regarding the intelligent energy control of a metro station in Barcelona [46], stochastic modelling of occupants, and reduced order modelling methodologies for robust energy consumption forecasting [39].

1.3 The Infrastructure Division

The Infrastructure Division does research for the design and management of hydraulic infrastructures and for the analysis of environmental impact and risk (Fluid Mechanics, Hydraulics) and on the themes of the transportation infrastructures with attention to sustainability environmental protection of road and airport pavement structures.

The Transportation Infrastructures group holds a leading position in the research activities related to sustainable and innovative materials and systems for pavement construction and rehabilitation. It has a long tradition of research on the mechanical behaviour of pavement interlayer systems, which led to the development of a standard testing equipment for measuring the interlayer shear properties of bituminous pavements. Pavement interlayer reinforcement has been largely investigated leading to substantial improvement in pavement grids and composite technologies. The group is also well recognized in the scientific community for its cutting-edge research activity related to low-energy and sustainable pavements. The main research topics are related to asphalt recycling, warm mixes and cold paving technologies, as well as mechanical characterization of bituminous materials. The main research topics are related to the three-dimensional viscoelastic behaviour [28], the fatigue and healing phenomena [12]. The Transportation Infrastructures group has long-lasting scientific collaborations and students exchange projects with several international research institutions and Universities. The members of the group currently hold leading position in international research groups within the RILEM organization [11] and participate in large research projects focusing on pavement recycling (the CRABforOERE project) and on environmental sustainability of marine and air transport services (the ADRIGREEN project).

Much of the research by the Hydraulics group of the Infrastructure Division focuses on coastal, riverine and urban flooding and climate changes. With the specific purpose to investigate coastal flooding, the wave runup and inundation over sandy beaches, typical of the Italian coasts, have been studied using a Nonlinear Shallow Water Equations (NSWE) approach [43]. Further, to better understand the main causes of coastal inundation, the hydrodynamics induced by traditional rubble-mound breakwaters and innovative coastal protection structures have been inspected [38]. Riverine and urban floods have been analyzed by means of field experiments and numerical tests. Specifically, summertime and wintertime field campaigns have been carried out at the Misa River estuary (Senigallia, Marche Region), to investigate the seasonal variability of the interplay between sea and river forcing actions at an estuary characterized by cohesive sediments. The dynamics evolving during storms lead to high-flow conditions in the river, which potentially lead to sediment

removal off to sea and floods in the surrounding of the river mouth, including the urban area of Senigallia [10]. Such urban flooding has occurred in the recent years, causing large damages and deaths. Fundamental to the understanding of any type of floods is the analysis of the rainfall. That occurred in the Marche Region, has been inspected to find significant trends in the observed data, even in the perspective of climatic changes. The maximum annual rainfalls have been analyzed, using time-series longer than 50-years [44].

1.4 The Structures Division

The Structures Division is well-known for the long-lasting and solid research activity in several fields of structural engineering, characterized by the integration of a theoretical approach to engineering problems with a more experimental and application-oriented point of view. The main research topics are: mechanics of materials, structural modelling of buildings, computational mechanics, dynamics of structures, vulnerability and seismic assessment of structures and infrastructures, dynamic interaction between soil and foundation-structure, reliability of structures, analysis and control of bridges, innovative seismic protection techniques, dynamic identification and monitoring of structures. Research on mechanics of materials and structures concerns the theoretical aspect of electromechanical interactions in materials. Among the various topics are the mechanics of piezoelectric and ferroelectrics, the photoelasticity of anisotropic crystals and the propagation of electric charge carriers in scintillators [21]. A second main research topic regards multi-layer complex structures and laminates, analyzing the non-trivial interface conditions between the constituents of the composite [42]. The research concerned with the dynamics of structures investigates the nonlinear dynamics of cables, beams and composites loaded by time-dependent excitations and laid on spring beds and with different boundary conditions. Dynamical integrity has been largely studied as well, by determining the properties and dimensions of basins of attraction of structural systems. In the study of the seismic hazard of masonry structures, the so-called Non-smooth Contact Dynamics Method has been used, taking into account sliding and impacts between blocks [32]. The dynamics structural health monitoring has also been deeply investigated [30]. Regarding bridges, advanced models for box- and twin-girder steel-concrete composite continuous decks have been developed accounting for different features, such as, for example, the connection deformability [26]. Models have been used to analyze composite girders with internal and external prestressing systems and to investigate construction aspects such as fractionated casting of the slab. Moreover, the research on bridges has been focused on the soil-structure interaction effects [17], on seismic isolation systems and on structural monitoring techniques, under static and dynamic loads. Regarding buildings, the research activities have included the seismic protection through dissipative internal or external systems; in addition to advanced numerical simulations, experimental investigation on structural elements, mock-up and real structures have been performed [27] and tests for the dynamic

identification and for continuous structural monitoring have performed. Experimental investigations have been also carried out on historic and modern masonry walls and on reinforced concrete elements strengthened with carbon FRP [13, 14].

2 The 2017 Departments of Excellence Award Experience

In 2017 the Italian Minister of Instruction, University and Research (MIUR) opened a call named "Dipartimenti di Eccellenza" (Departments of Excellence) aimed at awarding the best 180 Departments in the Italian Universities (according to the Law 232/2016). The call was managed in two steps. In the first one the best Departments were selected based on the results of the previous Italian Departments assessment done by the National authority (ANVUR). After this first stage the DICEA ranked first with the score of 100 point out of 100. Thus, the Department was admitted to the second stage, where the submission of a specific 5-years project for the Department's development was required, including objectives, strategies and implementation plans. The deadline was 17 October 2017. The Department's council established a dedicated committee to define the research topics and to prepare the application. It was realized that the development of a resilient built and natural environment through a sustainable engineering effort was, from the one side, a topic of major social interest and, from the other side, a topic where the various Department's divisions would have been able to provide innovative, interdisciplinary and coordinated research advances. The project was submitted, and DICEA was one of the 14 selected and awarded in the field of Civil Engineering and Architecture.

The research approach to sustainable engineering for resilient environments addresses the fundamental issues of resilience and sustainability by developing a coordinated methodological perspective among the various research groups and a technological framework to tackle them in a combined and optimized way. Three research lines, encompassing extremely wide fields of the civil and building engineering and architecture research, have been identified as the driving perspectives of the future research at DICEA:

- Environmental Resilience and Risk Mitigation, encompassing resilient infrastructures, environment protection and safety-oriented structural design.
- Advanced digital technologies for smart facilities, life cycle engineering, lean design and construction management.
- Digital cultural heritage for landscape protection and fruition.

3 Environmental Resilience and Risk Mitigation

This section briefly introduces the four companion papers, which detail further the research themes outlined in the previous section, so as to provide a self-contained overview of the Department research. The first section introduces the themes of

the digital revolution in construction and the second discusses aspects of cultural heritage preservation. The last two sections describe papers addressing the research in the structure and infrastructure domains.

3.1 Cultural Heritage and Landscape: Digitization, Analysis and Design Aiming at a Resilient Future

The research activities about cultural and built heritage at various scales, from architecture to landscape, highlight how innovative analysis and design approaches can challenge the current methods and pursue the main scope of increasing heritage resilience.

Major results and findings in several disciplines, such as history of architecture, geomatics, drawing and survey, restoration, regeneration and design, are discussed throughout a set of case studies. These allowed to develop tools to perform rapid surveys and multilevel readings (stylistic, structural, historical, behavioral, etc.) as well as robust procedures for interventions and recycle of built heritage. The main idea is to highlight overlapping and consonances of different approaches although each discipline intends in a specific way the heritage: ranging from heritage as motor of development, as digital cultural innovation, as identity, as experienced landscape to heritage as conservation.

The Cultural and Built Heritage collection, conservation and access in novel, accessible and attractive ways demand for digitizing museums and archaeological/historical sites, as well as for designing methodologies to represent, manage and exploit cultural heritage data at different levels, ranging from 3D/4D models to domain specific e.g., architectural, historical, etc. The generation of virtual "facsimiles" of artworks, monuments and architectures can unify their scattered elements, enables public access to inaccessible places and visitors to interact with perishable objects, promotes the preservation of fragile sites and simulates damaged or lost objects. The availability of semantically enriched data enables smart applications for fruition, preservation and study of DCH collections. This development has the potential both to collect and disseminate the cultural heritage in an effective and low-cost mode and to implement a key strategy to increase cross-curricular skills. In particular, the sustainable valorization and resilient management of CH require effective participatory (i.e. multi-level and multi-stakeholder) governance and enhanced cross-sectoral cooperation.

The relationships between history and project, between project and city and between heritage and contemporaneity are the centers of the research action, dedicated to the regeneration of the existing heritage. Actions able to develop methods of intervention in the relationship between heritage and recent context, the result of plural stratifications occurred in an extended time that includes more stories, a time far away to cure, but also a close time, that modernity that produced a large heritage to be recovered. The idea of conservation should therefore give way to more flexible

readings and uses where "conservation and modernity are not opposites" (Koolhaas) and where creativity and design are for the recovery of heritage, an instrument of thought and invention architectural. This calls for an idea of urban regeneration specific, anchored to places, and oriented towards the construction of socio-cultural networks to trigger a process of transformation involving all actors and bringing design ideas closer to needs.

Finally, the studies try to extend the validated approaches to similar cases in the heritage field. The main research activities, indeed, entail the definition of the fundamental paradigms of resilience for heritage and landscape, against the backdrop of the contemporary techno-cultural revolution.

3.2 Rethinking Buildings Design, Construction and Management Through Sustainable Technologies and Digitization

A technological development not threatening natural and human life is one of the core concepts of sustainability. In the construction sector, which is worldwide responsible of a huge consumption of energy and natural resources, thus strongly impacting on climate change, sustainability means the need of a prompt transition towards eco-friendly, smart and resilient buildings. However, despite the current Fourth Industrial Revolution, where many sectors have been able to transform themselves improving productivity while lowering the impact, construction is still suffering from several intrinsic weaknesses. The research in the Construction Division investigates new approaches based on technology innovation and digitalization, aiming to develop and optimise innovative, durable and sustainable solutions for buildings and construction processes and management. This outlines the emerging challenges and future directions of the research at the DICEA of the UNIVPM in this long-established sector. Several research trends are identified for a more sustainable and resilient "Construction 4.0". Firstly, the development of building technologies aims to integrate, in a logic of constructive simplification, multiple aspects and functions (e.g. energy efficiency, seismic resistance and high durability), reducing environmental impacts, costs and construction time. It also includes the development of "cognitive" technologies, able to adapt and respond to the users' needs, involving several performance domains (e.g. energy, comfort, safety, durability). Then, future research also focuses on the development of effective building design and management tools, able to address in an efficient way all the complex set of design, performance, environmental and economic issues. Finally, future study trend will also involve the development of a real-time construction management approach, supported by pervasive sensing and on-site site intelligence, and the development of digitization of design and construction processes, in order to optimize these processes.

3.3 Research and Engineering for Resilient Infrastructures and Environment Protection

The Transportation Infrastructures group has been involved in research activities focused on the development of sustainable materials and systems for resilient transportation infrastructures, and organized the interlaboratory experiment "Advanced Interface Testing of Geogrids in Asphalt Pavements", promoted by the RILEM, to verify the effectiveness of pavement grid in improving the repeated loading resistance and for preventing or delaying reflective cracking. The *pavement reinforcement* by grid installation at the interface of structural layers has been studied through both full-scale applications and laboratory investigations. Within *cold recycling,* the group investigated the short- and long-term mechanical behaviour of the cold-recycled mixtures (CRM). Modelling has been carried out to analyse the evolutive behaviour of CRM and the combined effects of bituminous and cementitious binders on their mechanical response. Laboratory characterization was then related to performance monitoring of a full-scale test pavement to optimize the prediction of the stiffness properties of CRM layers over time [29]. Recent research efforts focused on the innovative technology of *Warm Mix Asphalt (WMA)*, aimed at significantly reducing the production temperature of bituminous mixtures without compromising their mechanical properties. The potential benefits deriving from the combination of WMA and recycling techniques have been also investigated [45]. Further important research topics have concerned *photocatalytic techniques* to de-pollute atmosphere from traffic emissions [7] and the *use of waste materials* (e.g. C&D material, rubber from reclaimed tires) for road applications.

Future research activities of the Transportation Infrastructures group will focus on the development of technical solutions for resilient transportation infrastructures according to environmental and economical sustainability. The acquisition of new testing equipment will increase the potential of the laboratory aimed at the advanced rheological characterization of recycled and low energy materials (through cold and warm technology) and the development of innovative solution for resilient pavements (e.g. reinforced pavements, low noise pavement and self-healing materials).

The group of Hydraulics focuses on themes related to both resilient infrastructures and environment protection. The riverine and estuarine environments have been studied through a series of field campaigns, funded by international institutions (e.g., the Office of Naval Research—Global), to inspect the interplay between river and sea forcing actions in micro-tidal environments of different kinds, like the Misa River estuary (Senigallia, Italy), typical of the Mediterranean area [10]. Such studies underline that riverine and sea forcing significantly affect the mixing and transport of nutrients and pollutants from the river to the sea. Furthermore, inspired by the Misa River flood recently occurred in Senigallia (Marche Region, Italy), numerical modelling has been undertaken with the aim to both characterize the hydrodynamics during the urban flood and analyze the consequent pedestrians' evacuation [6]. With reference to the coastal environment, studies of both numerical and laboratory nature have been carried out. Many of them where related to the development and application of an

in-house solver based on the Nonlinear Shallow Water Equations. This has been used for multiple purposes, including the analysis of: the wave propagation in protected coastal areas and following vorticity generation and propagation due to low-crested structures, the seabed erosion in either free-from-obstacle or protected beaches. Another important topic of research is the prediction and analysis of snow avalanches impacting into lakes, with the following generation of impulse waves [48]. Such phenomenon led to many important problems in mountainous areas, hence the prediction of the generated wave may provide important information for both risk assessment, design of suitable warning systems, protective civil engineering works, etc.

Active research is ongoing on the following topics:

1. modelling of river floods, turbulent flow structures, nearbed sediment transport, river bed morphology evolution;
2. prediction of the coastal inundation due to sea storms on real beaches; modelling of fluid-structure interactions and flows of interest for biological applications.

3.4 An Overview of the Structural Safety-Oriented Research in the Region Marche Seismic Area

In the last decades, Italy's central regions, including Marche, have been affected by several earthquakes, causing the partial or total destruction of masonry and reinforced concrete (RC) buildings. The seismic events have severely damaged ordinary constructions, structures of strategical importance, and historical and monumental buildings (e.g., churches, monasteries, towers). This has caused dramatic consequences within the urban fabric and inhabitant communities, confirming once more the high seismic vulnerability of the Italian existing RC and masonry constructions and the need of enhancing the mean safety level of the population. The importance of the prevention during these calamitous events has highlighted the urge of studying the dynamical behavior of structures in order to better understand their response under seismic actions, assess precise criteria of vulnerability and develop suitable protection measures against earthquakes, improving the structural capacity. The dynamic analysis and the seismic structural safety can be considered two of the most important research topics of the Structural Division. The researches can be gathered into the four main areas.

1. *New methods of modeling the dynamic behavior of structures*. The adequate modeling of the dynamic behavior of RC and masonry structures is needed for the assessment of safety and damage levels, the maintenance and the structural upgrading possibility. The researches have focused on the study of the global response of RC and regular and non-regular masonry buildings by means of dynamical linear and nonlinear analyses using bar-frame models with lumped or diffused plasticity. To investigate the mechanical behavior of structures, such as

masonry building, discrete element techniques have been developed in order to have a better knowledge of the collapse mechanisms [18].

2. *Vulnerability assessment of existing structures*. The evaluation of the seismic vulnerability of existing buildings has a key role in determining and reducing the impact of an earthquake. With reference to old RC and industrial precast structures, the research activities have focused on the experimental identification of some typological aspects that often characterize these buildings and the analysis of their behavior through nonlinear models. Masonry buildings, lacking an adequate lateral resistance and ductility, have been analyzed by means of sophisticated methods in order to asses or predict the seismic behavior and/or the expected damage [19].
3. *Experimental studies and advanced techniques of seismic retrofitting*. The researches have focused on the development of innovative dissipative braces (viscous, visco-elastic, elasto-plastic dissipative devices), in order to enhance the seismic structural performance, and on advanced techniques of strengthening through the use of near surface mounted fiber reinforced polymers (FRPs) [13].
4. *New prospects for safety*. In this field, several research activities are in progress aimed at studying efficient structural health monitoring systems, providing information about the modal parameters evolution of structures and infrastructures, which are often used for the calibration of structural models for the seismic vulnerability assessment or the retrofit design [30, 41]. Moreover, the researches have focused on the seismic isolation by means of High Damping Natural Rubber bearings, which represents a recognized technology able to protect efficiently structural and non-structural components and equipment.

4 Conclusions

We have introduced the research that is being carried out at the *Dipartimento di Ingegneria Civile, Edile e Architettura* of the *Università Politecnica delle Marche* towards the achievement of environments and buildings resilient to natural disasters, like earthquakes and floods, and the development of methods and techniques for a sustainable engineering as a fundamental tool for the circular economy. We have referenced the past research that has been carried out over the years at DICEA, steadily focused on resilient environments and buildings, and the pivotal experience of the strategic projects award gained from the MIUR *Dipartimenti d'Eccellenza* competition. We have then illustrated the DICEA's current trajectory in the analysis of sustainable engineering for resilient built and natural environments. Finally, we have briefly introduced the four companion papers produced by researchers of the four divisions of DICEA. A thorough bibliography of the Department research is provided.

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Research and Engineering for Resilient Infrastructures and Environment Protection

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Abstract We discuss the contribution of the research groups that work at UNIVPM in the field of infrastructure engineering to the design of resilient hydraulic and transportation infrastructures and related solutions for the protection of the environment. After recalling the long history of research and engineering intervention of the

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groups of Hydraulics and Transportation Infrastructures of UNIVPM, we show how the activities of such groups are becoming of increasing importance in response to the growing request of innovative solutions for resilient infrastructures (e.g. coastal protection and maritime structures, road and airport pavements) and environment protection (e.g. coastal and river flood, air pollution, waste recycling and materials reuse). Such activities have been recently boosted by the resources made available to the two groups through the "Dipartimenti di Eccellenza" award, which largely focuses on the issue of engineering for resilient built and natural environments. A projection in the future of the activities of above is also proposed.

1 Introduction

The groups of Hydraulics and Transportation Infrastructures of UNIVPM are actively involved in the fields of civil and environmental engineering research to promote innovation and knowledge, through experimental and theoretical activities, as well as technology transfer. Since the foundation of UNIVPM, the main objectives of both research groups have always been focused on the improvement of the life quality by developing advanced solutions for resilient infrastructures and environment protection.

It is well known that the preservation of the environmental heritage for future generations is a challenging task that must be adequately tackled in order to reduce environmental impacts without compromising modern human needs.

For this reason more resilient and sustainable solutions are needed to prevent and mitigate the risk due to natural events and anthropic activities, whose effects are more and more often dramatic for the population.

In this context, the aims of the activities described in this paper are to provide a summary of the main research goals achieved by the groups of Hydraulics and Transportation Infrastructures of UNIVPM mainly focused on: (1) the coastal protection, riverine hydraulics and water management; (2) resilient solutions for pavements, recycling and sustainable materials.

2 Hydraulics

The Hydraulics group of UNIVPM mainly focuses on the study of the mechanisms occurring in the coastal region, like those forced by wave breaking over beaches or induced by engineered defense structures. More recent is the research on the hydraulic processes that characterize the estuarine and riverine regions as well as on the management of surface waters and groundwaters.

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2.1 Maritime Structures and Coastal Protection Systems

The stability of sandy beaches is fundamental for ecological, touristic, and economical reasons. Coastal protection structures are realized to contrast the wave-induced erosion. The research of coastal defense solutions, alternative to the traditional detached breakwaters, aims at testing structures that can dissipate the wave energy by mechanisms different from the wave-breaking-induced near-surface turbulence, responsible of the formation of inshore water superelevation. The working features of alternative coastal protection systems able to dissipate the energy of incoming waves with a minimal change in water superelevations has been widely studied by the group of Hydraulics by means of experimental campaigns carried out at the wave flume for maritime physical models with reduced scale hosted at the "Laboratorio di Idraulica e Costruzioni Marittime" of DICEA. The flume is 50 m long, 1 m wide and 1.3 m high, in which can be reproduced unidirectional regular or random waves. The wave motion is forced by a piston-type wavemaker with active wave absorption. The side walls of the flume are glassed for the central 36 m and enable one to carry out optical measurements. The analysis on the performance of an innovative structure made of blades that induces wave damping by the action of large-scale bottom roughness has been performed by [12] (Fig. 1a). Similar wave height reductions were achieved for both vertical and inclined blades: their efficiency being slightly superior to that of traditional submerged rubble-mound breakwaters of the same cross-shore extension. For the incident waves examined, very low mean water elevations were observed inshore of the structures, with the inclined blades producing the smallest values. These results suggest that the structures analyzed can represent an alternative to submerged rubble-mound breakwaters from a hydrodynamic point of view to protect coastlines prone to erosion with minimal risk of dangerous rip currents. In [15], a comparative analysis on the wave energy dissipation efficiency of both traditional and innovative coastal protection devices has been reported, based on the wave transmitted behind the devices. Even if submerged breakwaters were found to be the most efficient

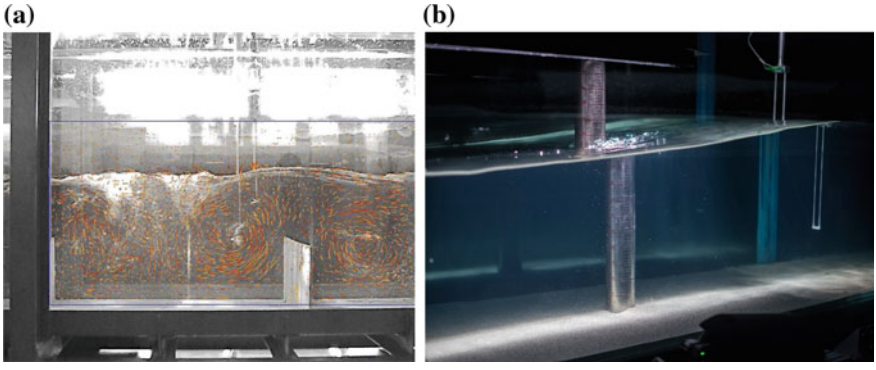

Fig. 1 Physical models of: **a** submerged blades; **b** vertical pile

wave dissipators, especially for large waves, comparable efficiencies are provided by different coastal protection devices if the flow is forced by moderate waves.

The analysis of the hydrodynamics around maritime structures is also an important topic for the protection and the management of hydraulic infrastructures. An experimental analysis of the hydro and morphodynamics induced by a slender vertical pile, fitted into a sandy seabed and forced by nonlinear waves in finite waters has been performed by [5] (Fig. 1b). The knowledge of the scour process around a structure under wave action is very important because it is one of the main factors able to compromise the structure stability. The scour depth at the pile and the seabed morphology around it were measured and analyzed for both regular and random waves. The effect of the water depth variation due to the sea level rise on the scour depth was also analyzed in order to estimate the resilience of such maritime structures. Moreover, the performance of scour protection systems has been experimentally studied. The evaluation of the velocity field around the pile and the wave force on it are currently being analyzed.

The available knowledge in the maritime engineering has been used for a number of applied studies on coastal and harbor engineering, detailed in consulting reports, for both public administrations and private companies. Among them, remarkable are, as an example, the studies for the overall coastal defense of the Regione Marche, the numerous and important studies about the expansion and development of the Port of Ancona, the studies of coastal defense for some littoral beaches, like those of Porto Recanati and Porto Sant'Elpidio, and the studies on the optimal configuration of some harbours, like those of Civitanova Marche and Numana.

2.2 Riverine, Estuarine and Nearshore Hydro-Moprhodynamics

Recently the Hydraulics group has undertaken a new research, funded through the Estuarine Cohesive Sediments (EsCoSed) project by ONR-Global, on the interplay between river and sea forcing actions in estuaries characterized by cohesive sediments. To this aim, a summertime (September 2013) and a wintertime (January 2014) field campaigns were carried out at the estuary of the Misa River (Senigallia, Marche Region, Italy; see left panel of Fig. 2). The Misa River, representative of many rivers discharging into the Western Adriatic Sea, is highly engineered and characterized by a micro-tidal inlet, which provides a controlled environment useful to properly investigate the seasonality of the involved processes and the interplay among the main forcing actions, i.e. sea/swell, tide, river discharge.

Like for other locations worldwide, low-flow river conditions characterize the summer periods, this providing flocculation and floc deposition within the final reach of the river, while the wintertime is typically characterized by high-flow discharges, river-bed erosion and floc deposition off the estuary [2].

Further differences between wintertime and summertime dynamics depend on both differences in regional precipitation and forcing conditions. These are mainly

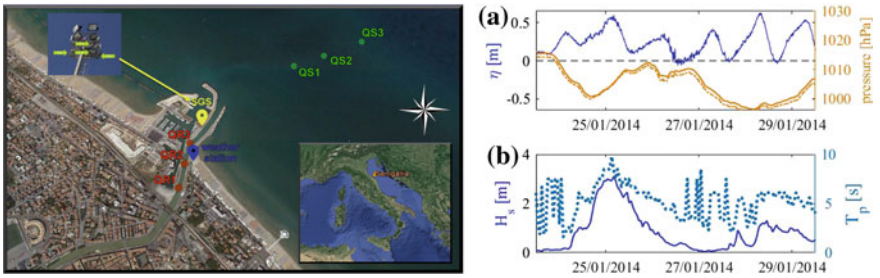

Fig. 2 Left: location of the EsCoSed-project equipment, insets of Italy map and SGS station. Right: **a** measured atmospheric pressure and storm surge; **b** measured wave height and period

driven by duration and intensity of the prevailing winds, these frequently changing direction in summer and keeping an almost constant direction for long periods in winter, thus generating major sea storms (see results in Fig. 2a, b).

The hydrodynamic conditions in the final river reach and estuary force sediment deposition in summertime, and sediment erosion and export in wintertime due to large flood events. Further, the storm-wave-induced mud transport leads to sediment deposition just off the river mouth and in the nearby beach. Such seasonal cyclic pattern of erosion and deposition has been confirmed by bathymetric surveys and is being monitored through the four videocameras of the SGS station located within the harbor.

Another issue analyzed is the medium-term evolution of the submerged bars in the nearshore close to the Misa river mouth. The main aim is to investigate the rate of protection of a free beach and its self-protection skill during highly energetic conditions (like storms) rather than calm conditions.

Problems related to the sediment transport and erosional problems in the nearshore region, which are strictly connected to coastal protection (e.g., use of defense structures) and coastal adaptation to sea storms and consequent inundation, have also been tackled by exploiting the potentials of numerical modeling. This activity produced numerical simulations on the coastal dynamics by exploiting the solution of the Nonlinear Shallow Water Equations and the Exner equation [16].

The coastal inundation has also been analyzed by means of numerical simulations aimed at evaluating the wave runup over a sandy beach. Different simulations have been carried out to study the effect of the beach geometry on the coastal inundation, the suitability of literature formulations for the runup prediction and the adequacy of using an equilibrium beach profile for the coastal flooding [17].

River hydraulics issues, concerning the flood risk and its mitigation, have been recently addressed in scientific consulting studies agreed with public administrations. The hydraulic risk in the mountain areas of the Marche Region and in the low valley of the Tronto River (Southern Marche Region) has been evaluated by means of both hydrological and hydraulic models, in order to evaluate the extension of the flooding area during events with critical return period.

2.3 Water Management

Studies on water management are focused on groundwater in porous media and water supply networks. These topics are crucial for the protection of water resources from the environmental pollution and for their sustainable use by humans.

Flow and solute transport in natural formations are related to groundwater utilization and the remediation of contaminated sites. These complex processes can be analysed by numerical solutions based on the Stochastic Finite Element Method (SFEM) coupled with a Lagrangian approach. Numerical models can support investigations for practical applications, with scenarios of considerable complexity. The medium inhomogeneity stemming from the combined effect of boundary conditions and a linear trend in the mean hydraulic conductivity has been examined for 2-D fields by considering a pollutant source of different dimensions and the analysis permits to define the nonergodic transport in bounded domains [6]. The discrepancy observed between theorical infinite and limited domains has been explained by the impact of the boundary conditions, which make head moments unsteady and asymmetric.

The protection of coastal aquifers from the Saltwater Intrusion (SWI) is critical for communities living in many coastal regions and in small islands, where the amount of freshwater available for human consumption or irrigation purposes depends on the equilibrium between the natural groundwater recharge from rainfall and the inland contribute from the sea. As this natural fluctuation may be exacerbated by climate changes or overexploitation of fresh groundwater, knowledge of the SWI is the main challenge for present day and future water supply engineers and managers. The definition of the interface between saltwater and freshwater in costal aquifers has been analyzed by considering the combined effects of the heterogeneity of the hydraulic conductivity and the pore-scale diffusion process. The density-dependent flow and transport problem has been solved by a Mixed Hybrid Finite Element—Finite Volume approach coupled with the Monte Carlo technique [8].

With reference to Water-Distribution Networks (WDN), systems should be designed and managed to operate efficiently and economically within defined operating requirements over the lifetime of the work. The analysis of the WDN performance in extended period simulations has been carried out by a probabilistic approach where uncertain elements like the system topology, the failure of some network elements (valves, pumps, pipes, etc.), the behaviour of the nodal demand, the losses and the pipe roughness are described by probabilistic laws chosen and parameterised on the basis of the network characteristics. In turn, the maximization of the WDN reliability or resiliency or the leakage minimization are used as performance metrics in rehabilitation decision models supporting water utility managers to ensure a proper service in term of quantity and quality of the water delivered to users. Since degradation due to ageing of the networks reduces their mechanical and hydraulic characteristics, only a rehabilitation strategy may restore the regulatory requirements. This issue can help the decision on interventions, based on technical and economic considerations and reduces the costs associated with such network maintenance.

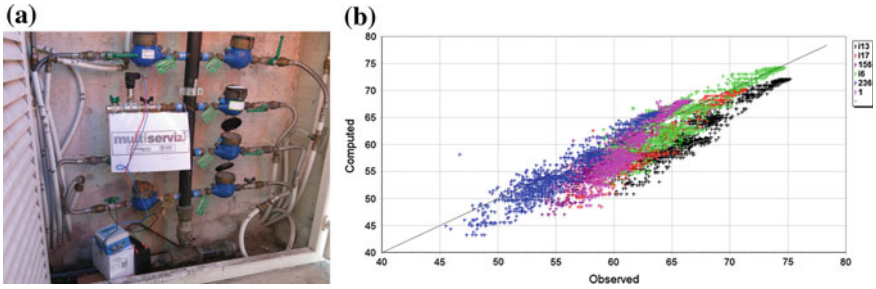

Fig. 3 Installation of a pressure sensor (left panel) and calibration of pressure data (right panel) within the Chiaravalle (Marche Region, central Italy) WDN

Alternatively, the reduction of leakage and pipe bursts can be obtained by reducing the excess pressure by the installation of a Pressure Reducing Valves (PRV). Towards a virtuous energetic policy, the energy dissipation can be converted in energy production although the large variability in flow rate and head drop of the WDS limits the economical convenience of dissipation conversion by means of classical turbines. The cheapest and most sustainable solution for energy production seem to be PAT (Pump As Turbine) systems, even if no standard design criteria are available. As an applicative example, the determination of the number, location, and setting of such machines is being determined together with the effects of the pressure control within the WDN of the town of Chiaravalle (Marche Region, central Italy). The hydraulic model of the network has been implemented with EPANET and calibrated after two successive campaigns of pressure measurements ad hoc carried out (Fig. 3) [7].

The skills on water supply networks were used for applied studies, described in consulting reports, for the private company CIIP SpA, Cicli Integrati Impianti Primari, Ascoli Piceno (Italy). The main aim was the definition of the layout of a supplying pipeline through the use of multicriteria analysis.

3 Transportation Infrastructures

In recent years, the increase of the traffic loading, as well as the growing awareness of environmental issues, led the pavement industry towards the development of sustainable materials and systems for pavement construction and rehabilitation. In this context, the research activities carried out by the Transportation Infrastructures group of DICEA focus on different topics: pavement reinforcement, cold recycling, warm-mix technologies, innovative techniques and materials. These are detailed in the following.

3.1 Pavement Reinforcement

The service life of flexible pavements can be prolonged by installing grid reinforcements at the interface of Asphalt Concrete (AC) layers. In this context, the Transportation Infrastructures group organized the interlaboratory experiment "Advanced Interface Testing of Geogrids in Asphalt Pavements" aimed at verifying the effectiveness of pavement grids in improving the repeated loading resistance and for preventing or delaying reflective cracking. The research was promoted by the RILEM TC 237-SIB "Testing and characterization of sustainable innovative bituminous materials and systems". Two full-scale test pavements were constructed, using full-scale paving equipment and grid installation techniques (Fig. 4a) [3].

The results of the Ancona Shear Testing Research and Analysis (ASTRA) test show that the installation of a pavement grid leads to a reduction of the interlayer shear strength, whereas the residual interlayer friction is not affected. Repeated loading 4-point bending (4 PB) tests carried out on reinforced systems show that grids lead to a remarkable increase of the permanent deformation resistance, especially at higher load levels. This suggests that the de-bonding effect highlighted by the ASTRA tests, is attained only in proximity of shear failure conditions. On the contrary, at lower number of cycles, the shear stress is effectively transmitted across the reinforced interface. The 4 PB test also reveals different cracking mechanisms. Grids with low in-plane stiffness delay the vertical crack movement, but the cracks eventually get across the interface, leading to reflective cracking failures. On the other hand, grids with high in-plane stiffness, induce the crack propagation along the interface, allowing for additional energy dissipation and longer life. Quasi-static 3-point bending tests (Fig. 4b) confirmed that the presence of the grid does not noticeably influence the crack initiation resistance, whereas reinforced systems show a post-peak deformation phase, bringing to higher toughness values.

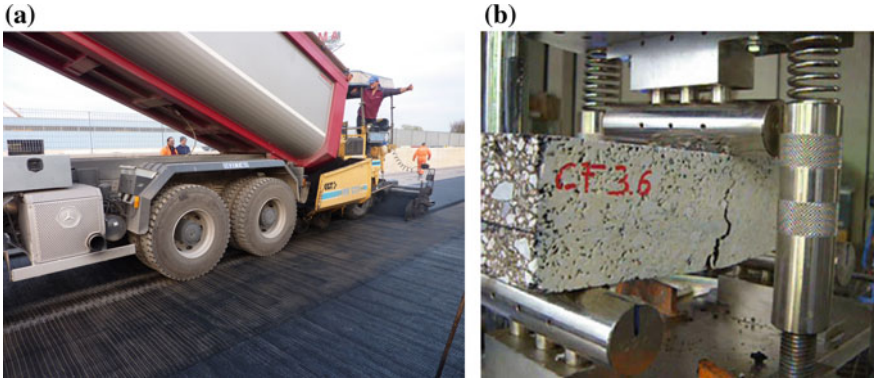

Fig. 4 **a** Example of a full-scale paving equipment and grid installation; **b** 3-point bending tests on reinforced system

The Transportation Infrastructures group also carried out full-scale field investigations to evaluate the effectiveness of pavement rehabilitation carried out with different pavement grids [14]. The construction of the field trials demonstrated that the reinforcement installation procedure is of fundamental importance to avoid lifting and corrugation of the grid. The results of ASTRA tests confirm that the application of a tack coat, as well as the use of grid coatings, improve the interface shear strength. The results of the Falling Weigh Deflectometer (FWD) test confirm that the grid reinforcement can improve the cracking resistance but does not enhance the pavement structural response.

3.2 Cold Recycling

With the Cold Recycling (CR) process, Reclaimed Asphalt (RA) is re-used at ambient temperature to produce Cold-Recycled Mixtures (CRM) for pavement bases and binder courses. The short- and long-term mechanical properties of CRM mixtures are obtained by combining a bituminous binder (bitumen emulsion or foamed bitumen) and a hydraulic binder (Portland or blended cements). Different from traditional Hot-Mix Asphalt (HMA) mixtures, the physical structure of CRM evolves in time because of water evaporation, emulsion breaking and cement hydration.

In this context the experimental activities carried out by the Transportation Infrastructures group focus on two fundamental aspects: the characterization of the evolutive behavior, also known as curing process, and the combined effect of bituminous and cementitious binders on the mechanical properties.

To describe the curing process in a quantitative way, the Transportation Infrastructures group developed a set of mathematical models to analyze and predict the physical and mechanical properties of CRM [10]. The models derive from the well-known Michaelis-Menten model, originally developed in the field of biochemistry. Specifically, the curing process is characterized by two parameters: the curing rate (the rate at which the mixture properties evolve in time) and the long-term value of the material properties. The model parameters can describe the evolution of moisture loss, indirect tensile stiffness modulus and indirect tensile strength during curing. Moreover, the model can be applied to relate stiffness and strength, regardless of mixture composition and curing environment.

To evaluate the combined effect of bituminous and cementitious binders, the Transportation Infrastructures group carried out both laboratory and field investigations. Specifically, an experimental pavement section was built along the SS38 highway, in collaboration with the Autonomous Province of Bolzano (Fig. 5a) [9]. Three CRM mixtures, with the same 100% reclaimed aggregate composition, were compared: a Cement-Bitumen Treated Material (CBTM) with foamed bitumen, a CBTM with bitumen emulsion and a cement treated material. The field performance of the CRM mixtures was monitored with annual FWD surveys. The FWD results

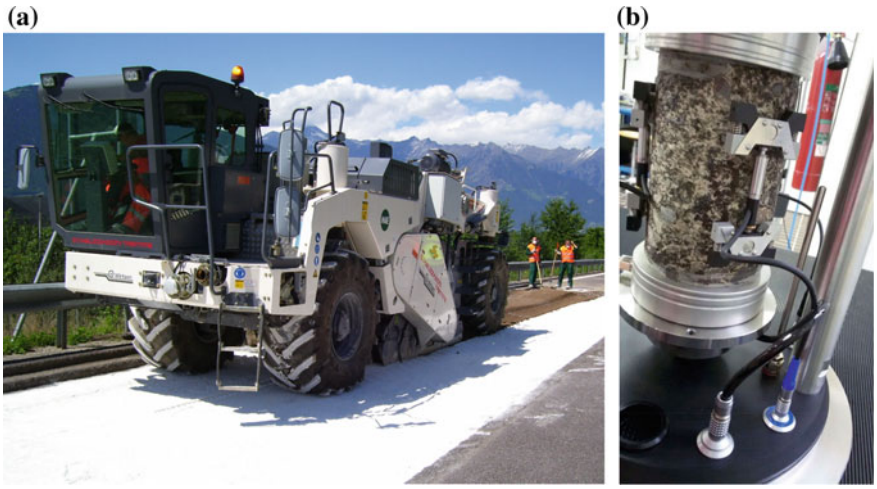

Fig. 5 **a** Construction of the experimental pavement section with CRM mixtures; **b** Complex modulus testing

were analyzed using the results of laboratory test carried out on field cores and aimed at measuring and modeling the complex modulus of the mixtures (Fig. 5b). The results showed that, due to the major effects of temperature, the FWD deflections are not suitable to evaluate the evolution of the mechanical behavior of the CRM layers. Instead, the FWD back-calculated moduli must be corrected using complex modulus values measured in the laboratory. The analysis of the corrected FWD moduli showed that the stiffness of the CRM layers increased for 3–5 years after construction. This is due to the curing process previously described, which is related to the simultaneous presence of Portland cement and bituminous binders.

3.3 Warm-Mix Technologies

Warm Mix Asphalt (WMA) technology gives the possibility to reduce mixing and compaction temperatures, with respect to conventional HMA. In this context, the Transportation Infrastructures group performed laboratory investigations on asphalt mixtures produced using different WMA additives (i.e. chemical, organic and water-based) [18]. Mixtures included polymer modified bitumen (PMB) and RA to evaluate potential benefits deriving from the combination of warm and recycling techniques. Mechanical tests on mixtures were integrated by rheological analyses on bitumen for a better understanding of the WMA additive effects. The results show that additives do not cause changes on rheological properties of unaged bitumen,

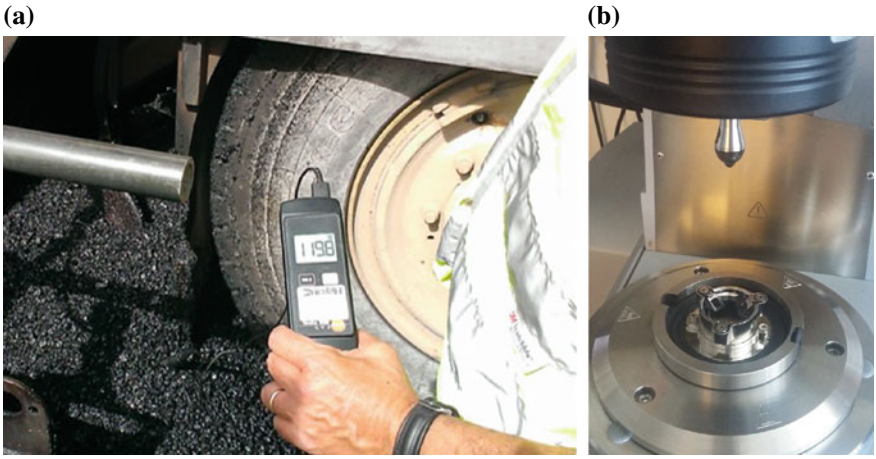

Fig. 6 **a** Measurement of laydown temperature of WMA mixture; **b** Ball-on-three-plates geometry for tribological tests

whereas aged bitumen demonstrated different behavior depending on the additive type. Results confirmed the possibility to produce proper dense-graded WMA mixtures at reduced temperatures (Fig. 6a) of satisfactory performance (i.e. workability, stiffness and fracture properties). In case of recycled mixtures containing RA and PMB, the chemical additives are able to balance drawbacks deriving from reduced production temperatures.

Recent studies proposed the improvement of the lubricating properties of the bitumen as a possible mechanism involved in the densification of bituminous mixtures. Tribological tests were introduced in the field of road materials to investigate the possible benefits provided by WMA additives on the lubricating characteristics of bitumen. In this sense, the Transportation Infrastructures group investigated the effect of different WMA additives on the tribological behavior of plain bitumen [11]. Fourier Transform Infrared Spectroscopy (FTIR) and viscosity analysis were performed on bitumen for a preliminary chemical and rheological characterization. Subsequently, tribological tests were carried out at different temperatures by means of a ball-on-three-plates geometry fixture (Fig. 6b).

Results showed that the additives seem to alter the oxidative state of the binder. Furthermore, the chemical additive affected the tribological behavior of binders, whereas the wax additive caused mainly a reduction in viscosity. It was found that the tribological behavior of bitumen is strongly related to the viscosity when the lubricating film is not excessively thin or excessively thick. Finally, with reference to the possible basic mechanism of additives on the compaction of WMA mixtures at reduced temperatures, the results suggest that the waxes might only act on the viscosity of the bitumen, whereas the chemical additives would be able to reduce the friction in the elasto-hydrodynamic regime of lubrication.

3.4 Innovative Techniques and Materials

The use of photocatalytic products aimed at de-polluting the atmosphere from traffic emissions, has aroused lively interest in many road Agencies. To this end, the Transportation Infrastructures group investigated the potential of innovative techniques dealing with the immobilization of titanium dioxide (TiO_2) on the surface of asphalt pavement. The study consisted in a full-scale application of different TiO_2 based products (two bituminous emulsion and a cement mortar) on an Italian highway section (Fig. 7a) [1]. Continuous flow tests for nitrogen oxides degradation evaluation and digital image analysis, applied on the treated area to identify the presence of TiO_2, were performed on cores taken after different times from the product application. Results showed a good performance for all the products after 1 day from application. However, the loss in performance was significant during the first weeks, particularly for the cement mortar treatment. The bituminous emulsions treatment was noticeably affected by the climatic conditions (low temperature and rainy days), whereas it is believed that the photocatalytic performance of the cement mortar is mainly influenced by the polishing caused by traffic.

Asphalt Rubber (AR) is a blend of plain bitumen and crumb rubber produced from reclaimed tires. AR can enhance the mechanical performance of bituminous mixes and its use results in environmental benefits by re-using a waste material and reducing rolling noise. In this context, the Transportation Infrastructures group investigated durability in terms of water and thermal sensitivity of two Open Graded (OG) AR mixtures (one containing expanded clay) by means of a CoAxial Shear Test (CAST) apparatus under different moisture and temperature conditions [13]. The results showed that OG-AR mixtures improved the fatigue resistance and significantly reduced the moisture sensitivity with respect to traditional OG asphalt mixtures (Fig. 7b). Although the expanded clay slightly reduced the fatigue response of the

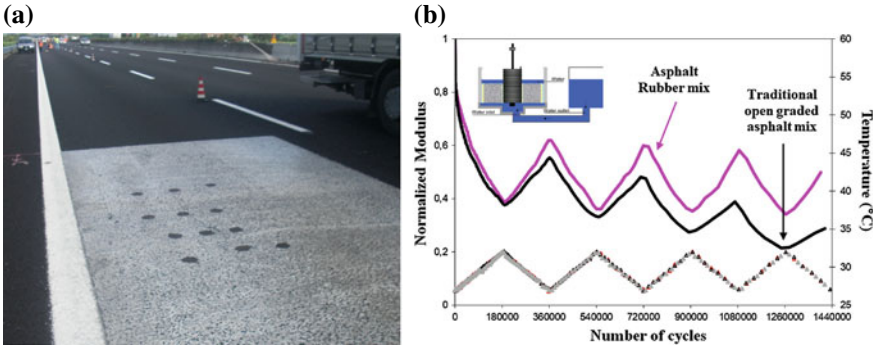

Fig. 7 **a** Full-scale application of TiO_2 treatment with cement mortar; **b** CAST results: OG-AR mixture versus OG asphalt mixture in wet condition

OG-AR mixtures, its presence seemed to improve the temperature cycle resistance, thanks to its higher heat capacity as compared to mineral aggregates.

The Transportation Infrastructures group also investigated the potential use of Construction and Demolition wastes (C&D) as aggregate for unbound pavement layers [4]. The study mainly focused on the analysis of the strain behavior of C&D mixtures under repeated triaxial loading. The strain behavior under different moisture conditions was satisfactorily described by the constitutive model proposed by the Authors. Test results show that C&D mixtures are characterized by a lower moisture and stress state sensitivity with respect to traditional mixtures, depending on the moisture conditions. Moreover, C&D mixtures accumulate lower strain under specific stress levels and sustain a higher stress level before failure.

4 Conclusions and Future Activities

Activities of the Hydraulics group focus on important topics such as the landscape protection aimed at increasing the resilience of both engineering infrastructures and natural environment. The new equipment and facilities that are being made available to the Hydraulics group through the "Dipartimenti di Eccellenza" award, are expected to provide a major boost to both fundamental and applied research of the group. In particular, the new flume for riverine flows will provide a fundamental asset for the analysis of the riverine hydro-morphodynamics (e.g. modeling of river floods, turbulent structures, nearbed sediment transport, river bed morphology evolution). Very important will also be the acquisition of a new Particle Image Velocimetry (PIV)/Particle Tracking Velocimetry (PTV) system, which will allow for detailed inspection of a variety of flows: (1) marine flows (e.g. inspection of the internal kinematics of breaking sea waves), (2) flows of interest for fluid-structure interactions (e.g. sea waves hitting foundation piles, floodwater impacting upon human bodies or buildings), (3) flows of interest for biological applications (e.g. blood flow in cardiovascular systems, feeding flows of sap sucking insects). Beyond these laboratory activities the Hydraulics group will strengthen its recognized activity in the theoretical and numerical modeling of flows of interest for coastal (e.g. shallow-water flows, breaking waves) and estuarine (e.g. vortex formation at a river mouth) dynamics. Numerical modeling will also be used to gain new insight in complex flows of biological and engineering interest.

The future research activities of the Transportation Infrastructures group will continue the development of sustainable materials and systems for resilient transportation infrastructures. The acquisition of new testing equipment, through the abovementioned award, will increase the potential of the laboratory aimed at the advanced rheological characterization of recycled and low energy materials (both cold and warm technology) and the development of innovative solution for resilient pavements (e.g. reinforced pavements and self-healing materials). This will further strengthen

the international presence of the Transportation Infrastructures group, its competitiveness and capacity of attracting research funding. Finally, this expertise will be employed to promote dissemination and exploitation thorough technology transfer towards public and private organizations.

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An Overview of the Structural Safety-Oriented Research in the Region Marche Seismic Area

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Abstract In recent years, Italy has been hit by earthquakes, causing significant damage to masonry and reinforced concrete (RC) structures. Especially, common buildings and ordinary structures in many small historical towns of Italian central regions, such as Marche, have suffered dramatic consequences and destruction.

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Dynamic analysis and seismic structural safety are important topics in civil engineering, which have been studied and deepened for many years by the researchers of the Structural Division of the Department of Civil and Building Engineering, and Architecture of UnivPM. The researches have been oriented towards the investigation of structures under seismic loads in order to improve the knowledge of the structural response under high actions, due to the soil dynamic movements and, thus, define adequate techniques to strengthen the damaged structures. In this paper we present a wide spectrum of main results of our research group, comprising experimental studies, vulnerability analysis and assessment of existing structures, new methods of modelling and theoretical approaches to define the dynamic behavior of structures, also in presence of damage. Finally, we show and discuss new prospects of research for safety, employing advanced techniques and materials to prevent collapse and/or relevant damages in structures.

1 Introduction

The recent earthquake events affecting central Italy regions, such as Marche, have caused a significant number of severe damages on buildings and many injured, proving once more the high seismic vulnerability of the Italian existing RC and masonry constructions. This often provides an inadequate safety level against seismic actions. Common and ordinary buildings, structures of strategic importance (e.g., bridges), together with several historical and architectural constructions, belonging to the cultural heritage (e.g., monumental churches, monasteries, towers), suffered disruption during earthquakes, depriving them of their structural and functional capabilities. The seismic events and the importance of the prevention have highlighted the necessity of investigating the dynamic behavior of the structures in order to improve the knowledge of the structural response under high actions, assess the capability of the existing building heritage to sustain earthquakes and, finally, enhance the average safety level of the population as well as the community resilience to earthquakes.

The dynamic analysis and seismic structural safety represent two of the most prominent research topics developed by the Structural Division of the Department of Civil and Building Engineering, and Architecture of UnivPM. In this paper we present the main researches, gravitating towards seismic engineering, which can be collected in four macro-areas: (1) new methods of modeling the dynamic behavior of structures; (2) vulnerability assessment and analysis of existing structures; (3) experimental studies on advanced techniques of seismic retrofitting, based on new materials and innovative dissipative systems; (4) new prospects for safety, including structural health monitoring and seismic isolation.

A performance-based seismic engineering design is based on rigorous modeling of the dynamical behavior of structures, which allows a more feasible assessment of safety risks and damages. The study of the global response of RC and regular masonry buildings has been carried out through linear and nonlinear dynamic analyses by means of bar-frame models, considering lumped or distributed inelastic hinge

[11, 12, 21, 25]. Moreover, the analyses of masonry structures have been extended considering the non-smooth nature of the dynamical behavior by virtue of discrete element methods, which better capture their damage and collapse [19, 20, 24].

The vulnerability assessment of ordinary and historical constructions against seismic actions represents the necessary prerequisite for seismic protection. The high vulnerability is due to many aspects, mostly related to the age of the buildings, the low standards of construction and maintenance and the overall lack of the basic rules of capacity design. Old RC framed buildings and industrial precast structures have been analyzed by identifying the specific vulnerabilities, through different nonlinear models [10–12, 21, 25] and experimentally characterized via Operational Modal Analysis [22]. While masonry historical structures, which were not conceived to resist lateral forces, have been analyzed by means of sophisticated methods in order to asses or predict the seismic behavior and/or the expected damage [7, 8, 19, 20, 24]. Vulnerability assessment of bridges and viaducts, which are typically structures of strategic importance, have been carried out by using on purpose developed higher order beam models and finite element based numerical solutions which also permitted the formulation of advanced design procedures for new steel-concrete composite bridge decks [14–16].

Concerning with experimental studies and retrofitting of existing structures, the researches focus on advanced techniques, based on new composite and layered materials, such as fiber reinforced polymers (FRPs), for the strengthening of existing structures [2–4, 29], and innovative dissipative systems for an effective protection solution against seismic actions, offering the ability of dissipating the earthquake-induced energy and provide a suitable level of protection, improving the structural capacity [13, 17, 26].

Finally, new prospects for increasing the average safety level against seismic actions of existing and new structures include the Structural Health Monitoring, which continuously provides information about the modal parameters evolution of structures and infrastructures [9, 18, 23, 28], the seismic isolation, which is another protection solution able to efficiently protect structural and non-structural components [27, 30], and the assessment of soil-structure interaction effects, which can sensibly modify the seismic response of structures [1, 5, 6].

2 Dynamic and Safety of Structures

Emerging performance-based earthquake engineering design approaches seek to enable more accurate and transparent assessment of both life-safety risks and damage, using advanced analysis models and design criteria. The study of the global response of the building can be typically performed with bar-frame models: this particular approach is usually used in the practice for RC buildings, but it can sometimes be extended in the study of regular masonry buildings through the “equivalent frame” scheme. The analysis of structures subject to seismic action can be linear or nonlinear, and among different type of analyses, dynamic ones could be certainly the most

accurate for designing and predicting the structural seismic behavior. In the majority of structures, especially when an ex-post evaluation is required instead of a design, the uncertainties about the nonlinear behavior are relevant: generally, the presence and location of potential inelastic zones, as well as their ductility capacity, are not known. Therefore, the definition of a direct correlation between the nonlinear internal forces, developing in the system during the seismic excitation, and those experienced by an equivalent indefinitely elastic structure, becomes quite challenging. For this reason, a force-based assessment obtained using an elastic analysis and reducing the internal forces by the behavior factor q does not yield, in general, satisfactory results unless in the design a new structure. Hence, the nonlinear behavior of the structure should be faced directly, with corresponding considerable increase in complexity of the assessment procedure.

As known, there exist several types of nonlinear analyses applicable within the context of "beam" element, which differ essentially by two aspects: firstly, the distribution of inertial forces (static or dynamic) induced by an earthquake; secondly, the chosen nonlinear modeling (lumped and diffused plasticity). Since the inelastic behavior of RC frames often concentrates at the ends of girders and columns (Fig. 1), an early approach to modelling this behavior was by means of nonlinear springs located at the member ends [11, 21]; this approach is used also in the modelling of regular masonry buildings [25]. A more accurate description of the inelastic behavior of reinforced concrete members is possible with distributed nonlinearity models. The constitutive behavior of the cross-section is either formulated in accordance with classical plasticity theory in terms of stress and strain resultants or is explicitly derived by discretization of the cross section into fibers [12].

In this context, alternative modelling strategies can be pursued for the study of the global, regional and local hysteretic response of buildings and bridges under strong ground motions. It becomes crucial to limit simplifications and, at the same time, to

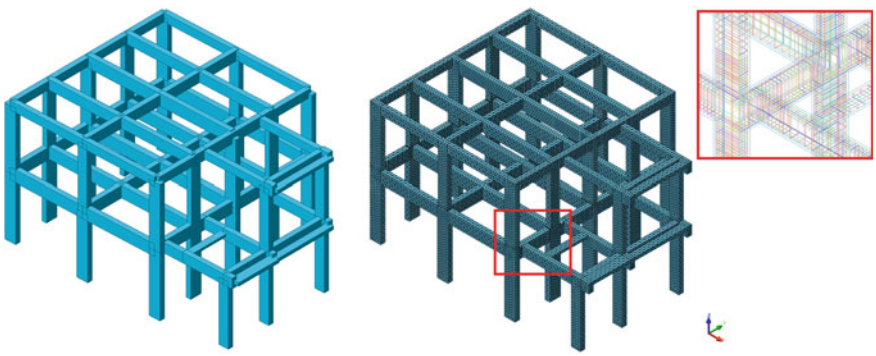

Fig. 1 Bar frame model with "beam" elements with lumped or diffuse plasticity versus solid numerical elements with imbedded rebars

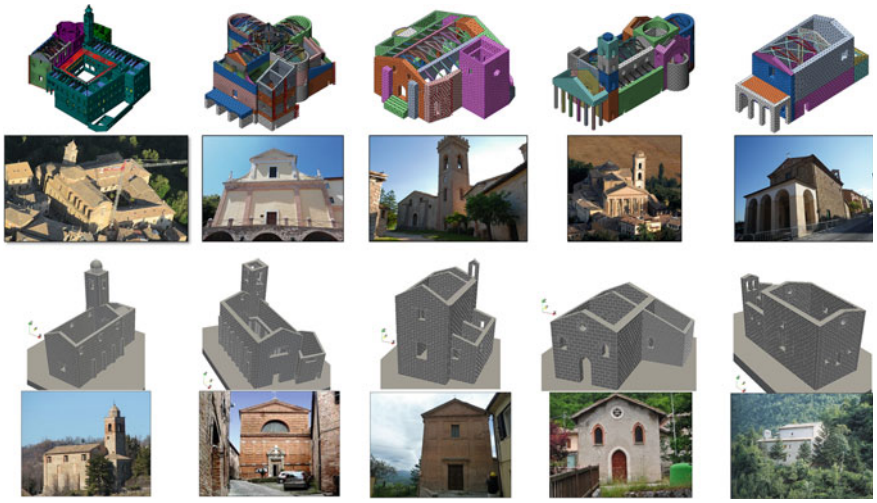

Fig. 2 Continuous versus discontinuous modelling approaches for different damaged churches during the Central Italy Earthquakes of 2016–2017 in the cites of Camerino, Sarnano, Montefortino, Ussita, Fiuminata, Offida, Fiastra, San Severino Marche

enhance the necessary modelling accuracy especially when complex and irregular structures are considered. For these reasons, it should be useful to consider enhanced modeling.

To investigate the mechanical behaviour of structures, especially of masonry buildings, commonly finite element methods within a continuum mechanics theory are utilized, often including very sophisticated constitutive laws considering post-elastic behaviours and damage. These methods, while being very appealing, do not focus on the possible non-smooth nature of the dynamic response, which can arise from possible sliding and impacting between different blocks, and situation that is common just before and during the collapse. For this reason, discrete element methods are developed in the last years in order to have a better insight of damage and collapse, especially for masonry structures, see e.g. [19, 20, 24] (Fig. 2).

3 Vulnerability of Existing Structures

In the European seismic countries, the assessment of existing structures is a priority, since the majority of the building heritage was designed according to out-of-date or even no seismic codes. The recent seismic events have highlighted the necessity of assessing the capability of the existing building heritage to sustain earthquakes, in order to improve the average safety level of the population. The adequate modelling of existing RC and of Cultural Heritage buildings as well as of bridge is a crucial issue, related as well to the maintenance and to the structural upgrading possibility,

too. The evaluation of the seismic vulnerability of existing buildings has a key role in determining and reducing the impact of an earthquake.

3.1 Reinforced Concrete Structures

RC buildings currently represent the greatest portion of existing structures, and mostly have been built after World War II when building stock increased exponentially. Through the study of the requirements of the coeval legislation and the suggestions of the manuals of that period, some typological aspects that often characterize these buildings have been defined [10], analyzed with different nonlinear models [12] (Fig. 3a), and experimentally characterized with Operational Modal Analysis [22] (Fig. 3b). Industrial Precast Structures are also analyzed in order to assess the limited capacity of beam-column connections to allow relative displacements without losing beam seating, and to transfer lateral horizontal forces from the beam to the column, without losing load carrying [11, 21], see Fig. 3c.

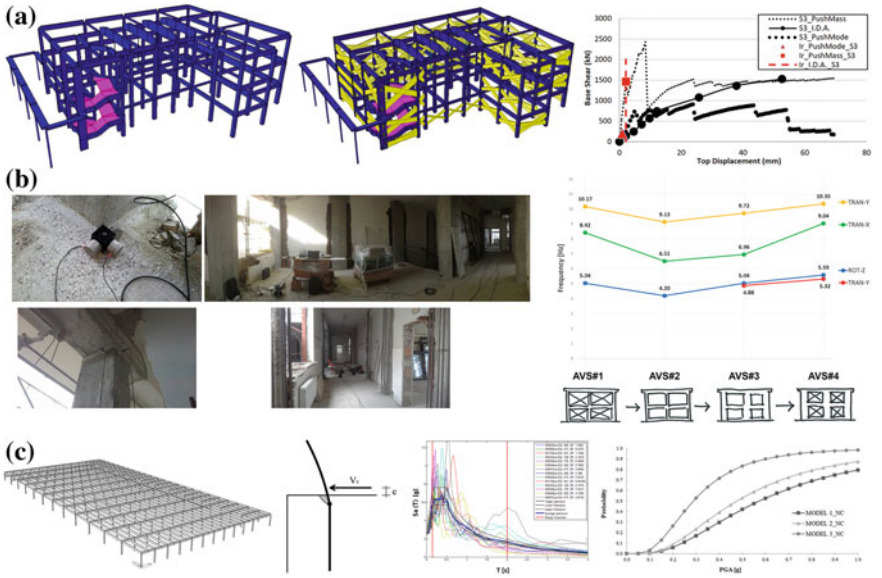

Fig. 3 Different numerical models for the analysis of typical and specific vulnerabilities in RC school buildings (**a**), tracking modal parameters evolution of a RC school building during retrofitting works (**b**), and the influence of deformable connections on the seismic response of precast industrial buildings (**c**)

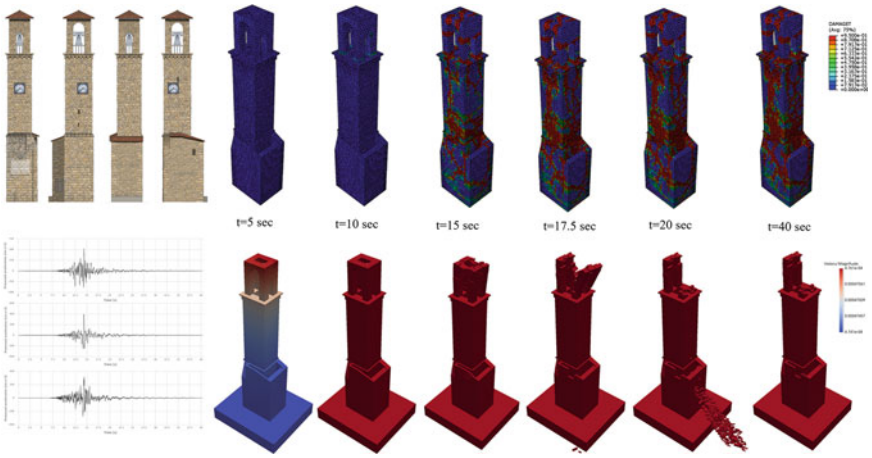

Fig. 4 Continuous and discontinuous approaches applied to the Amatrice Clock tower symbol of the damage of the Central Italy seismic sequence of 2016–2017

3.2 Masonry Buildings and Cultural Heritage

Masonry constructions are complex structures, usually characterized by a lack of knowledge concerning the behavior of their structural systems and, in particular, their seismic response. Typically, these structures are more massive than today's structures and they usually carry their actions primarily in compression. Successful modelling of a masonry historical structure is a prerequisite for a reliable earthquake-resistant design or assessment. In this framework, different sophisticated methods are used in order to asses or predict the seismic behavior and/or the expected damage (Fig. 4): continuous [7, 8] and discontinuous [19, 20, 24] approaches.

3.3 Bridges

Bridges and viaducts are constructions of strategic importance, especially in countries like Italy where, due to topographic conditions, there is a large number of existing viaducts and many others should be built to guarantee a proper social and economic development. Due to the high ratio between self-weight and sustained loads, in the vulnerability assessment of bridges gravity and traffic loads, material degradations, time-dependent and fatigue effects, play a significant role that is often comparable to that of seismic actions. With respect to steel-concrete composite bridge decks, which is the most popular typology for viaducts on medium span length, advanced and theoretical higher order beam models have been developed together with ad hoc finite element based solutions [15]. This approach has been applied to set up advanced design methods with particular focus on the construction phases of the

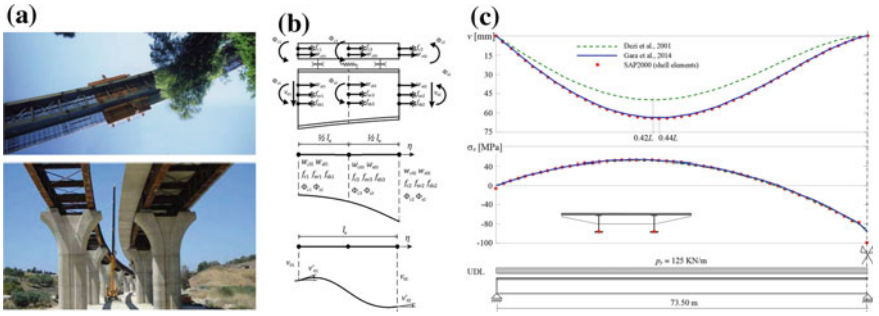

Fig. 5 **a** Traveling formworks for the slab casting in steel-concrete composite viaduct; **b** 25 dof finite element for the higher order model of composite bridge deck; **c** Results of different modelling of a twin-girder composite deck under uniformly distributed load

deck [14], durability and cracking of the concrete slab, fatigue verifications of the deck [16], as well as on the seismic response of dual load path bridges, of slender bridge pier and of continuous multispan bridges with partial isolation (Fig. 5).

4 Experimental Response and Retrofitting of Existing Structures

Damages occurred during recent earthquakes have shown the high vulnerability of existing buildings, both masonry and low-ductility RC structures, and the need of modern retrofit techniques for increasing their safety. The research in this field is carried out by focusing on advanced techniques recently developed, based on new materials or innovative dissipative systems. In the following sections the main experimental and numerical research activities are illustrated. Experimental investigations are carried out mainly at the Laboratory of Materials and Structures of the Department of Civil and Building Engineering and Architecture. Experimentations on real retrofitted buildings have been also conducted.

4.1 Composite Materials

In the last years numerous researches have studied the strengthening of existing structures through the use of near surface mounted fiber reinforced polymers (FRPs) such as strengthening of reinforced concrete damaged beams or external bounded FRP sheets/strips to masonry walls [4]. Dynamic analysis of free vibration, studied from the experimental [2] and theoretical [29] point of view, may be convenient to control availability and safety of RC beams strengthen by composite materials. A key issue in the design of externally bonded FRP strip/sheet is the strength of

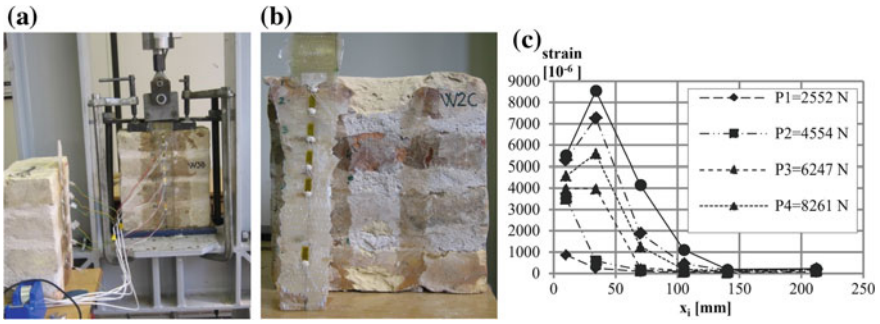

Fig. 6 **a** Pull-out test and **b** delamination failure of GFRP strip; **c** experimental strain values recorded for specimens made with historic bricks

anchorages. Many tests indicate that a dangerous mechanism of brittle failure is due to delamination, especially if the FRP strips are glued to historic clay bricks with a weak clay surface. The behavior of Carbon-Glass-FRP/SteelRP-to-historic brick bonded joints has been experimentally studied [3] by pull–push shear on specimens (Fig. 6a, b). Experimental data were processed to evaluate: strain-external bond length (Fig. 6c) shear-slip laws of tested specimens; energy fracture and failure load values.

4.2 Dissipative Systems

Systems with passive energy dissipation devices are an effective protection solution against seismic actions, offering the ability of dissipating the earthquake-induced energy and, if necessary, additional lateral stiffness. Among the different dissipation systems, the research activity in this field is focused on Buckling Restrained Braces (BRB) and on bracing systems based on High Damping Natural Rubber (HDNR). The first system is widely used thanks to their large dissipative capacity due to the elastic-plastic behavior of steel, while the latter generally provides less energy dissipation but has the advantage of supporting a large number of cycles without permanent deformations and of making the structure less inclined to storey mechanisms [13]. Experimental and numerical investigations are performed on a real scale steel mock-up [26] equipped with BRBs and HDNR-based bracings (Fig. 7), aimed at evaluating and simulating the experimental response of these kind of structures.

Dissipative systems can be also placed outside the building frame, permitting to avoid strengthening of the existing foundations and limiting indirect costs related to the interruption of the building utilization during execution of the retrofit. An innovative external system for seismic protection of existing buildings (patented as “Dissipative Towers”), based on the structural coupling of the building with new steel truss towers equipped with dissipative viscous devices, is recently studied. The research includes numerical studies on the structural dynamic behavior [17] as well

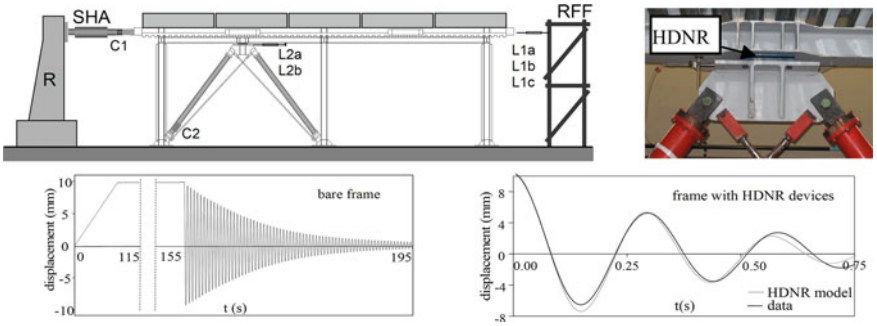

Fig. 7 Set-up of experimental tests on the real-scale mock up with HDNR devices and displacement history of snap-back tests without and with HDNR devices

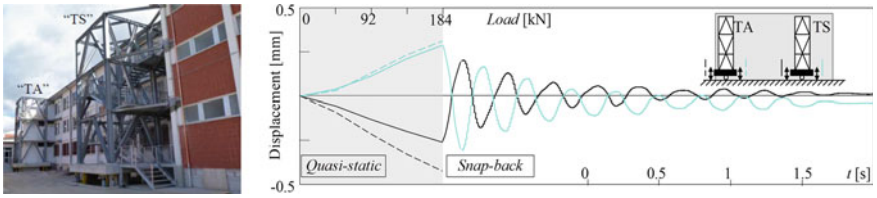

Fig. 8 Dissipative towers on an existing school building and time history of the base tower vertical displacement during a snap-back test

as experimental investigations on real buildings retrofitted with the above system. In Fig. 8, the application of the system to an existing school is reported on which snap-back tests are carried out to evaluate the experimental response of the building-towers system.

5 New Prospects for Safety

The seismic protection of existing structures as well as the seismic design of new ones, including important structures such as bridges, are two central topics for ensuring an adequate safety level in seismic active countries. In this field, several research activities are in progress aimed at studying efficient structural response monitoring systems and advanced seismic analysis, as described in the following sections.

5.1 Structural Dynamic Monitoring

In the framework of Structural Health Monitoring (SHM), the continuous monitoring provides information about the modal parameters evolution of structures and infrastructures. Information is often adopted to calibrate structural models for the seismic vulnerability assessment or the retrofit design. The research is oriented to the dynamic characterization and monitoring of structures, both building and bridges, subjected to ambient vibrations or seismic actions. The response of structural systems subjected to actions of different magnitudes, as well as the effects of ambient conditions on the modal parameters are investigated. Figure 9 shows an application to the RC Tower of the Engineering faculty of university [28].

In this context, the occurrence and evolution of structural damage in different types of real structures [9, 23] (e.g. see Fig. 10) is evaluated and a combination of experimental and numerical methodologies for the damage detection [18] are also used.

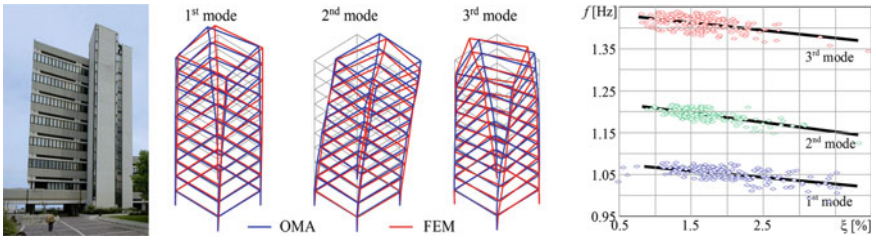

Fig. 9 The Tower of the Università Politecnica delle Marche: mode shapes and correlation between frequencies and damping ratios, which vary with ambient temperature and wind velocities

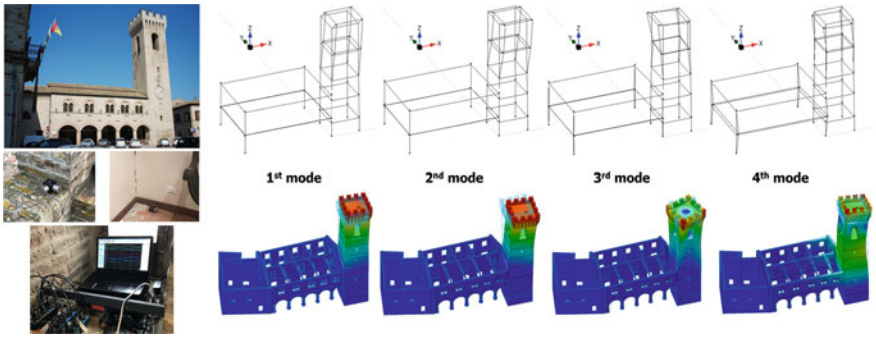

Fig. 10 The Podestà Palace in Montelupone damaged by the seismic sequence of the Central Italy in 2016–2017: dynamic identification and calibration of the numerical model for damage assessment

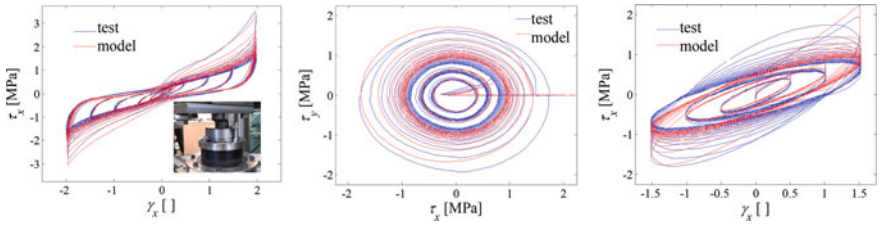

Fig. 11 Experimental and numerical shear response of HDNR material under uni-axial and bi-axial tests

5.2 Seismic Isolation

Seismic isolation is widely recognized as a technology able to protect efficiently the buildings structure, as well as its non-structural components and equipment. It is also widely used for the protection of bridges. Among different isolation bearings, High Damping Natural Rubber (HDNR) bearings are extensively employed because of their low horizontal stiffness and high damping capacity due to the introduction of filler in the rubber compound. However, in many cases the filler introduction also induces a stress softening of the cyclic response of the devices (Mullins effect), see Fig. 11. Thus, the research on this field has been oriented to evaluate the experimental response of virgin HDNR material samples and to develop adequate biaxial models for describing the force-deformation behaviour of HDNR bearings to be used in the seismic analysis of isolates structures [27, 30].

5.3 Soil-Structure Interaction Analysis of Bridges and Buildings

Soil-Structure Interaction (SSI) may sensibly affect the seismic response of both buildings and bridges, particularly in the case of soft soil conditions. With reference to deep foundations, the research focuses on the development of analytical and numerical models to address the problem of soil-foundation interaction in the frequency domain [6]. Models are also used to perform nonlinear SSI analysis of structures in time domain, in the framework of the sub-structure approach, adopting suitably strategies to include the frequency-dependent behavior of soil-foundation systems. In this field, both numerical studies [5] and in situ experimental campaigns are performed [1] (Fig. 12). The role of SSI in the dynamic identification of bridges is also investigated (Fig. 12).

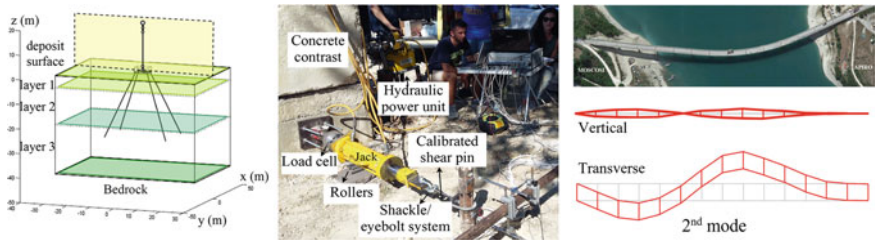

Fig. 12 Numerical studies on bridge piers, experimental set-up on micropile foundations and dynamic identification of a multispan prestressed concrete bridge

6 Conclusions

The present paper summarizes some of the main research activities of the Structural Division of the Department of Civil and Building Engineering, and Architecture of UnivPM related to seismic engineering and developed through the last decade. The research activities carried out on advanced seismic design and analysis of new structures and infrastructures as well as advanced retrofit techniques of existing ones, will allow a significant increase of the average safety level of the population. The obtained results represent a solid base for the actual and future development of rational tools for the evaluation of the seismic risk of constructions in seismic active countries, such as the Marche region, considering also structural health monitoring techniques, as one of the key topic of future activities.

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Rethinking Buildings Design, Construction and Management Through Sustainable Technologies and Digitization

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Abstract A technological development not threatening natural and human life is one of the core concepts of sustainability. In the construction sector, which is worldwide responsible of a huge consumption of energy and natural resources, thus strongly impacting on climate change, sustainability requires a prompt transition towards eco-friendly, smart and resilient buildings. However, despite the current Forth Industrial Revolution, where many sectors have been able to transform themselves improving productivity while lowering the environmental impact, construction is still suffering

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from several intrinsic backwardness. A new approach is required. Sustainable product innovation and process digitalization are established roadmaps to reinventing construction throughout the whole building life-cycle: conception and design, planning and execution, operation and maintenance, end-of-life, reuse and recycling. This paper goes back over the major research results achieved by Construction division of the Department of Civil and Building Engineering and Architecture of Università Politecnica delle Marche in this context. It also outlines the emerging challenges and future directions of the research in this long-established sector.

1 Introduction

Construction industry is one of the largest sectors of the world economy. Every year, there is about $10 trillion in construction-related spending globally, equivalent to 13% of GDP, and the sector employs 7% of the world's working population. Furthermore, the buildings in which we live or work, which create our energy, materials and goods, and on which we travel, have an impact well beyond their own operational boundaries, including the natural environment and the social life. It is estimated that the building sector consumes about 40% of primary energy contributing to 23% CO_2 emission of the global economics activity [6], so a prompt transition towards sustainable buildings is urgent and vital. However, despite its enormous environmental and economic impact, the construction sector is not evolving at the right pace. Both high performance buildings and efficient construction processes are still on the horizon of the research perspective. The construction techniques of the inhabited areas have remained almost unchanged for centuries, even with variations linked to the different geographical and climatic contexts in the world. Only in the first decades of the twentieth century, with an ever-increasing use of reinforced concrete and the strong industrial drive of the post-war period, the way of living inside the buildings has been rethought and more performance has been required to building components, especially in the field of energy efficiency and sustainability.

On the other side, the construction process has suffered for decades from remarkably poor productivity and high environmental impact compared to other sectors. Concerning productivity, construction has evolved at a glacial pace with respect to manufacturing, where lean principles and aggressive automation have been transformative. Indeed, global labour-productivity growth in construction has averaged only 1% a year over the past two decades (it was flat in most advanced economies). Contrasted with growth of 2.8% in the world economy and 3.6% in manufacturing, this clearly indicates that the construction sector is underperforming [3]. Causes of this situation are manifold, however a common fundamental factor is that the construction industry has not yet embraced the new digital technologies that are needed to manage the complexity imposed by the globalization of the markets. Thus, large projects across asset classes still typically take 20% longer to finish than scheduled and are up to 80% over budget. A parallel trend to industry 4.0 is expected to invest the construction sector, generally known as Construction 4.0, implementing a significant

growth phase through the adoption on a large scale of information and automation technologies.

In this paper these challenging issues are investigated, as they are driving the research at the Construction division of the Department of Civil and Building Engineering and Architecture (DICEA) of Università Politecnica delle Marche.

Section 2 reports the main results obtained by the Architectural Engineering group (AE) of DICEA in the development and optimisation of innovative, durable and sustainable technological solutions for existing and new buildings. Section 3 will investigate the enormous potential that the digitization of the construction process has in terms product quality, workers' safety and increase of productivity, as it is outlined by the research that is being carried out by the Design and Construction Management group (DCM) of DICEA. Main conclusions are drawn in Sect. 4.

2 High Performance Components, Advanced Assessment Tools and Occupant Behaviour-Based Building Design and Operation

Today, the building designer comes up against the need to choose among several design solutions and construction technologies, having to assess their performance according to multiple, somehow conflicting points of view, also considering current construction codes and standards. This process is even more complicated for existing and historic buildings, subjected to further architectural, social, cultural constraints, with high energy consumptions and safety issues. Furthermore, buildings are places where people live, work, enjoy, so the mutual interactions among occupants and built environment should be properly considered to improve the design and operations of buildings based on end-user needs, requirements, safety and preferences. DICEA AE group has been dealing with research in these topics for years, especially aiming to:

- the development of innovative, durable and sustainable materials and technological solutions for new and existing buildings and for cultural heritage;
- the development of advanced optimization and assessment tools for building performance, especially focusing on sustainability, energy, CO_2 emissions and costs;
- the development of smart and cognitive building components, based on embedded specific sensors-actuators, able to adapt their configuration to users' needs, in terms of environmental conditions and safety.

The following sub-sections presents the main research findings related to these topics and outlines future research perspectives, aimed to make future buildings and components, through their intelligent and "cognitive" features, able to more and more adapt and respond to the users' needs in terms of comfort and safety, by also considering economic and environmental issues in the building life-cycle.

2.1 Durability and Sustainability in Built Environment: Towards Highly Performing Building Components and Assessment Tools

One of the first research area of the AE group focused on existing buildings and cultural heritage, aiming to rediscover the technical know-how of the past in order to better safeguard both the material vehicles and the constructive systems that characterize the historical architecture. These studies concerned, for instance: wooden structures (floors and trusses), finishing elements (plasters), decorative elements of façades (Renaissance cornices, frames for window linings). Special attention was given to earth constructions in Marche Region and to the architecture of early decades of the 20th century [22].

In the last decades, in response to the first energy crises and with the emerging awareness of the environmental impact of the construction sector, energy efficient and sustainable components have been proposed and applied to new and existing buildings to reduce the energy consumption and the consequent environmental impact. AE group contributed to this research field, by developing and/or optimising innovative, durable and sustainable technological solutions. Investigations were conducted through integrated methodologies including laboratory tests, on site monitoring of real buildings, experimental campaigns on test rooms and numerical evaluations. The main outcomes in this field concerned the building envelope, including the development and optimization of external opaque components, transparent surfaces, internal finishing materials and load bearing preassembled units.

As regards the *opaque components*, several numerical and experimental studies, both on-field and on test rooms, were focused on the comparison of different type of components in order to identify the most efficient solutions according to several points of view (e.g. energy efficiency, mitigation of urban heat island (UHI), optimization of indoor comfort, costs reduction), especially considering the Mediterranean climatic context. Studies included passive solar systems, ventilated facades and insulated envelopes, as in [1]. Prototypes for facades with different typologies of layers and external claddings were experimented and patented (Italian Patent no. 0001407018).

Special attention was paid to building roofs, as a significant amount of the heat exchanged between building and internal and external environment is via the roof. In [20], Di Giuseppe et al. carried out experimental and numerical activities in order to extensively characterize the optical properties of roofing materials and investigate their impact, also coupled with above sheathing ventilation, on the thermal performance of a roof under warm-temperate climate. In [17], ventilated, green and cool roofs have been compared under real climatic conditions.

The impact of the introduction of specific requirements on highly insulated envelope for energy efficient buildings in Mediterranean climate has been investigated in detail, considering the potential negative effects in terms of indoor summer overheating and biofouling of internal and external facades [16], in order to actively contribute to a review of the current legislative framework.

The *transparent surfaces* of the building envelope have been largely investigated through experimental comparative studies on several glass smart coatings and frame materials, also evaluating the potential of integrating nanotechnologies [30]. Moreover, different external shadings were experimentally compared, the consequent thermal and visual comfort analysed, and the best solutions identified. A new profile for glazed wall facades to reduce the visual impact of the external frame was also developed [33] and patented (European Patent WO2015/071882A1). Researches carried out on the interaction of building occupants with windows, led to the development of an automatized system for windows opening/closing according to real users' preferences, by tuning a behavioural algorithm on experimental data.

Several studies of AE group also focused on *building internal envelope finishing and components,* aiming to improve the thermal and hygrometric performance. Stazi focused on the identification of the optimal levels of thermal inertia to achieve occupants' comfort and energy saving and proposed new limits for envelope dynamic thermal parameters, to guide the design of future building envelopes [29]. Studies have been carried out on different internal finishing systems, also including phase change materials. New components aiming at the improvement of the Indoor Air Quality have been developed, e.g. a dynamic insulation systems integrating thermal and filtration functions, and an active device for indoor humidity control based on moisture buffering materials [18].

As regards *the loadbearing envelope components*, studies have been carried out on the development of integrated energy-structural solutions using new materials such as composite profiles, nanofoamed insulations, seismic dissipating rubbers, cross-laminated timber panels. The materials and assembled components were tested to identify durable and energy efficient solutions with improved seismic performance.

Furthermore, during recent years, the development and application of further new materials and technologies has been investigated, aiming to reach a technological and construction simplification compared to the existing products. These are, e.g. structural glass, structural adhesives, ceramics. A new constructive/structural principle, based on tensegrial structures, has been patented (Italian Patent no. 0001426973). Alderucci et al. have tested the mechanical performances of structural joints with several possible applications (for example pultruded/pultruded, glass/pultruded, glass/aluminium, pultruded/steel, glass/glass, etc.) made with different structural adhesives typologies in environmental conditions [2]. Further invented technologies are being patented, including a collaborating deck with structural adhesives and a strut for curtain walls. In collaboration with small and medium enterprises, the industrial production processes of some of these technologies have also started.

Given the growing need of proper decision-support tools for buildings design and operation, addressing all the complex set of environmental and economic issues, AE group research is recently geared toward the development of advanced assessment methodologies and softwares. An assessment tool has been developed, combining parametric building energy simulation and life cycle cost calculation, to provide designers an efficient mean of comparing the affordability of energy efficiency measures. Stochastic approaches to Life Cycle Assessment (LCA) and Costing (LCC)

Fig. 1 Exemplary page of the software tool developed by AE group for the probability-based LCA/LCC of building renovation measures

of building renovation were proposed [19], in order to overcome the limits of traditional "deterministic" methods based on notable simplifications and hypothesis that may affect results' reliability. A specific building renovation LCA and LCC software, based on these methodologies, has been developed during the framework of the Horizon 2020 project RIBuild[1] (Fig. 1). These works demonstrate the potential of probability-based building assessment in providing robust and realistic results.

2.2 Safety and Energy in Built Environment: Towards a (Human) "Behavioural Designed" Approach

The design of architectural spaces generally follows a "schematic" and "deterministic" approach. The architect generally believes that space configurations could be enough for inducing occupants to behave as he imagines. This approach seems to exclude behavioural aspects: real-world environments demonstrate how theoretical solutions scarcely comply with users' attitudes, desires' and, above all, behaviours inside buildings. People behaviour is indeed recognized as one of the key factor for the buildings energy assessment. People actions have a strong influence on the indoor environment both in a passive and active way. The former is related to users as sources of heat, vapour and CO_2, the latter concerns the interaction between people and building systems and devices (windows, heating equipments, etc.), not necessarily coherent with the energy reduction needs and caused by the perceived quality of the internal environment at each moment of the day [31].

[1] www.ribuild.eu.

The underestimation of the importance of the human component in the simulation environment led in the past to significant discrepancies between real and simulated building performances. Most of simulation softwares adopt yet simple deterministic rules to model behavioural features. These tools, neglecting the stochastic character of people behaviour and possible interactions between different users, are barely able to reproduce the actual patterns of occupancy and the interactions with the building devices. Unfortunately, this approach is still the most diffused, although some signs of progress have been achieved in last years.

Following the necessity of a shift in the research paradigm from the optimization of the components to the optimization of the interactions among people and components, AE group directed its efforts towards the experimental recognition of typical behavioural patterns and the development of simulation tools able to predict human-building interactions. Experimental activities have been performed to recognize typical behavioural patterns related to offices, dwellings, schools and other building types [23]. Surveys were performed using dedicated sensor networks to monitor environmental variables, and to determine the presence of people and their interactions with windows, plants and appliances. Then data-driven behavioural models have been developed to predict users' interactions with building devices [32]. The behavioural framework has been coupled with a simulation engine through a co-simulation approach which allowed the data exchange during the simulation runtime (Fig. 2). The research is addressed to extend to different building typos and climates developed behavioural models.

Human behaviour issues are relevant especially in emergency conditions (e.g.: evacuation and post-disaster phases) and are noticed at both building and urban scale. In fact, in case of disaster, the individuals' safety depends on interactions between buildings vulnerability, related to post-event damages and environmental conditions, human reaction to hazardous situations. As demonstrated by the recent research at the AE group, such interferences are critical in case of different man made (fire, terrorist acts) and natural (flooding, earthquake) emergencies, because of built environment features like: intrinsic hazard (presence of fire sources; positioning in earthquake or floods hazard-prone areas); intrinsic built elements vulnerability and

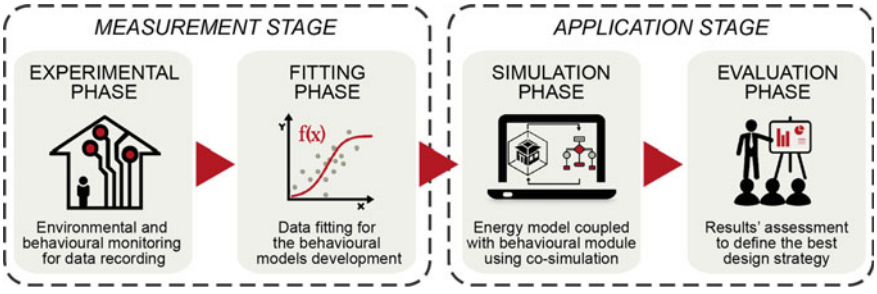

Fig. 2 Schematic illustration of the methodology developed by AE group for the experimental recognition of typical occupant behaviour patterns and their application in energy simulation softwares

correlation with event-induced damages (materials fire vulnerabilities; seismic vulnerability; structural vulnerability to floods); spatial layout, especially in complex spaces like urban ones, historical scenarios and public buildings, which can also have hinder safety to specific individuals' categories (disabled, elderly); possible individuals' low familiarity with the layout (visitors, tourists); high hosted people's density that introduces crowding safety stressors; organization of emergency management to cope with disaster by supporting the population evacuation (i.e.: evacuation plan; monitoring, alarm systems, wayfinding facilities). AE group work focuses on a "behavioural design" (BD) approach for increasing people's safety in architectural spaces [4]. BD is aimed at adapting architectural spaces depending on human behaviours. Defining how individuals behave in emergency conditions provides essential elements for safety assessment evaluation and risk-reduction strategies proposals. Evacuees-evacuees, evacuees-environment and evacuees-emergency management system interactions can be highlighted during the assessment and design phase, thus focused interventions and evacuation planning strategies can be proposed. Hence, methodology phases include:

1. *Understanding behaviours*: experiments/real world events analysis (mainly focused on human motion) both qualitative (behavioural), quantitative (motion quantities) and perception (i.e. brain activities) data are collected in relation to specific disasters conditions (fire, flood, earthquake);
2. *Developing evacuation simulation model*: models and simulators are defined and validated against experimental results [12] by integrating disaster-induced architectural spaces modifications due to disaster;
3. *Analysing emergency processes*: simulators are used to represent specific emergency conditions [4], and risk indexes are considered to include human factor in overall analysis [4, 27, 28], as: evaluation on the number of injured people/fatalities due to the disaster; probabilistic assessment of used evacuation paths in terms of evacuees' flows/densities; estimation of assembly areas use and possibility of "spontaneous" gathering areas; calculation of overall evacuation times.
4. *Proposing safety solutions*: they are based on retrieved critical behaviours and the impact is verified by simulator or drills [5]. Solutions include management strategies for rescuers, Internet-of-Thing based solutions which can directly help evacuees by using personal devices and intelligent evacuation signs.

Results show how emergency patterns could be retrieved to allow safety designers to propose a scheme for evacuation modelling and risk-mitigation strategies depending on the peculiar disaster reactions, especially for motion quantities. Using similar design methods based on effective human behaviours could lead to high level of sustainability for tomorrow architectural spaces, by: proposing interventions within the built layout where they are effectively needed by occupants; activating the response of building components only when they are needed by occupants; supplying information to occupants in the clearest way, and in each environment condition.

3 Construction 4.0—Productivity and Sustainability in the Digital Construction Industry of the Second Millennium

Having access to accurate information on time and in place is pivotal for construction management to tackle the remarkably poor productivity suffered for decades. The latest development of Digital Information and Communication Technologies provide the background to implement new revolutionary construction methodologies that will ensure the design is built and delivered in accordance with quality requirements, on time and within budget. The digitization of design and construction processes will drive the near future development of the construction sector. Digitization is about knowledge and value encountering connected systems and processes at every level of the operational chain. It is about working with ICT tools and processes that empower managers, filed engineers and workers by untangling the projects' values, allowing in-depth analysis of real situations, shortening reaction time to unforeseen events, and in general connecting the abstract understanding of the project with the contingency and the variability of the real domain. Four research lines have been identified at the DCM group of DICEA for the implementation of the digital construction vision, which are based on the envisage of a planning process grounded on lean design and construction principles:

- *Lean Building Design*—The biggest impact on productivity would come from institutionalizing value management and engineering throughout the building life cycle, from design to construction and operation. Strong and clear value chains propagating through the project development will reshape the relationships and interactions between owners and contractors. Constructability, sustainability and resilience will thus become major drivers of the design process, operationalizing along new dimensions the long-established efficiency end economy objectives.
- *Building Intelligence*—New constructions and refurbishment projects can achieve significant improvements in terms energy efficiency and sustainability by lowering the use of materials with high energy footprints, through the adoption of advanced intelligent technologies aimed at optimising the overall building behaviour in existing conditions.
- *Real-Time Construction Management*—Substantial improvements in construction efficiency can be achieved by means of real-time management supported by pervasive sensing and on-site site intelligence. Capturing information in real time, while the site and the whole process is in operation provides readily available data that improve the construction process in several areas, namely finance, quality and progress monitoring. Improved site information management would enhance progress measurement, equipment and material tracking, safety planning and productivity tracking. The new management approach will be supported by ubiquitous computing, on-demand access to a shared pool of configurable computing resources (e.g. networks, servers, applications, devices, data) that can be quickly accessed and discharged with minimal service provider interactions. Platforms such as 5D BIM would establish transparency in design, costing, and progress

visualization. On-site productivity can be boosted by implementing a cloud-based control tower that rapidly assembles accurate data in near real time, which supports advanced analytics to improve on-site monitoring of materials, labour and equipment productivity. Once working places can be connected, off-site fabrication can be encouraged by developing new lightweight materials and construction methodologies, which facilitates the adoption of advanced automated equipment and tools (bricklaying and tiling robots), which can accelerate on-site execution.

- *Operation and Maintenance*—Information management during the building operation phase represents one of the most critical aspect in the management of facilities. The retrieval of specific data during the lifecycle of buildings in fact represents a high cost for all the stakeholders involved in this field. The digitalization of the Architecture, Engineering and Construction industry is a great opportunity to improve this process, by providing geo-located and timely information pervasive sensing and through augmented reality technologies.

In the following sections, some of the main results achieved so far by the DCM group for the above topics are summarized, providing reference to the main papers.

3.1 Real-Time Construction Management

Construction projects are significantly affected by the level of awareness about the project status. Information has inherent value for real-time or near real time decision making in construction management. Good resource procurement and allocation, project risk mitigation and safety assurance can be effectively assessed if a relevant and timely information flow is provided to the decision makers. In this field a proper ICT technology development is necessary to interface the construction site dynamics and harshness. The following results show that current technology let one trace the construction site workflow in such a way that safety and productivity can be significantly improved.

In [9] an advanced system for the real time tracking of workers' paths in construction sites, aimed at preventing workers' hazardous situations, has been investigated. This research was part of a wider ongoing research concerning the development of a new generation of advanced construction management systems, allowing for real-time monitoring and coordination of tasks, automatic health and safety management, on-site delivering of technical information, capture of as-built documentation. Exploiting the high accuracy provided by the ultra wideband (UWB) system responsible for position tracking, the proposed solution can trace movement patterns of workers and induce likely paths. The system constantly monitors hazardous areas accesses, using its path prediction capability, in fact performing virtual fencing. In [14] the strength and weakness of UWB position tracking technology, and its completion with Zigbee technology, applied to building construction environments have been further investigated. UWB position tracking has demonstrated to be completely reliable in real world construction sites up until the completion of structural

frames, providing support for real time management and health & safety tasks. The UWB indoor tracking capabilities in boundary installations fade considerably when envelopes and partition walls are raised. In these cases, optimized UWB design with increased number of receiver or hybrid design merging UWB with *ZigBee* based zoning systems are both possible. In the first case the tracking resolution of the UWB system is maintained at the expense of an increased number of receivers, rising significantly the equipment and installation costs. Anyway, it is often the case that UWB boundary installation cannot suit indoor tracking in some spaces whatever number of receivers is used. In that frequent case hybrid mode position tracking design can provide support for high level management tasks. In general, hybrid mode position tracking in construction sites is still an open research issue. More specifically the open issues concern the sensor fusion approach and the relation between the tracking accuracy and the level of support of high-level management tasks. Sensor fusion can be as simple as switching between systems in case of tracking failure, or much more complex as merging information at data processing level, developing hybrid TOA-SS algorithms. How optimized performance can be achieved in hybrid frameworks through careful layout design of hybrid sensor systems is a second point that requires investigation and on-site testing. In this chapter we have shown how boundary UWB set-ups can be complemented by *ZigBee* zoning systems deployed in the inner indoor spaces. Nevertheless, in these cases some redundancy can be used to increment reliability of the UWB tracking and the robustness of the overall solution. To what extent this can be done is still a research topic. Finally, the localized lower resolution provided by the *ZigBee* zoning system may potentially downgrade the support to the high-level management tasks. This depends both on the resolution and on the specific lay-out of the tracking solution with respect to the spatial arrangement of the working activities. Naticchia et al. [25] and Carbonari et al. [10] survey the feasibility of a cable less real-time monitoring system to provide prompt support for inspectors in charge of health and safety management on construction sites. The system was tested in the specific application of monitoring interference between teams working on large construction sites. The system accounts for a wireless and untethered tracking technology and a local server running a software tool for handling collected data, real-time site state visualization and remote interaction with safety inspectors. The low-level tracking technology is a ZigBee-based easily deployable and reconfigurable technology. In this paper the system is found to be able to cover large fields while keeping its non-invasive features, thanks to the implementation of a novel low-power approach. This paper shows the degree of support inspectors can get from the system: it is able to alert in the occurrence of interference and to log any unexpected behaviour.

Giretti et al. [13] provide further development of real-time monitoring technology by investigating the application of intelligent probabilistic models to real-time estimation of construction progress, which operate based on a continuous data flow collected by monitoring networks deployed on-site. Several authors listed the advantages that would be provided by the availability of such models, like project performance and quality control, timely onsite inspections, better control of health and safety prescriptions against job injuries and fatalities. The findings reported in this

paper represent a feasibility study and preliminary examples of Bayesian Networks, which can infer the work progress attained at every step, starting from real-time tracks of the construction site activities. Activity tracks are represented as a set of state variables representing workers' effort, equipment and materials usage rates and other knowledge about the context. As estimations are always related to dynamic processes, Dynamic Object-Oriented Bayesian Networks have been used to develop a set of first order Hidden Markov Models. Hence, the models are arranged as a sequence of time steps, where each time step propagates evidences collected by the site monitoring sensor network along the time line. The actual cumulative progress is computed as a function of the progress achieved in each time step. Models representing several typical tasks (external piping, on-site cast of reinforced concrete floor slab, walls erection, ceiling installation) for a real case of a construction site have been developed. Their structure has been designed as part of a general monitoring framework, covering all the phases from design to execution, where BIM design, monitoring systems, methodological process innovations, intelligent inferences and advanced visualization are combined. The networks have been developed and validated through data collected from a real case, and they have been shown to be able to infer work progress, the accuracy of which depends on the resolution and quality of the collected data.

3.2 Digital Frameworks for Real Estate and Facility Management

Building operation is the phase of the entire building life cycle which produces the highest costs. However, to date little attention has been paid to its optimal management. ICT can provide significant advances in this field. The digital approach to real estate and facility management relies on a juxtaposition of emerging ICTs which are all grounded on the BIM technology. Then cloud systems for distributed data management, artificial intelligence for decision support, and mixed reality for on-site operation support, provide the background for advanced facility management solutions.

The efficiency issue in facility management surveying is discussed in [7]. Surveying of large real estate management is an expensive activity that affects strategic management, providing data for key performance indicators, and the operation & maintenance, through the assessment of the status of systems' components. The paper proposes a system that performs multicriteria probabilistic assessment of key performance indicators related to accessibility, energy efficiency and acoustic comfort with reduced time and costs. This is made possible using Bayesian Networks models that are able to incorporate different level of certainty about data, thus providing a graded and smoothed outcome of the assessment process with respect to the available information. The research discussed in [8] is analogously concerned with

the management of large building stocks, where available information is often incomplete and the process of information updating is expensive and time consuming. Many public administrations, developing BIM models of their stock to mitigate the lack of information issue, are encountering severe problems in making the modelling process sustainable, due to the high cost of surveying and information filling. The paper presents a decision support tool, aimed at can help prioritizing refurbishment actions on large building assets, based of probabilistic models, that mitigate the information lack by quantifying the uncertainty level of approximate assessment. The system supports multi-criteria decision by means of Bayesian Networks models instantiated automatically from BIM models. Key Performance Indicators corresponding to different requirements are compared through multi-criteria analysis, each building is assigned an overall score and a ranking is created. Naticchia et al. [24] aim to provide advanced support for the operation and maintenance phase during building life-cycle. This study focuses on the combined use of three key technologies, the BIM for data management, cloud-based management of the information flows and onsite operation support through mixed reality.

3.3 Intelligent Control of Building Systems

The construction 4.0 revolution cannot but affect the building itself. Intelligent buildings are the natural technological evolution of traditional passive buildings. The pervasive layout of sensor and communication networks makes possible intelligent control, optimised performance and advanced interactions with the occupants. So, intelligent building modelling and controlling, and occupants' behavioural models are key research themes in this area. Casals et al. [11] and Vaccarini et al. [34] reports about the intelligent energy control of a metro station in Barcelona, developed within the SEAM4US FP7 EU project. The predictive energy control was implemented by means of a stochastic model of the energy behaviour of the metro station. High rate of energy saving was achieved by dynamically adapting the various fan speeds to the environmental indoor and outdoor conditions measured to an extended sensor network. Predictions were provided by a stochastic model of the station whose parameters were induced from measured data. This kind of models can be extended to house environment once behavioural models of the occupants are developed. Jones et al. [21] investigate about the possibility of predicting home occupants' behaviour concerning windows operation from environmental data. Finally, the same models used for control can be adopted in performance contracting. Intelligent buildings are more reliable in providing established level of performance. Thus, both Principi et al. [26] and Giretti et al. [15] investigate minimum information modelling methodologies suited to provided rapid and reliable assessment of energy consumption and robust forecasting.

4 Conclusions

Even if construction industry is one of the largest sectors of the world economy, it is suffering for decades from poor modernisation, thus maintaining huge energy and environmental impacts. The recognized road to innovation in this sector is based on technology development and digitization, in order to reach higher levels of sustainability and resiliency facing the actual climate challenges. The paper discussed the major research results achieved by the Construction division of the Department of Civil and Building Engineering and Architecture (Università Politecnica delle Marche), concerning optimised innovative, durable and sustainable technological solutions for building design, construction and management. From the outlined framework, the following key research directions emerged:

- the development of building technologies able to integrate, in a logic of constructive simplification, multiple aspects and functions, as energy efficiency, seismic resistance and high durability, reducing environmental impacts, costs and construction time;
- the development of "cognitive" building technologies able to adapt and respond to the users' needs, involving several performance domains (e.g. energy, comfort, safety, durability);
- the development of effective building design and management tools, able to address in an efficient way all the complex set of design, performance, environmental and economic issues;
- the development of a real-time construction management approach, supported by pervasive sensing and on-site site intelligence;
- the development of digitization of design and construction processes, in order to optimize these processes.

Addressing all these challenges is the actual contribution of the Construction division of DICEA for a more sustainable and resilient Construction 4.0.

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Cultural Heritage and Landscape: Analysis, Digitization and Design Aiming at a Resilient Future

Antonello Alici, Paolo Bonvini, Paolo Clini, Maddalena Ferretti, Eva Savina Malinverni, Fabio Mariano, Gianluigi Mondaini and Ramona Quattrini

Abstract The paper aims to present research activities about cultural and built heritage at various scales, from architecture to landscape, highlighting how innovative analysis and design approaches can challenge the current methods and pursue the main scope of increasing heritage resilience. The main scientific focus, heritage, works as a cross-cutting topic that is investigated according to the different disciplinary perspectives. At the same time this issue is able to merge the diverse souls of the research team: history of architecture, geomatics, drawing and survey, restoration, regeneration and design. Major results and findings are discussed throughout a set of case studies. These allowed to develop tools to perform rapid surveys and multilevel readings (stylistic, structural, historical, behavioral, etc.) as well as robust procedures for interventions and recycle at different scales of built heritage. Technologies and procedures are tested and validated on these cases that serve as prototypes. Finally, the paper aims to possibly extend the validated approaches to similar cases in the

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heritage field. The main research activities, indeed, entail the definition of the fundamental paradigms of resilience for heritage and landscape, against the backdrop of the contemporary techno-cultural revolution.

1 Introduction

In recent years the main scientific focus of our research team[1] has been the cultural and built heritage, a cross-cutting topic investigated according to the different disciplinary perspectives. Yet, especially in the European Year of Cultural Heritage 2018, this issue gathers together the diverse souls of the group and it best represents our current and future scientific focus for further development in research and innovation, both at local and international level.

Heritage is read throughout the paper according to its potentials, as expression of identity, as digital cultural innovation, as experienced landscape, as sensitive object of restoration, as motor of development. Clearly, this reading leads to consider heritage as the most valuable legacy of the past, but at the same time it stresses its condition of vulnerability and fragility. What we decide to preserve and how we perform this action involves a quantitative and qualitative evaluation that, when it comes to heritage, must consider the values, but cannot overlook the risks. Resilience becomes thus a crucial concept to be embedded into heritage. Therefore, this contribution highlights how innovative analysis and design approaches can challenge the current methods and pursue the main scope of increasing heritage resilience (Fig. 1).

2 Positions Towards a Methodology

The consolidated approaches on heritage are historically based on a strict disciplinary methodology that we consider as a starting point and a solid base to configure and strengthen a multidisciplinary and horizontal approach that potentially builds an innovative way to study and act on heritage. This paradigm change, as expressed in the positions below, possibly opens to follow-up projects and cross-fertilization opportunities for the team. Moreover, the multidisciplinary methodology enables fruitful and more integrated exchange with local communities and stakeholders to root more effectively these actions on cultural and built heritage.

[1]This paper gathers contributions from the Architecture Section of the Department of Civil and Building Engineering and Architecture of Università Politecnica delle Marche.

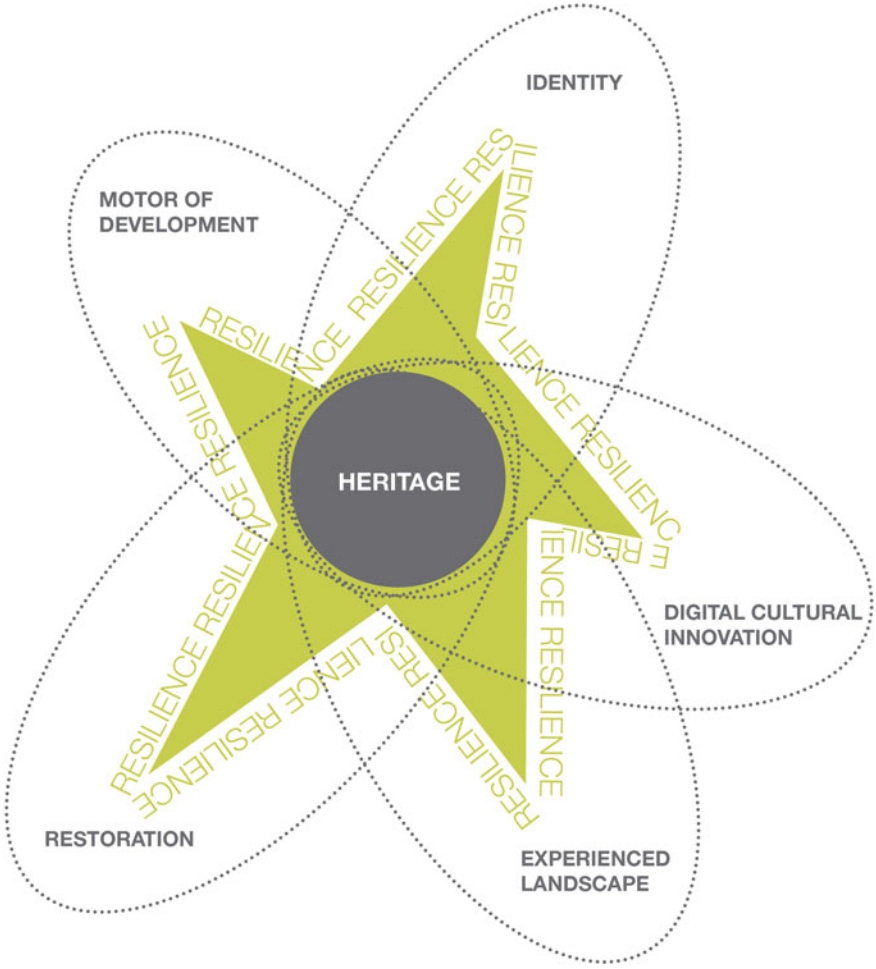

Fig. 1 Positions towards a methodology to increase heritage resilience in fragile contexts. Graphical abstract of the paper

2.1 Heritage as Identity

> It must become a common belief what Italian and foreign scientists say, that Italy must learn to live with earthquakes (…) if the damage to the significant architectural heritage is serious, much more serious are announced damages to choral values, episodes of minor interest (…) We need interdisciplinarity extended to the most difficult relationship: the one between the sciences of nature and the human sciences. Soil and habitat technology must meet with anthropology, sociology, the psychology of space….[2]

[2]Pane R. (1980) Proposte per la ricostruzione, Napoli, pp. X–XI.

The extreme fragility of Italian Apennines, frequently marked by traumatic events, imposes a drastic change of strategies and suggests the urgent need of long-term planning action. Among the primary causes of this fragility is the growing distance between the urban sprawl on the coast and the river valleys and the depopulation of the internal areas, hills and mountains.[3] The national and regional policies have largely ignored the risks linked to this phenomenon, which can preclude a future to a cultural heritage of a certain value, and particularly relevant for its variety. To raise the awareness of these values among the citizens is among the primary responsibilities of the scientific community, called to translate research into a capillary educational action. The first step is to consider the concept of heritage not as a static inheritance to which fixed and enduring values are applied, but based on a process of identification of significant places understood as valuable for their communities. The establishment of value is central to the act of conservation, which gives a place (building, object or environment) cultural, economic, political and social value. According to 'Historic England', "Conservation is the process of managing change to a significant place in its settings in ways that will best sustain its heritage values, while recognizing opportunities to reveal or reinforce those values for present and future generations" [6]. This leads to modern conservation strategies principally characterized by the fundamental change of values in contemporary society, sensible to the specificity of heritage resources in relation to their cultural and physical context [2, 16].

The seismic events that have again hit the four Apennine regions—Umbria, Lazio, Marche and Abruzzo—in 2016–2017 offer an interesting scenario and an opportunity for a new approach in research and experimentation. The starting question is to consider the seismic nature of these areas as a constituent element, not extraordinary, as earthquakes have always formed part of the region's history, and its identity, also in the adaptation of the building forms and technics. The identity values of these internal regions and provinces are deeply rooted in the place, the links of the inhabitants with their own land are just as profound and ancient. The risk of loss of collective memory is exacerbated by the practice of the despoliation of mobile artistic assets collected in external repositories and the dispersion of populations in other areas, as was in L'Aquila after the 2009 earthquake.

The research has to focus on how the response to the earthquakes has shaped towns and villages, how it has affected the evolution of building technics, marked religious worship, as well as the rituals of the communities. Therefore, to study the history of these events is a priority, it can offer an opportunity to re-write the history of these places, with the help of the archival sources, mainly unexplored, and through a systematic survey of the wide urban, architectural and artistic heritage. This is the base for the assessment of the values and the way to preserve the authenticity of the places, orienting their conservation and sustainable changes [1, 7, 14].

[3]The Post-Seismic Reconstruction of the Apennines areas hit by the 2016 earthquake is the topic of a Univpm research unit named "M.I.A.—A Multitemporal and Interdisciplinary Approach to the Post-Seismic Reconstruction": Augusto Ciuffetti (coordinator), Francesco Chiapparino, Micol Bronzini, Antonello Alici, Marco Armesano. On the topic see Zullo F, Marucci A, Fiorini L, Romano B (2018) The Italian Apennines between earthquakes, high naturalness and urban growth. In *Environment and Planning B: Urban Analytics and City Science*. 0(0) 1–16.

From this picture comes the research project 'Living with Earthquakes. A strategic plan for earthquake prone regions', a cooperation between Università Politecnica delle Marche and University of Cambridge, to establish a strategy to prevent or mitigate damage in the future.

The aims and strategies were discussed in a two-days seminar in Cambridge, Jesus College, in 24–25 October 2017, gathering international experts from the disciplines of engineering, earth sciences, sociology, architecture, history and the history of art, to address holistically an issue that is frequently only examined with a narrow focus, as well as to establish a larger scale strategy for the prevention of damage in the future, that ensures the sustainable rebuilding of communities, and the recording and analysis of cultural heritage. The choice of a small town—Amandola in the Marche region—as a case study was valued as a unique and time-specific opportunity to work with a particular community in the key post-catastrophe phase of reconstruction, carrying a much, larger significance [7, 14, 19, 29] (Fig. 2).

A postgraduate summer school held in Amandola in July 2018 proved the advantages of the dialogue between different approaches and expertise. The main interest was into the focal area of the partly abandoned historic town waved into a beautiful hilly morphology. Here is the medieval convent of San Francesco, with severe damages. The first architectural proposals were informed both by the analysis of the fabric that the engineers produced and by the work of art and architecture historians, who

Fig. 2 Comparison of point clouds model after the 2016 earthquake and FEM model of the monastery of San Francesco, Amandola: data processed during the summer school

were able to inspect the building and to consult the remarkably complete archives. The final work has been organized in four topics—*urban history*, *landscape*, *public spaces*, *San Francesco*. A special attention was given to the participation of the inhabitants, with filmed interviews aimed to learn from their stories and memories but also to give them hopes for a better future of their place.[4]

2.2 Heritage as Digital Cultural Innovation

Digitization of Cultural Heritage is a multidimensional process, which helps in the rescue of common European Cultural Identity increasing awareness of values and memories. Making sense of Europe's Cultural Heritage (CH) means to shape the new reflective societies [8] starting from digital cultural heritage and diffusing adaptive methods for conservation, fruition and social inclusion. A specific standpoint to the CH lies in the digitization processes in order to answer to well-known needs and to face challenges such as to increase synergies of competencies among all actors with the main goal of its sustainable use. Advancements in those fields are able to enhance the principle of shared responsibility [10].

A favourable arena to perform this kind of researches is certainly the museum context: museums are more than just places where collections of artworks are preserved and exposed, they display identities and cultures. These institutions make culture accessible to the mass audience and, in the majority of Italian cases, they are hosted in a historical building. The Cultural and Built Heritage collection, conservation and access in novel, accessible and attractive ways demand for digitizing museums and archaeological/historical sites, as well as for designing methodologies to represent, manage and exploit cultural heritage data at different levels, ranging from 3D/4D models to specific domains such as the architectural and historical one.

The use of virtual "facsimiles" of artworks, monuments and architectures can unify their scattered elements, allowing public access to inaccessible places, easing the visitors interaction with perishable objects, promoting the preservation of fragile sites by simulating damaged or lost objects. The availability of semantically enriched data enables smart applications for fruition, preservation and study of Digital Cultural Heritage (DCH) collections. The development of DCH has the potentiality both to collect and disseminate the cultural heritage in an effectively and low-cost mode and to implement a key strategy to interact with virtual "facsimiles" in order to engage users, increase capabilities thanks to the application of the "learning by interacting" paradigm, to diversify museum's cultural proposals, etc.

In this context, we are developing a Strategic project (PSA) founded by our University and called CIVITAS[5] (ChaIn for excellence of reflectiVe Societies to exploit

[4]For further details, see https://thecultureofthecit.wixsite.com/cultureofthecity.

[5]The CIVITAS team is composed by: Paolo Clini (PI), Paolo Bonvini, Enrico Cori, Aldo Franco Dragoni, Filippo Gabrielli, Danilo Gambelli, Maura Mengoni, Christian Morbidoni, Ramona Quattrini, Mauro Silvestrini, Massimo Tamberi.

dIgital culTural heritAge and museumS. A pilot case in Palazzo Ducale at Urbino). The project deals with 5 strong Challenges:

- Digitalization of Cultural Heritage at different scales,
- Digital Content Management for 3D/4D semantic-aware models,
- Enhancement of Visitor Experience and Social Inclusion,
- Fruition by multisensory (visual, haptic, sound) Interaction paradigms,
- Business models based on Digital Heritage for Culture, Research, Tourism, Reflective Society promotion.

They open up a large variability of chances in sustainable exploitation and conservation of cultural heritage: the present paragraph explains main achievements connected with the resilience paradigm as depicted in all approaches of the paper. The development of the DCH concept in the light of resilient heritage challenge requires a chain of interdisciplinary competences able to face the main issues, both methodological and technological, from different and interlinked perspectives (Fig. 3).

With particular regard to the digitalization workflow, we experimented the combination of a large variability of 3D sensor technologies to acquire and merge shapes at different scales (geospatial, architectural, sculptural, pictorial, and archaeological) and with different levels of accuracy. A really innovative technique based on the combination and matching of the various datasets with different levels of detail

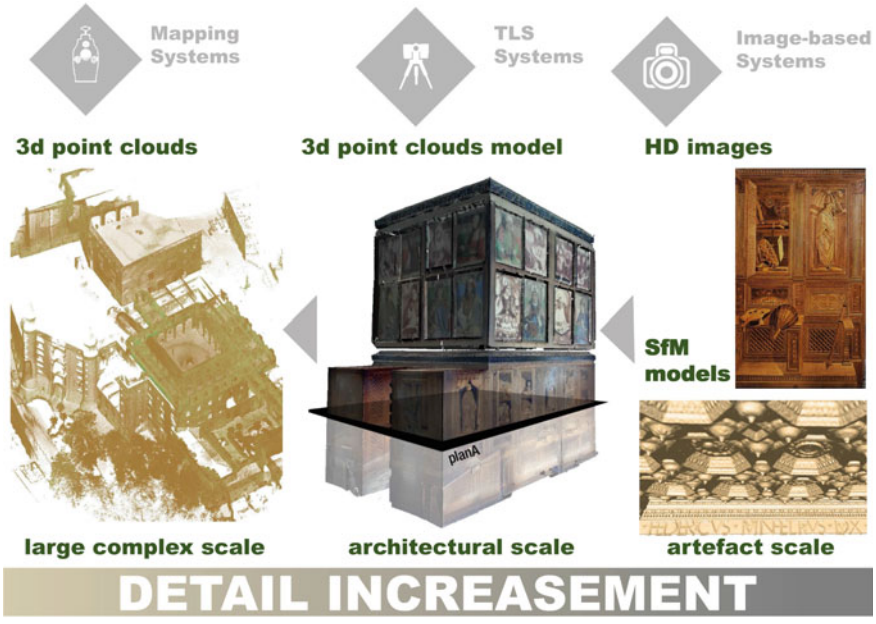

Fig. 3 Different acquisition systems, data and LOD obtained in the CIVITAS project on Urbino's Ducal Palace

(LOD) captured by photogrammetry (SfM), 3D terrestrial laser scanner (TLS) and wearable mapping systems are developed and assessed. The 3D models include HD pictures, to obtain a high-quality realistic representation.

In this research line an innovation is represented by the study and application of non-invasive acquisition systems to digitize paintings, frames, frescos, tapestries, etc. The first achievement is a points cloud of the Urbino's Ducal Palace characterized by high resolution and accuracy to match it with the captured HD images in order to use the model both for digital collections and fruition, and for conservation and restoration.

The workflow and the LOD technique are applied for the digitization of the Palace and its art collections (National Gallery of the Marche): the first multi-scale experience in an Italian museum.

The challenge regarding the DCH archiving and management has been developed with a particular focus on HBIM (Historical Building Information Model) tools and solutions. In this context the application of Linked Data and Semantic Web technologies [21] are expanded and a methodology has been implemented to provide accurate, semantically reach representations of the BIM models. Addressing this challenge, CIVITAS project enables advanced intelligent exploration by building on top of emerging specifications and by enriching the data model with domain knowledge and links to the Web of Data. The adoption of the Linked Open Data paradigm offers new possibilities for the heritage, making it easier to aggregate, publish and expose data to users and smart applications developers. This, in turn, constitutes a key element for enabling on-line presentation of DCH. CIVITAS designed and validated workflows from reality-based models to deliver 3D and paradata/metadata, with different purposes/Level of Details/users/enrichments (crossing of disciplinary boundaries).

Finally, to serve dissemination purposes, advanced Virtual/Augmented/Mixed Reality technologies [4, 5] are combined and adopted, suited and adaptive to different user profiles e.g., children, average users, professional users, etc. Although these technologies are mature enough, they do not represent a mass phenomenon, especially in DCH. This step represents the backbone of the heritage democratization implementing shared responsibilities.

Similar researches are dealing with Strategic Objectives and Actions of the New European Agenda for Culture [9]. In addition, further development in the mid-long term time are expected to face the social dimension in order to protect and promote Europe's cultural heritage as a shared resource with the aim to support culture as an engine for sustainable social and economic development and to enable and reinforce the cooperation on cultural heritage. In fact the address documents by EU commission in the European Year of Heritage [11] remembered that, in order to realize fully the potential of cultural heritage, the safeguarding, enhancement and management of CH require effective participatory (i.e. multi-level and multistakeholder) governance and enhanced cross-sectoral cooperation. Those considerations move our research in the future to implement their interdisciplinary character.

2.3 Heritage as Experienced Landscape

This paragraph presents the use of ICT (Information and Communications Technology) and geolocated information to improve the quality of life in Public Open Spaces (POS), responsible for the identity of our cities, from different points of view. The challenge is to foster the landscape by the growth of digital devices, so that they become common tools in several fields of human activities, connecting, guiding, informing, and making people interconnected and informed in spaces such as parks, gardens, squares, plazas. The geo-located information allow a new approach in planning POS, in order to create more attractive and inclusive spaces in our cities, following the new concept of resilience. Moreover, the use of digital technologies attracts people to spend more time outdoors for a more active lifestyle by means of pervasive but not intrusive services to increase the knowledge about uses of public open spaces. The type of results produced allows a quick and efficient collection of data that may be essential for creating new public spaces and improving existing ones.

In few years the use of ICT and the introduction in fast and spread way of mobile devices have grown the interaction with the outdoor spaces, from architecture to landscape, highlighting how innovative solutions can challenge the current way to approach and to live the space increasing the heritage resilience.

The multidisciplinary experience made on the Cardeto Park in Ancona (in the frame of CyberParks COST Action TU-1306) has provided new forms of interaction with the space [27]. The Cardeto Park, for its characteristics (from the natural and historical side) and its geographical position, is a good testing area for the experimentation of new ICT oriented strategies.

The innovative solution improves the use of Public Open Spaces (POS) by the visitors; in fact tracking the user digital footprints, the knowledge of POS, in terms of security, cities management and cultural heritage, is improved [15]. In the same manner, the stakeholders, which can have access to the so-called User Generated Data, in the future could use them to analyze the dynamics of the environment and guide the planners [22]. This approach could allow to develop tools to perform fast surveys and multidisciplinary procedures for interventions in emergency situations such as seismic areas, improving heritage and landscape resilience.

The main advantages of combining ICTs and POS are related to the possibility to have real-time data gathering, to maintain and update the data in a geographical information system, related to different activities of the users, recording the user opinion and sharing them with different stakeholders to plan the space.

The people, using increasingly mobile devices in public spaces, change the way to interact with other people and their surroundings and the ICT tools represent a good opportunity to foster a “cyber” dimension for the POS. In fact, the interaction between digital and real worlds, create an augmented way to live the open spaces [28].

Our experiences related to a green public open space (Cardeto Park in Ancona) produced a solution called “CyberCardeto”, where the ICT potential innovative solutions enhanced the space, not only improving the information on the POS useful for

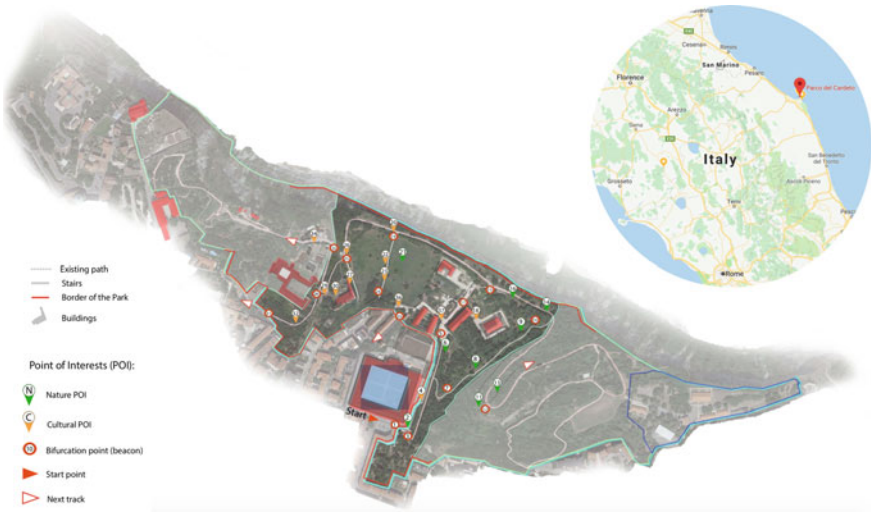

Fig. 4 The map of the Cardeto Park with highlighted the POS developed for experiencing the heritage landscape by a mobile application

the visitors but also transforming this public open space in an interactive space useful for its planning (Fig. 4).

CyberCardeto is a mobile application developed to create a Senseable Space, where there is a seamless exchange of information between the users and the technology installed on it [20]. In fact, the application can be used once the user gets into a public park, since it provides contextual information about the POIs by multimedia contents. The user is geo-localized continuously into the map of the park. The application is paired with sensors (beacons), installed in the park and activating the notification of the attractions once the user gets into the radius of influence of each sensor. The sensors are also enabled to collect the information from the user devices, storing data in a remote repository for future statistical inferences.

The mobile application was designed to guide the user among the visit path and promote a close synergy between visitors and the place. Moreover, to improve the capability of the park to suggest the path to the visitors, beacons have been also installed in bifurcation points leaving to the user the free will of choosing his/her own preferred path [18]. Notwithstanding, other functions increase the users experience.

Improving the quality of public urban spaces is a challenging task, that can become sustainable only if there are healthy and livable places. The quality of a sustainable city is expression of a variety of benefits and opportunities linked to social interaction where the aspects as safety, accessibility, quality, resilience and design of these spaces are mandatory. This is a good opportunity not only for landscape architects, urban designers, planners and so on, but also politicians to prioritize the inclusion of quality public spaces in the urban agenda, moreover for the resilience of the urban and not urban place.

Digital technologies can help in the future the development of cyberparks or cyber public open space in general. The central challenge remains how to use digital technologies to transform our cities into interactive landscapes and urban places, encouraging involvement and better social environments, supporting sustainability, responsibility, and knowledge about nature, people, and city.

2.4 Heritage in Architectural Restoration

> Two are therefore the cornerstones of every restoration: one concerns the problems of architectural criticism with all the implicit premises of historical knowledge and creative sensibility through which the formal quality and the degree of intervention on the building to be restored are filtered and controlled; the other consists in the possession of the most various and most advanced technological procedures and in the ability to adopt them in the moment and in the right and appropriate measure.[6]

The statement of Sampaolesi [25], admired master of the late friend Marco Dezzi Bardeschi, configures the profile of the "Restoration Designer" in its modern and consolidated sense over time, which is becoming more and more the coordinator of the intervention team (structural, physical, chemical, plant engineering, etc.) for the conservation of a monument of recognized historical architectural value, certified by the official attachment of the bond by the state officers for the protection of the monumental heritage.

To this irreplaceable professional figure it is up to the burden and the honour of the evaluation of the ensemble of information and cognitive data essential to achieve the necessary awareness of the complex system of values on the basis of which a credible design criterion of restoration/conservation intervention can develop.

The Architectural Restoration Course aims at training the Restoration Designer as a professional able to know and understand an architectural and environmental asset in its historical evolutionary aspects, in its structural and material components, in its intrinsic and environmental cultural values, in order to coordinate with conscience and competence the overall project of restoration/conservation of the historical artistic artefact according to the updated principles of theory and technique, for the purpose of its correct recovery, reuse, protection and future maintenance.

For "Restoration/Conservation" should be understood any intervention aimed at protecting and transmitting to the future a historical-artistic and environmental artefact, facilitating the reading of its parts evolved over time, placing in a reversible way its structures and surfaces and guaranteeing the duration and its transmissibility over time, finally providing the criteria for its maintenance over time. However, it is a "critical act" by the designer, whose reliability increases as a function of the analytical knowledge of the artefact on scientific and cultural bases.

The cognitive aspects of the monument (documentary history, dimensional surveys, documentation on previous restorations, diagnostic analyses, etc.) are therefore

[6] P. Sampaolesi, Discourse on the general methodology of restoration of monuments, Florence 1973.

an indispensable basis for any correct restoration work. The history of the factory's past must be reconstructed, aware that the great book of architecture is a stratified and constantly changing palimpsest where every generation continues to overwrite, leaving traces of its history and its own passage.

Parallel to historical documentation, the preliminary step to any restoration work is the survey; an instrument that provides the necessary basic knowledge of the existing physical state of the artefact on which it is necessary to intervene. Now the phase of the "representation survey" has passed by, the evolution and the widespread availability of digital and informatics tools has provided new ways of restoring graphics through the combination of digital photography and CAD programs and graphics, and today always the ever more ineluctable collaboration between the restoration/conservation designer and the Geomatics disciplines, with the contribution of the geo-referencing of the works aimed also at the direct reading of the specifications. The relief for conservation is not limited to a geometric restoration of the building but investigates the state of degradation and the pathologies suffered by its materials. Next to the geometric survey it is therefore necessary to produce a "pathological" material survey in which the different materials of which the factory is composed, their forms and causes of deterioration are highlighted. In these updated forms of importance, the IQM or "Masonry Quality Index" should be added, now recognized, also at regulatory level, as one of the focal points for the analysis of the structural behavior of a masonry construction.

Finally, bearing in mind that the specificity of architecture is the fact of being an artefact with respect to which an exclusively contemplative attitude cannot be implemented, having its sense in a functional destination. From this point of view the restoration/conservation of a monument cannot but imply a reuse purpose. To implement a concrete and effective conservation of the existing must therefore reactivate its use, a use that may be different from the past destination but still compatible, that is to say it must imply less consumption and maximum respect for the reached material consistency of the factory. "Knowing how to preserve in order to innovate" is the motto that summarizes the restoration theory of Dezzi Bardeschi. What it means to combine conservation, intended as the maximum respect for the existing, innovation, that is the recognition of the autonomy of the new project. As a consequence of the theoretical premises, the course of Architectural Restoration provides students with the guidelines for the use of the indispensable tools for the complex preliminary process of cognitive analysis of the monument, and the development of a synthetic vision of the restoration/conservation project, simultaneously giving awareness of the social ethical value of this professional commitment.

2.5 Heritage as Motor of Development

Although it might look like an oxymoron, there is a very strong invention behind the idea of preservation. Preservation was *invented* as a modern theory and architectural practice, as well as a disciplinary field, in the time between the French revolution

and the industrial revolution in England. It was an innovative approach to existing architecture that was crucial to manage how societal radical changes would affect physical spaces and living habitats. In the exhibition Cronocaos, at the XII Venice Architecture Biennale in 2010, Rem Koolhaas highlighted this aspect to stress that preservation and modernity are not opposites [17]. As far back as 1992, in her book "The invention of the historic monument" [3], Françoise Choay expressed a similar concept, stressing how different times and cultures produce different concepts of permanence, tracing back from Aldo Rossi's theory on 'urban artefacts' and 'monuments' [23]. Nonetheless, during most part of the XX century, a more conservative approach to built heritage is noticeable, somehow overwriting the original inventive character of preservation (Ruskin, Morris, Viollet-le-Duc).

The idea of heritage as isolated element disconnected from its context, due to its fragility and vulnerability to environmental and anthropic factors, has prevailed for decades, focusing mainly on the conservation of the physical and spatial characteristics, often without a clear address about usage and maintenance, and thus with consequent risks of decay. As heritage's value is intrinsically linked to time and perception, permanence and memory, it may be difficult to acknowledge new forms that, despite not being included in monuments' protection lists, still could or should be recognized as shared societal values. The idea of conservation should then give way to more flexible readings and uses of heritage to open up a wider and more comprehensive perspective. Design and creativity could become tools of this more inclusive approach, as well as preservation, in the sense addressed by Koolhaas in Cronocaos, an instrument of architectural thinking and invention [17].

After all, as Tancredi puts it in one of the last scenes of "Il Gattopardo" addressing the prince of Salina: "If we want things to stay as they are, things will have to change". And, sharing the position of Rossi in his s*cientific autobiography*, "To conserve everything in cities, does not prevent the change" [24]. How to govern this inevitable change is a matter of design. It is about how to shape and address needs, risks, and potentials, both at strategic and operational level in order to give impulse to the sustainable development and spatial enhancement of places and increase quality and resilience in fragile contexts. Indeed, design can help replacing traditional approaches to heritage with a fresher perspective. New concepts related to architecture and urban design and connected to city and territorial development can be introduced (e.g. recycle [26]), as well as a more open idea overcoming canonical interpretations. A refreshed understanding of heritage, as part of more complex spatial structures, as potential and crucial motor for new dynamics of development[7] [30], as pattern of a larger system of relationships with new aesthetic qualities is needed [12].

This perspective is particularly relevant when looking at post-earthquake territories, fragile emergency areas that need to regain resilience after a traumatic event. The areas affected by the 2016 seismic events of the Marche Region have been investigated through design classes and graduation theses. In June 2018 these works have

[7]In 2015 the UNESCO Convention on World Heritage has included for the first time the concept of sustainable development associated to heritage.

gathered into the event "OPEN HERITAGE", which represents the first milestone of this *research by design* process.[8]

The emergency situation can become the impulse to activate new opportunities and uses, to adapt the spaces to the new needs of living, to undertake technological innovations and to involve local communities in a more conscious and shared way in the recycling and enhancement of their built environment, in order to revitalize the perception and the feeling of identity that only the care of their heritage can convey. Through the design experiments carried out, we tried to explore methods of intervention that are able to represent a record of practicable intervention models, verifying them on some case studies of the seismic crater of the region, aimed at the selection of specificities capable of constituting a solid basis for rebuilding an identity and an economic system.

Among the possible intervention models already pursued, there were some possibilities, alternative and antithetical for the consequences that they imply: to proceed by building *New Towns* or through the restoration of the existing heritage. Building new houses outside the perimeter of the destroyed municipalities or rebuilding the houses devastated by the earthquake. Is it about placing new interventions according to Civil Defense plans, in a formal, technocratic and supposedly 'neutral' way to solve immediately the critical situation? Or is it about questioning the duration of these new forms of settlement, that intermediate time which constitutes the temporal horizon during which they will affect the lives of the inhabitants, interacting with their social, economic, emotional needs? (Fig. 5)

Fig. 5 Examples of architectural designs in the seismic areas of the Marche Region. Design studio class 3, 2017–2018, prof. Gianluigi Mondaini

[8]The event—a conference, an exhibition, and a party—was held in Ancona on 2 July 2018. It was promoted by the professors of the Design Area of the Department of Civil and Building Engineering and Architecture, Università Politecnica delle Marche—Gianluigi Mondaini, Maddalena Ferretti, Paolo Bonvini—, and organized in collaboration with the student association CENTO55. The exhibition held at the Museo della Città of Ancona, with the title "From emergency to emerging places", collected the results of the 2017–18 Design Labs (professors G. Mondaini, P. Bonvini, F. Pugnaloni).

The outcomes so far undoubtedly strongly contrast with the concept of ***polis***. Citizens are 'boxed' in standardized prefab houses and live in isolated and depressed sectors, missing services for the community and places dedicated to socialization, communication and aggregation, assembly and recreational places, collective gathering or market places. Perhaps a more meditated intervention is needed, able to structure a new urban form, which involves the meaning of the *intermediate space* or *space in between*, open or semi-open, as an element on which to articulate a sustainable urban project (resilience), as a conceptual dimension within which all the tangible and intangible interactions at stake are framed, in the tension towards a balanced relationship between the design of the context and the environmental context, leading to profound changes to be worked out in the formal and functional redefinition of space [31]. The question of identity also passes through these aspects and brings into play the concepts of memory and nostalgia [13], interpreted not in a regressive key but in an 'open' form, translating it into an active force that becomes a critical tool. In fact, through pain and affectivity, nostalgia is configured as that feeling that links the private sphere with the public one, the personal memory with the collective one. This solicits an idea of urban regeneration that concerns the refusal of the homologation of the interventions but is oriented towards the active reconsideration of local specificities through a flexible and adaptive action. This aims at enhancing the diversity of places and contexts, considering their respective vocations to effectively interpret the needs of an environmentally conscious architecture, also oriented towards the construction of socio-cultural networks and the re-signification of the historical built heritage, to trigger a process of transformation in continuity, requiring the involvement of all the actors, both private and public, to identify the real needs and to bring more and more design ideas to the needs of the people who will inhabit the new urban spaces.

3 Conclusions and Outlook

The positions expressed in the previous paragraphs have been outlined according to the perspective of heritage resilience, an aspect that represents a shared root among the different disciplines. This narrative aims to stress the overlapping of the scientific fields as a major achievement, as well as a chance to overcome sectarian boundaries. Working on these overlapping zones allows to envision innovative investigation areas for multi-faceted teams. Furthermore, this approach opens to a new concept of technology transfer that is turned to share awareness and blend knowledge with local population and public institutions. In this case, the technology transfer is more related to an innovation in processes to demonstrate their scalability to actual conditions and real contexts. Another achievement lies in the response to needs and demands in the field of heritage analysis, surveying, dissemination, conservation and enhancement, which can be regarded as the core result of research in disciplinary fields near to social sciences and humanities.

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Earthquake in Italy: From the Past Decades to the Future. Strategies and Innovative Tools for Urban Planning and Territorial Regeneration

Maria Angela Bedini and Fabio Bronzini

Abstract Some results of the study on the past history of earthquakes in Italy and on the prospects of protection from seismic risks in the next decades are presented. The problems generated by the earthquake in various Italian regions and in particular in central Italy were evaluated, proposing an economic and integrated settlement system for a new economic and social model, aimed at the rebirth of territories in crisis. Finally, the conclusions summarize the objectives and strategic choices, which can be considered consolidated acquisitions by the scientific community in order to identify the disciplinary and management paths be followed in the coming decades.

1 An *Excursus* from the Past History of Earthquakes in Italy: Positive and Negative Aspects of the Interventions Carried Out

It has very often not been possible in Italy to develop alternative economic, social and settlement models, after earthquakes or other natural disasters. Far too often, actions have been limited only to the actual emergency and reconstruction [4, 20, 49]. In order to define concrete operational solutions when planning prevention, emergency and resurgence actions, the economic and time gap between objectives and the desires of residents, and the possibility of satisfying the same, must be taken into account.

In Friuli region (1976) the earliest studies on seismic microzonation had a positive impact on future studies involving vulnerability, technical regulations and the classification methods used in the areas affected. The focus in this particular case was on risks, risk mitigation and the fact that interactions between different fields cannot be forgotten, even if the political world failed to make courageous and innovative choices.

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Temporary wooden structures (MAP) were constructed immediately after the earthquake, while the fact that the Municipalities involved were very small, made it possible to complete reconstruction in just two or three years.

In Marche region (1972; 1997) the experience of the Ancona earthquake dating to 1972 [16, 32] may be seen as an example where the Historical Centre was fully recovered, thanks above all to the very substantial funds received. Thanks to these funds, a traumatic event became a unique opportunity to turn the ancient Guasco and Astagno districts—built on two hills that were difficult to access, with interconnected buildings stacked on top of each other, and hundreds of small inaccessible spaces, overrun by nettles and mice—into hygienic and clean districts, with a tidy network of paths and courtyards, that ended up by becoming public areas, in a beautiful setting of historical buildings.

The distant remote experience, together with the new General Zoning Plan, were based on the use of private reconstruction in detailed sector Plans, that also defined the aggregation, separation and recomposition of public and private property units, by highly qualified architects, where the urban regeneration strategy was based, right from the start, on a *vision* of the collective good and urban socialisation.

In this case, post-earthquake reconstruction did not require specific planning, because the new General Zoning Plan had recently been introduced. The reconstruction of the historical centre, which took a decade to complete, was based on a "unitary project".

Taking into account the question of reconstruction alone, the fitness for occupancy certificates—that were used in Italy for the first time in Marche Region, after the 1997 earthquake [44]—ensured a certain uniformity in assessing fitness for occupancy (resolving, at least in part, the enormous assessment differences that occurred in the past), although they did not help to identify buildings that were not demolished and reconstructed.

These experiences show that by creating a multi-sectoral system of economic, urban planning, a social system, and a geotechnical and hydrogeological protection system, while closing the gap between technical-engineering and geological studies and social and economic studies, it is possible to create an *intellighenzia* to "manage the expectancy" of a territory of this kind.

Conversely, the uncertainty of the population and administrators of the small Communities in Central Italy is now quite evident, since all that is being done is run around in a sort of vicious circle created by the emergency, trying to understand where and when to construct wooden shelters for people and animals.

Moreover, most of the home owners involved in the drama of the earthquake, do not have the funds to carry out the works required on these historical buildings, despite the creation of consortia (Minimal Intervention Unit) [31]. And this is a very evident difficulty, despite the great urban planning consistency and value of the Minimum Intervention Units [60].

Everyone seems to agree on the need to plan Minimal Urban Structures (SUM) [3, 8, 23], above all taking into account the developmental stages of the SUM tool, intended as good risk planning practices [34].

In Umbria region (1979; 1984; 1997), in the case dating to September 1997 [48], the choice of soft reconstruction made it possible for residents to return to the district within a reasonable period of time, when it was possible to repair the damages incurred with anti-seismic technical solutions. In this case, seismic microzation made it possible to identify areas with different geological and geomorphological characteristics, over and above the seismic aspect.

Pursuant to Regional Decree no. 64 dated 8 February 2010, the Region approved the guidelines to define the Minimal Urban Structure for the Reduction of Seismic Risks, pursuant to article 3.3.d of Regional Law no. 11 dated 22.02.2005. And with Regional Law no. 1 dated 21.01.2015, the SUM was structurally included in Urban Planning, in order to identify approaches, spaces, urban functions and strategic buildings to ensure an urban response to earthquakes during the emergency, and maintain and resume urban, economic, social and relational activities, after the earthquake.

The SUM includes the *lifelines*, the main railway communication routes and nodes, the escape routes, the secure open and closed spaces, key centres, collection points for the population. The SUMs include the critical elements: historical urban gateways, steep or very narrow sections of roads, sharp bends, hydrogeological hazards, buildings close to the road, etc.

In Emilia Romagna region (2012) the experience represents a milestone in the approach to dealing with the aftermath of earthquakes. For the first time in Italy, this was an earthquake that struck an enormous area with a dynamic industrial, urban and agro-industrial fabric. An experience that was developed with a laborious bottom-up process.

It was also the first time that a Special Reconstruction Commissioner was appointed in Italy; the Commissioner was the President of the Regional Council Vasco Errani, who supervised each and every step of the regeneration process of the Municipalities affected by the earthquake.

The Reconstruction Plan (Law No. 16/2012) for Emilia-Romagna [47], not applicable to ordinary urban planning management, made it possible to construct permanent essential services very quickly. The 2015 Special Area Programmes for 24 Municipalities (Regional Law no. 30/1996) [31] and the Plans for the historical centres, all reconfirmed the fundamental importance of the established fabrics, while the Operational Plan (OP) defined an innovative urban plan associated with economic and financial programmes for the social and economic regeneration of the urban historical centres [38].

In other words, this was a shared and planned urban planning strategy, which was part of a vision whose aim was to strategically relaunch a very large territory, that risks abandonment, by introducing preventive planning earthquake measures. The plan focuses on supporting the population, by reprogramming new production and tourist-cultural functions for the tiny historical centres scattered throughout the territory.

The experience of Emilia-Romagna (where reconstruction was carried out under a new Regional Law and Urban Plan), including the new Special Area Plan, is an example of effective concerted urban planning (in compliance with Regional Law

30/1996), that ensured cross-functional collaboration between municipal and private administrations. Not even this positive experience however, managed to ensure an integration of public strategies and policies with the national and international economic resources available.

The 2012 experience, involving the smaller centres of the Ferrara district, whose infrastructures dated to the Romanesque period and the early Middle Ages and later, the Renaissance period, revealed, with very few exceptions, the degradation and abandonment of the historical centres. These settlements were mostly occupied by low-income immigrant families, who were unable to carry out maintenance or renovate buildings.

The Department of Economy and Management of Ferrara University used its ReBuilding Project to coordinate advanced courses on reconstruction themes. A cycle of seminars, workshops and the experiences of experts were used to provide organic, rather than merely casual or improvised support to the populations in the affected areas. An initiative that Marche Polytechnic University is offering, for the 2016–2017 Earthquake Damaged Area, through its Master "City and Territory. Strategies and innovative tools for protection against the risks experienced by territories in difficulty", with the direct involvement of the SIU (Italian Association of Urban Planners), the INU (National Institute of Urban Planning), the ISTAO (Adriano Olivetti Institute), and CeNSU (National Centre of Urban Planning Studies).[1]

In Abruzzo region (2009) the choices made by the government, that are completely devoid of any urban planning and social culture, have led to the pseudo-inventions of the New Towns («19 tiny districts in the middle of nowhere») [17] after the Aquila experience, which Campos Venuti defined in *Urbanistica*, no. 154, as a «deplorable action» [15, 51]. An opinion echoed by Federico Oliva when he says that describing these as settlements as New Towns (15,000 people in 4,500 lodgings) is «a totally ridiculous and disrespectful description, in the history of urban planning, given their dimensions and the very poor urban planning quality».

At L'Aquila, after rapidly erecting metal scaffolding, to "jail in" the inaccessible "red zones" of the historical centre, there was a great deal of coverage of the nineteen tiny settlements constructed in the middle of nowhere. An explosion of the attention-seeking behaviour of engineering seen as an anti-earthquake cure-all (that has so

[1] Master "City and Territory. Strategies and innovative tools for protection against risks of territories in crisis" was promoted in 2017 by Marche Polytechnic University, with scientific coordinator prof. Fabio Bronzini. 40 Italian Universities and more than 60 professors from the most prestigious universities, took part in the Master. Graduates from many parts of Italy subscribed to the Master. The scope of the course was to train researchers, for the complex inter-sectoral and inter-cultural task of starting a prevention and planning process for the future of these territories in difficulty. The Master deals with preventive protection from seismic risks, hydrogeological instability, degradation and abandonment, including post-earthquake planning. This is a high-profile course, which represents one of the few professional skills in high demand on the professional Italian market. The concrete results attained include that of supporting typical local products, a revaluation of the excellence of the territories in terms of innovative companies in the agro-food and wine sector, tourism-culture, typical handicrafts and recreational-creative activities, receptivity even for "new social members" and organising improved urban-territorial and technological protection for the territories, in event of future natural disasters.

far produced no other strategy than basic technical building regulations for seismic zones).

And given their irreparable vulnerability, it has also become apparent that it will not be possible to reconstruct many of the residential settlements as they were before [50].

The time has come to acknowledge that rebuilding and seismic engineering skills are simply not sufficient to protect these territories from permanent abandonment.

Bruno Gabrielli made no bones about this when he said that when one poses a single objective (that of the immediate construction of new non-temporary buildings), while neglecting objectives linked to the system of interconnected and perspective activities, the result is bound to be unsuccessful [37].

Far from the media spotlight, in Abruzzo (57 municipalities in 3 provinces), the negative recovery model that was being implemented in the historical centre of L'Aquila, was not followed. A completely different regeneration model for small Municipalities was being developed and proposed by university groups 9 uniform Areas were identified, where the scope was to ensure coordinated administrative management and pooling of services between different Municipalities. Forms of governance involving several municipalities, interrelated at a wide-area level, were also introduced the Reconstruction Plan also acts as a Strategic Plan. The Reconstruction Plan, that involves other building aspects, also acts as a Strategic Plan, namely for social-economic and territorial planning. The Minimal Urban Structure (SUM) was again used, at an urban and territorial level. The possible locations and conditions of collapse of the Minimal Urban Structure were also identified. The places, with the highest level of protection and urban connecting areas, were on the other hand identified. It was in this way possible to integrate the historic centre and the rest of the urban area. And these locations will moreover be safe and beautiful, becoming not only functional elements of the SUM but also areas of cultural, environmental and social value with which the local community can identify itself.

The use of resurgence strategies based on the SUM can therefore guarantee to residents who have moved from the disaster area to other areas, that they will return, because with respect to the past the SUM ensures a social organisation of spaces where citizens are informed of the safe areas, where to collect and the escape areas in order to accelerate the intervention of civil protection services.

2 Post-earthquake Experiences in Other Countries

Post-earthquake experiences in other Continents. The references to post-earthquake experiences on other continents (Chile, 1960; Alaska, 1964; China, Tangshan, 1976; Japan, Kobe, 1995, Tohōku, 2011; United States, California, Los Angeles, 1994; Mexico, Mexico City, 1985; Sumatra, 2004; New Zealand, Christchurch, 2010–1011; Chile, Maule coast, 2010, Mexico, Chiapas and Mexico City, September 2017, etc.) are interesting but are not directly pertinent to this study, given that many studies focus above all on the technical aspects of the emergency [28], on protecting buildings

from seismic risks [62], on the post-earthquake reorganisation of transport [46], on models to forecast seismic risks [57], on the attitude of citizens to seismic risks [39], on the dangers and opportunities of the peculiar Japanese experience [27] or on the expected "big one" [26], as stated by Tom Jordan [40] at the National Conference on the Danger of Earthquakes, in Long Beach in 2016, all of which are unrelated to this paper. Other devastating earthquakes (Iran and Iraq) have just happened in November 2017.

Some experiences of European countries (Turkey, Izmit, 1999) focus on the emergency [53], pointing out the inadequate urban planning aspects.

Many Italian earthquake studies face the problem in terms of projects and "prevention" techniques [44] in order to mitigate risks during an earthquake. These important technical-scientific studies deal with an ex-ante approach to the event, which is completely different to the post-earthquake approach proposed by this paper.

3 The Earthquake in Central Italy

The Earthquake hit Central Italy in 2016–2017. The Damaged Areas include the hinterlands of four Italian regions, involving a number of settlement systems. This is an extensive area, which is mostly mountainous, with winter tourist facilities and animal breeding and agro-food product processing industries for well-known *brands* of many typical products (lentils, cured meats, cheeses, trout, liqueurs, etc.), as well as a University and paper manufacturing district.

The Italian government has allocated almost one billion Euro for urban redevelopment through to 2020, and another 6.1 billion Euro for extended tax credit deferment facilities until 2047.[2]

[2]On 24 August 2016, a violent earthquake struck the territories of Marche, Umbria, Abruzzo and Lazio in Central Italy. The most significant damages occurred in Amatrice, Accumoli and Arquata del Tronto. Thousands of people were involved.

On 26 and 30 October 2016, another strong earthquake occurred in the area between Marche and Umbria, in the provinces of Macerata, Perugia and Ascoli Piceno, with the epicentre close to Castelsantangelo sul Nera, Visso, Ussita, Preci, Norcia and Arquata del Tronto.

The Council of Ministers approved a number of Law Decrees to finance interventions for the areas affected by the earthquakes in 2016 and 2017 (Law Decree dated 11 November 2016, no. 205; Law Decree 8/2017; Law Decree50/2017) subsequently extended the so-called earthquake damaged area, and on 11 December, pursuant to the 2017 Budget Law (Law 232/2016), the Parliament authorized a number of allocations for repairs, reconstruction, assistance to the population and economic resurgence of the territories affected by the earthquakes:

6.1 billion euro (100 million for 2017 and 200 million per annum from 2018 to 2047) for tax credits;

1 billion euro (200 million for 2017, 300 million for 2018, 350 for 2019 and 150 million for 2020) for the allocation of public reconstruction contributions (as set forth by Law Decree 189/2016).

The affected Regions were allowed to allocate another € 300 million.

The resources of the Fund are mainly to be used to ascertain the vulnerability of buildings, public and private reconstruction interventions, ten work sites for the seismic defence of public buildings, the purchase and maintenance of the resources required for rescue operations for the population,

This teamwork may well lay the foundations for a Law, that is long overdue, on risk protection, management, settlement and production reconversion processes.

In such an extensive settlement, like the Earthquake Damaged Areas, it would appear that there are still no territorial rehabilitation or local social-economic development projects. There still appears to be a hope that plentiful funds will be provided, to support the resurgence of a crippled economy, where there will be business for everyone, totally disregarding the confirmed and proven fact that reconstruction alone is substantially pointless [13, 14].

The key focus, "the mother of all objectives", is to bring back the old and new populations to the areas affected by the disaster; but the institutions, at different levels, do not seem to be aware that they should be concentrating on the one truly important resource: people.

This emergency phase focuses on moving the population in order to build the temporary wooden houses, before commencing reconstruction, which is desired both by the former residents, who are alone and do not know what the future will bring, and the bevy of engineers who, on the other hand, are well aware of the opportunity they have of making money.

Once again, the resurgence of these places is strongly linked to the reconstruction of a strongly motivated social fabric, consisting of former residents who have ripped away from where they were born, and new residents: young people who want to rediscover social and economic values linked to the "land", as a source of pleasure and livelihood, small centres of immigrants with paid, programmed and monitored activities, as well as a community of "carers" for the elderly, who do not intend to give up their history, or the places in which they have lived, and who refuse to accept the rooms allocated to them in hotels along the coast, which are places of isolation, with which they do not relate.

In this vision, the support provided to high-quality products, the provision of collective services for local businesses, and the creation of highly qualified "itinerant" consulting and promotional activities (such as the Itinerant Chair of AgriCulture of Valnerina, Giacchè, in press), to help local businesses, as already tested in part [42], are indeed of strategic importance.

As regards the suggestions and operational proposals for the Earthquake Damaged Area, no comparison is made with respect to what has happened in other countries, given the specific characteristics of the Italian territory: countless buildings of high historical and cultural value, buildings constructed in stone, environmental values and, in particular, a residential, social and production system that extends over enormous territories. This environmental situation makes it necessary deal with the post-earthquake phase of social, economic and urban-territorial regeneration, very attentively. A phase, that focuses on the absolute priority of repopulating the territories, that is even more important than reconstruction alone.

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the creation of an urban free zone, greater economic resources in the payslip, seismic micro-zoning studies, prior to the presentation of projects for the construction of emergency structures, a regeneration coordination cabin, a fund to finance investments and the development of infrastructures of the Country, that will also be used for seismic risk prevention interventions.

This objective should be coded by law and become a cultural, social and economic choice, even through a different allocation of resources to reconstruction and territorial regeneration planning strategies.

The latter should, moreover be based on detailed urban planning projects (SUM Minimal Urban Structures) prepared by experienced urban planners, with concerted urban planning practices and without forcing private individuals to become members of expensive consortia.

The use of these valid urban planning tools (SUM) ensures greater safety in earthquake damaged areas, encouraging citizens to return to the area to take up their business activities and services.

A system of Smart land projects, that improve the services to the community and businesses in the territory.

A system of new functional relationships between small urban centres in earthquake damaged areas and urban centres outside earthquake damaged areas (transport, cooperatives, itinerant services for production activities etc.) and intangible relationships that strengthen the new ties between residents in mountain, hillside and coastal areas (historic-cultural memory, visual perception, identifying oneself with the emotional enjoyment of beautiful environmental areas, awareness of the quality natural and anthropized areas etc.).

The experiences in the past have produced successful (Emilia Romagna, Umbria, Marche), but also negative (historical centre of L'Aquila) results. The lack of a permanent guidance centre in the prevention, emergency, and post-earthquake resurgence phases is a particularly negative aspect, given that all these phases should be addressed simultaneously and not successively.

Contemporaneity based on assumptions: there should be no emergency Plan without prevention Plans for protection against Risks. There should be no emergency Plans with temporary settlements and building reconstruction as a separate and distinct phase, prior to the planning-management of resurgence. The management protocols should impose, in the case of an earthquake, the simultaneous implementation of emergency plans and social-economic regeneration plans.

This practice is applied in Umbria where, with Umbria Regional Law 11 dated 22.02.2005 called "Law for Governance of the Territory", the SUM is included in Territorial and Urban Planning. This practice is currently examined and tested at the weekly workshops of the national University Master (2017–2018) "City and Territory. Innovative tools and strategies for protection against risks for territories in difficulty", in which 40 Universities and Research Centres participate.

Moreover, as already confirmed by experimentation carried out in Lazio, different planning tools must be integrated, given that the territory regeneration system entails a more complex security, protection and maintenance system of the territory [18]: SUM, Minimum Urban Structure to reduce urban seismic vulnerability, QSV Strategic Valorisation Framework of Historical Centres, Civil Protection Plan, PAI, Hydrogeological Structure Plan, Seismic microzonation and risk theme maps.

4 New Economic and Social Model for the Rebirth of Territories in Crisis

Programmatic suggestions are consequently required for the resurgence of the territories affected, based on the economic and social model of the so-called "productive landscape". In other words, an investment in the human capital entrenched in these places, in the historical rural settlements, the environmental values and products of excellence, and on a new relationship of solidarity between abandoned areas, hillside areas and coastal areas.

This solidarity already exists in some environments, and consists of introducing common social, health and emergency services including assistance to businesses, producer-consumer associations, etc.

An integrated economic and settlement system that may become a driving force for a new lifestyle model: social and production reconversion of the countryside and protected regeneration of the extensive settlement system, with its historical and cultural values.

A model where services to agro-zootechnical companies in the territories, as in the case of Valnerina (Umbria), will once again become, itinerant: the itinerant Teaching Post of AgriCulture, the itinerant butcher and many other "door-to-door" activities, including advisory services for production, access to credit, cooperation.

In others words, to keep the population in the foothill settlements of the hinterland, it is not sufficient to construct houses, but it is necessary to bring back not only the original citizens, given that their sense of attachment is a part of its *genius loci*, but even new members of the community.

In order to encourage these residents to return [1], it should be remembered that reconstruction is closely linked to the financial situation of citizens and businesses before the disaster, given that it is citizens with more money who are better equipped to face a disaster. And as researchers have observed, reconstruction may lead to a "boom-and-bust" economy, where the reconstruction process fuels a temporary economic growth, at the expense however of the long-term sustainability of the local economy.

That is why it is so important to choose which economy to support.

For example, the decision may be made to support the so-called "Production Landscape" [2, 6], with a programme of strategic incentives.

The investment in rural settlements of landscape and environmental value may therefore be a driving force for development, for a new growth model based on the social and production reconversion of the countryside and the environmental and cultural revaluation of the network of widespread settlements, typical of central Italy.

An investment made, for example, with the substantial funds allocated by Marche Region to the so-called "Advanced Cultural District" (Regional Law 4/2010, involving 13 regional projects, 3.05 million Euro; 4 regional initiative projects, 1.75 million Euro), based on the concept that financing cultural and creative projects in areas of historical, architectural and environmental value, may attract businesses and people to the area.

Numerous studies have made it easier to understand the mechanisms and interrelations between policies, the landscape and social-economic and benefits [63].

In some Italian regions, above all in Central Italy, there are new potentialities for this type of development, based on the rural dimension and a new production-settlement model, such as that proposed by the rural policy of the CAP, the approach of Urban Agriculture [29, 54, 59] and the new Agropolitan forms [24, 25], Agrourbanism [30], the Food Plans applied in Europe and the USA, or the urban horticulture projects [22] which appeared, in the late 90 s, as a way to reorganise Irish agriculture.

In order to reconvert the agro-zootechnical industry, in line with food and production requirements, and social, tourist and cultural needs, agricultural planning should include the introduction of Area Plans in Associated Districts Administration Areas.

This is confirmed by the successful experience of small groups of associated municipalities in Marche Region (in the hinterland of Pesaro) and other towns in Emilia Romagna, where it has been demonstrated that small Municipalities are unable to plan new and existing farming activities, that can only be done at a district level.

An economic-territorial policy is therefore required with diversified operational tools: urban plans, farm park plans [35], agro-urban programmes (SDRIF) (agro-urban programmes to protect farming areas and encourage the active participation of farmers in territorial planning choices) [7], *agriurbanism* projects [41, 61], Integrated Territorial Projects (PIT), [56], and tools to implement the structural funds of the European Union.

Consequently, in this moment of instability caused by the global and local crisis in Central Italy, and the difficult resurgence of lands devastated by the earthquake, the settlement filaments, the urbanised countryside and the hundreds of historic-rural buildings may represent an opportunity to reconsider values, in order to relaunch local values and lifestyles in areas of high environmental-landscape value with small populations.

The multi-scale strategy suggested hinges on the desires and involvement of residents [11], who are determined to return to the places where they born. The identity of these contexts should therefore be strengthened and supported more carefully. Plans for the hinterland areas, the intermediate hillside areas and coastal areas should be reconsidered as a whole, in order to create a new pact between city and countryside, an understanding of reciprocal usefulness, in order to overcome the current deadlock, and relaunch the development and integration of resources which are, on one hand, widespread and underused, and on the other hand centralised and consolidated [5, 9, 10].

The pact for an integrated strategy between city and countryside becomes a coherent pact between the coastal and hinterland areas, the areas of the capital and neighbouring territories, putting aside one-sided development of competing Municipalities, in order to develop common territorial services (water supplies, maintenance of sewerage systems, waste disposal sites, waste recycling, distribution of zero-mile foods, health facilities and schools for several Municipalities, supra-municipal public transport systems for the hinterland areas, cooperatives of city-countryside consumers, etc.).

In the territories of Central Italy, the city-country dualism, that has been studied in great detail in other contexts [19, 58], has different and peculiar aspects. And these environments are perfect to regenerate a close relationship between consolidated systems and the rural environment, securely linked to the cultural, food and wine system, environmental and tourist networks and the network of over one thousand small historical-artistic "treasure troves", to which the "advanced cultural districts" (in which cultural and creative projects create new production activities) are connected.

But an effective strategy must be adjusted according to the endogenous potential of places, involving different levels of operators: 1. local government authorities (responsible for protecting farm lands and functionality); 2. groups of agricultural entrepreneurs [45] (whose responsibility is to increase the quality of products and offer recreational, educational and social-environmental services); 3. tourist or food and wine entrepreneurial groups (who also supply sports, social services, environmental recreation); 4. cultural groups (in order to insert the historical rural and natural heritage in the economic network); 5. artisanal businesses (with typical products); 6. old and new local residents (with whom the preservation and functionality of places should be agreed).

This leads to a new planning approach of public spaces in the extensive territory, suggesting elements of recognisability, identification, the boundaries of the settlements and environmental qualification.

This approach was examined in great detail in the scientific paper published by Paolo Colarossi (*Urban planning*) and in the Urban Plans developed by the same authority in Cisterna Municipality (Rome) [21].

It should also be considered that "modifying an economic policy variable may produce different responses in different territories, in other words, modifications of this kind may have different local values rather than a single global value" [52]. It is therefore necessary to «evaluate and develop the endogenous potential of rural areas […] with differentiated typologies» [43] and to plan interventions according to the different relationships between the rural areas and linear settlements of the territory.

Despite these strategic approaches however, there is a gap in the governance of the regional territory, at an Associated Districts Administration Area level, and a total lack of programming-management for these scattered settlements.

Given the shortcomings of the public bodies, that are evident in the governance of these territories with scattered high-risk settlements, the production Landscape approach and the new city-countryside relationship offers a new and unrepeatable opportunity for the economic and social development of production landscapes. It suggests a policy, which is perhaps the only possible option, to relaunch local values and lifestyles in more balanced man-environment settings. Planning should be holistic, given that it is not only a question of substituting damaged assets and infrastructures, but also a question of reconstructing communities, to ensure equity, access to resources and equal opportunities for disadvantaged persons. Only in this way will it be possible to reduce the community's vulnerability to risks.

In a precarious economic and social scenario, the *intellighenzia* of urban-territorial knowledge is called to take a stand against the deplorable shortcomings of risk protection and prevention, combating the abandonment of the hinterland, while focusing on a culture to safeguard the territory and regenerate the products of the landscape-environmental system. Without a regulatory front of this kind, the academic world will end up being an accomplice of the deplorable choices of political power.

5 Conclusions and Strategies to Live with Earthquakes in the Coming Decades

Examining the experiences of previous difficult post-earthquake situations, it is apparent that there has been a general difficulty to capture the right opportunity to rethink unsustainable settlement models that are today no longer sustainable: the population, activities, urban and rural homes, historical-artistic artefacts and environments, services scattered over enormous territories that are inadequately protected in the case of natural disasters and have no technological rescue networks, super-equipped urban shelters, or a constantly accessible network of central structures, located in strategic hubs at the service of the territory.

An earthquake breaks the existing fragile balance of the territory and makes it necessary to rethink the lifestyle model in these places [55], based on: 1. A territorial urban risk protection system. 2. A system of Smart land projects, that improve the services to the community and businesses in the territory. 3. A system of new functional relationships between small urban centres in earthquake damaged areas and urban centres outside earthquake damaged areas (transport, cooperatives, itinerant services for production activities etc.) and intangible relationships that strengthen the new ties between residents in mountain, hillside and coastal areas (historic-cultural memory, visual perception, identifying oneself with the emotional enjoyment of beautiful environmental areas, awareness of the quality natural and anthropized areas etc.).

In this enormous and very beautiful area, involving a number of territorial systems, that are not easy to access, territorial—urban planning should focus on rapidly drawing up the projects for Minimal Urban Structures at an urban and an Associated Districts Administration Area level, that should include urban reconstruction objectives (mitigating risks and seismic vulnerability, *lifelines*, etc.) and strategic objectives (new associated forms of *governance*, future visions of cities, circular processes, privileged places of beauty, safety, social identification), based on six key points: a. the recovery, through social *housing* and self-reconstruction practices, of the small and very small historical centres that are scattered throughout the area, linked by a dense web of farm paths; b. the stable integration of "new social components", through non-complex strategic public programmes, which are conducive to creating a new economic development model. A model concentrated on the resources available, resources that are under-used or badly used, cultural tourism, food and wine, modern agro-zootechnics, creative artistic activities, alternative ways of recovering

buildings, in new economic circuits [12]; c. the introduction of all the most advanced technologies in order to make these territories less isolated, less abandoned, and no longer heading towards a terminal phase of decline: from broadband networks to the remote management of public and private services, energy control, the reorganisation of the waste system and slow mobility for the re-appropriation of the values of the green heart of Italy. An advanced monitoring system [33] that alerts residents and the emergency services of the potential cascading effects of earthquakes, landslides and flooding. d. the localisation of territorial "hubs", i.e. "functional equipped pivots", at the service of extensive settlements and the conservation or re-localisation of primary services (schools, health care facilities, public offices, etc.); e. the identification of new business areas, and new protected areas to shelter animals; f. the identification, on detailed maps, of buildings, public spaces and protected routes, that, in case of natural disasters, ensure internal and external access and the continued efficiency of network services.

From what has been explained up to now, the following strategic choices can be considered consolidated acquisitions by the scientific community to live with earthquakes in the coming decades: a clear and decided "No" to focusing exclusively on reconstruction in post-earthquake interventions. "No" to the uncontrolled delegating for the reconstruction to the mayors of small municipalities, with little resources, experience and skills and many local conditionings, even illegitimate. "No" to abandoning home owners to a bevy of engineers, interested only in taking professional assignements. "No" to encourage the purchase, by residents of the earthquake zones, of new housing away from the affected areas. "No" to build new settlements, declared improperly temporary; in non-building areas, intended for environmental protection, by way of derogation from urban planning tools. "Yes" to planning multi-scale Minimal Urban Structures, at an urban and wide-area level, with forms of governance that include several associated Municipalities. "Yes" to simplification/integration of several interrelated Plans (SUM, Civil Protection Plans, Hydrogeological Defence Plans, Seismic Microzonation Plans). "Yes" to the Masterplan, intended as a programmatic tool in order to demonstrate the complexity of the urban planning regeneration strategy. "Yes" to Area Plans and Wide-Area Plans, in order to plan the reorganisation of a large urban widespread system, where the focus is on the economic, social, cultural and productive resurgence of the areas affected. "Yes" to the provision of advanced network technologies to allow coexistence with the earthquake in areas spread over large territory, ensuring the maximum protection, assistance, evacuation in case of recurrence of disasters. "Yes" to the main great objective: to bring back to the devastated places the population and activities present before the earthquake.

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New Multimedia Technologies as Tools for a Modern Approach to Scientific Communication and Teaching of Mathematical Sciences

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Abstract This paper describes various technological tools and e-learning resources used by the authors in their work as university teachers and communicators of mathematics to a general public. As pointed out by recent developments in mathematics education research, a technology enhanced teaching may have significant potentialities at tertiary level: e-learning is an essential support to overcome some logistic obstacles such as the large number of students per teacher, the small number of hours of lesson available, the heterogeneity of the freshmen's mathematical background.

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Moreover, a fine design of digital environments can foster an engaging, inclusive, flexible and meaningful learning of mathematical topics. In this paper we give a perspective on some educational experiments carried out with engineering students of Università Politecnica delle Marche through specific functionalities of the Moodle platform (quiz, forum, workshop) and the dynamic geometry software Geogebra. We also report shortly on our approach to the use of new technological devices in the dissemination of scientific knowledge to a broader audience.

1 Introduction

In the last few years, research in mathematics education [2, 4, 5, 7] highlighted the potentialities of e-learning environments and digital resources in supporting the teaching/learning processes at the university level: for example, they are an essential tool to face the large number of students per teacher and the small number of hours per course, to reduce the heterogeneity of freshmen background and to overcome the difficulties due to the impossibility of a close relationship between lecturer and learner.

The opportunities offered by e-learning are crucial both for students and teachers: the former have the possibility to visualize some abstract mathematical concepts and explore them from different representations, to check their own preparation without fear of judgment, to access different kinds of resources whenever and wherever they want. The latter can obtain remarkable advantages for their work by a suitable use of digital resources: through these tools they can keep trace of the students work, progresses and mistakes, use platforms to share clarifications to some frequent doubts rather than repeat many times the same explanations, gather some information about the cognitive styles and aptitudes of their students, which is impossible at university level without the use of technology.

In our teaching experience with engineering students, we often observe the difficulty they encounter in grasping some mathematical ideas beyond a formal and mnemonic level. In order to foster a meaningful, engaging and aware learning, we design digital resources and online environments as a teaching support. For example, through the geometry package Geogebra (which is an application for learning and teaching mathematics from primary school to university level), we implement applets with various functions: some of them allow the students to explore and visu-

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alize the mathematical concepts through animations, some explain ideas or connections, some others are devoted to self-assessment. They are collected and avaliable on the web site "Matematica per immagini e animazioni" http://math-diism.univpm.it/progetto/.

Moreover, we provide educational activities for engineering students of Università Politecnica delle Marche by using some specific Moodle features. Some of them allow assessement and evaluation (quizzes), other ones foster the sharing of comments (forum and chat), some others support role-play (workshop). Finally, we refer about our activities of communication of mathematics to a broad audience and education to teachers.

2 Chats, Role-Play and Workshop

As a part of the e-learning Teaching Enhanced activity addressed to first-years students in Mechanical Engeneering, we used chats in order to increase students' skills to deal with complex numbers. Indeed, though complex numbers are explained during the preparatory course and are a prerequisite for the Geometry course, they are often a trouble for freshmen. The chat tool is well-suited to overcome this difficulty: the supervisor posts a list of exercises on the topic she/he lectured on and the members of the audience post their answers, which are corrected by the tutor with comments and remarks and are also answered by other students creating a debate on the different strategies of approach to the solution.

The advantages of this instrument consist mainly in its flexibility and its usefulness to engross students' attention. As for the first, the instructor can follow the learning path of the public and adapt the following steps to its reactions; in addition, the members of the learning community can work on the assignments according to the timetable they prefer. The solicitation of the chat tool is due to the exchange among students and between students and teachers: when students post their solutions, they see the comments of both the instructor and their peers, so that they have a feedback on the importance and quality of their effort.

Another appealing activity is role-play, in which the student acts as a teacher and is asked to evaluate the work of other students. This activity seems to induce students in facing learning of mathematical topics in a critical and meaningful way [1]. The setting of our experimental e-learning activity were second-year classes on Algebra and Logic of Computer and Automation Engeneering. We used the Workshop tool provided by the Moodle platform. The activity was on a voluntary basis, involving students willing to have a more interactive and engaging use of the e-learning platform.

Our experiment consisted of two parts. In the first part, the teacher proposed a list of exercises on the topics of her/his class and all the students were asked to solve the exercises and submit their own solutions. In the second part, every student was asked to assess the works of three other students, assigned automatically by the system. In order to perform the assessment task, the students used a structured assessment form provided by the teacher. The assessment form was very detailed and, for every item

of the list of exercises, included a mark range and some questions about the correct solution. At the end, the students received two marks, one for their own work and another for their peer assessments of other students' work.

The students feedback on this activity was very positive: in particular, they appreciated the possibility to compare different works and often discovered that they could use more than one strategy to solve a problem. Moreover, when students act as teachers in the assessment procedure, they are induced to pay attention to the formal language and to the presentation of the solutions.

Indeed, one of the main difficulties for students is how to formally express and correctly write the arguments they use in the solutions of the exercises. At the end of the activity, the files produced by the students were revised by the teacher, and some particularly well-written solution was shown to all the students in the class. Also at this final step, more mistakes and doubts of the students were clarified by the teacher. This activity is also well-suited to overcome the problems of large classes.

3 Interactive Quiz: An Effective Tool for Self-correction

One of the main difficulties in Mathematics learning consists in the correctness check of the final result and the execution of a problem or an exercise. In order to overcome this problem one can arrange interactive quiz containing not only the final result, but also the correct execution and the possibility of driving the student step by step. Moodle platform allows the use of many possible types of questions that can be used for an interactive quiz, both with open reply and with closed reply, such as multiple choice (with one or more correct answers), true/false, matching, etc. The quiz can be arranged both with a general feedback explaining the correct execution, and with a specific feedback regarding the wrong answers. For instance, in the multiple choice type questions, the teacher can put, among the wrong alternatives, the answers that usually are obtained owing to typical executions mistakes. In this way, if the student chooses such wrong answers, he receives a specific feedback explaining him what kind of mistake he made, together with an advice about the correct way.

The student can also be allowed to do more attempts, before he discovers the correct execution. Each attempt, if wrong, is followed by indications on the type of mistake and increasingly clear suggestions about the right way. Moreover, if a type of exercise turns out to be particularly hard for a student, he can repeat the same kind of question many times with different data, till he reaches a good level of understanding.

Finally, the use of interactive quiz is an efficient tool for the teacher too, in order to have a clear real-time feedback on the progress of the class of students about any specific subject, since the platform furnishes a detailed report on any single question of the quiz. So, the teacher can decide to come back to a particular topic if the report of the quiz indicates a high rate of wrong answers.

In particular, as a part of the e-learning Teaching Enhanced activity for the Geometry course addressed to first-years students in Mechanical Engeneering, we made a large use of tests in order to stimulate a continuous work by freshmen.

One of the biggest difficulties Italian undergraduates undergo in their first months at college is that they are (almost) completely free of organizing their time and they do not have any deadline before January. The outcome is that often students do not follow closely the schedule of the course and at last they suddenly realize they do not master the subject anymore.

This issue is even more evident for the Geometry course, whose contents–mainly Linear Algebra and Analytic Geometry–are not as familiar to the students as the contents of Analysis I–Calculus–and Physics I–Kinematics and Dynamics–are, because of the curriculum of Italian high schools. The Teaching Enhanced scheme includes different kind of homeworks; in particular each weekend or so, an online self-evaluation test is assigned on the topics explained during the lectures of the previous week.

The test contains 10 questions which can belong to the categories True/False, Multiple Choice, Numerical Question, Matching, it has no time limit for its completion, but it is accessible only for a limited period of time (in the academic year 2017–18 the limit was two weeks, after a questionnaire given to the audience at the end of the course, from this year the limit was increased to one month) and it can be performed only once by each student.

After the completion of the test, the system shows the score, the correct answer to each question and gives a feedback which contains a detailed solution and sometimes lists also the most typical errors. This task proved to be quite effective in increasing the active participation of the class.

4 Online Resources Through Geogebra to Foster Students' Awareness in Learning

Here we describe some of the educational paths which we have designed and organized in "routes of online activities"(RA) ([3]). These activities are implemented by using the software Geogebra and submitted to students through the university Moodle platform. The mathematical topic addressed by the RA is the theory of multiple integrals. In particular, we have concentrated on two specific points, which arise in the resolution of a double integral and which are frequent sources of difficulties: (i) the conversion between graphical and analytical representations of a subset of the plane; (ii) the description of a planar region as a normal domain, together with the choice of the most convenient description for the calculation of a specific integral. The RA include exploratory activities, some tasks requiring short open-ended (numerical or symbolic) answers, and one final open-ended problem. In all tasks, a planar region is given graphically and its analytical representation or its description as normal domain in Cartesian or polar coordinates is asked for. The final problem provides the analytical representation of a planar region and requires the calculation of its area and the justification of the adopted method. The RA are engineered so that the tasks have an increasing level of difficulty, from the first activities up to the final problem; they require not only a deep understanding of the involved techniques of representation, but also the metacognitive ability of evaluating different ways to

obtain the solution. All the tasks envisage the possibility of asking for some hints. For each answer, request for a hint, or action by the student, the program returns a feedback, which is strongly dependent on what the student has done. When a task is correctly performed, the access to the next one becomes available.

As an example, we present a task concerning the conversion between different representations of a set. The region to be described is a half-disk (see Fig. 1). In the first part of the task, the student is required to choose the correct analytic descriptions of the given subset among four options (with the possibility of asking for hints, which would provide the equations of the curves which delimit the region). In the second part, the student should describe the same subset in polar coordinates (ρ, θ) by inserting the minimum and maximum values for the parameters ρ and θ in appropriate input fields. A brief summary of the transformation between polar and Cartesian coordinates is available. An immediate feedback is given both for the first and for the second part, and it concerns not only the correctness of the answer, but also the processing of the task ([8]). For example, if the answer to the second part is wrong, two sliders for ρ and θ appear on the graph: as the student moves the sliders between the minimum and the maximum values previously inserted, the program draws the corresponding set in the plane, thus showing the student's mistake.

In order to evaluate the impact of our educational resource, we collected different kinds of data: video-recording of the students' interaction with the RA; questionnaires and interviews about their perception and ways of thinking; qualitative and quantitative analysis of the final written exams. These data show that students feel very positively about the digital approach for several reasons: it is intuitive and quick, it avoids the fear of judgment, and it offers the advantage of a direct interaction with a tutor (not human in this case). This is, in our opinion, the most important role of technology in this resource: each student is allowed to have an immediate and specific feedback on her/his own actions, learning process and difficulties. In addition, the available hints should become a graphical and dynamical scaffolding for the student, serving as a step-by-step guide towards the solution; obviously, this is not possible at the tertiary level of education through a traditional approach.

Some criticality emerged from the cognitive point of view, such as the students' difficulty in facing unstructured tasks, in visualizing and in choosing autonomously the optimal strategy towards the solution of a problem. Neverthless, our data show that the tool has positive effects in this respect; this results from the evolution of the behaviour of the single student in facing the RA (diminished number of mistakes and increased awareness of the difficulties) and from the comparison between the final written exams of students who faced the RA (the experimental group, EG) and the other students (the control group, CG). In the problem concerning the double integral, the EG obtained an average score of 5,25/8 points, while the CG obtained an average of 4,31/8 points. A qualitative analysis of the texts shows that only students in the EG realize that for some choices of the solution strategy there are too many difficult calculations to perform and it would be advisable to change method. This suggests that the interaction with the RA stimulates the students' autonomy in choosing the most convenient solution strategy.

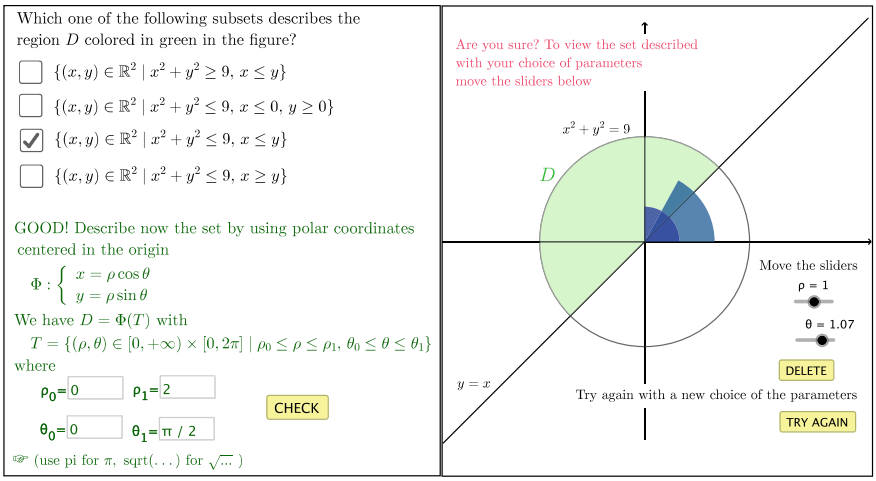

Fig. 1 A screenshot from a task of the RA

5 Dissemination of Mathematics to a Large Audience and Permanent Education for Teachers

We carried out a broad activity of mathematics communication addressed to a large audience by using several technological resources. At national and international conferences, in secondary schools, and at public meetings, we reported on contaminations between mathematics and literature (with specific focus on Leopardi's and Camus' works as well as on the classical Greek tragedy), deepened the philosophical issues concerning the nature and the development of mathematics, and described how we created a versitile approach to analyze an artistic work (such as a poem or a painting) by means of mathematical techniques in order to obtain a set of parameters that were subsequently used by a musician to compose a piece inspired by the artwork (Fig. 2).

In particular, Chiara de Fabritiis together with Maestro Davide Amodio (Conservatorio Benedetto Marcello, Venezia) made a large use of graphic programs like Inkscape to deal with the different forms (coloured regions, brush strokes, curves, dots) that appear in "Summertime n. 9", a painting by Jackson Pollock owned by the Tate Gallery of London.

After creating a reference frame on the canvas, we used a technique due to Filchakov to compute the most relevant coefficients of the transformations (under the form of power series) that map the first region of each colour (red, yellow, and blue) to the following ones (see Fig. 3), while we used a frequency principle to deal with curves and dots that were "translated" in percussions [5].

Using Geogebra we applied an analogous approach to study Giacomo Leopardi's poem "L'infinito". In this case, we followed two road paths: the first follows the position of syllables in the planar scheme that represents the lyric, creating a family

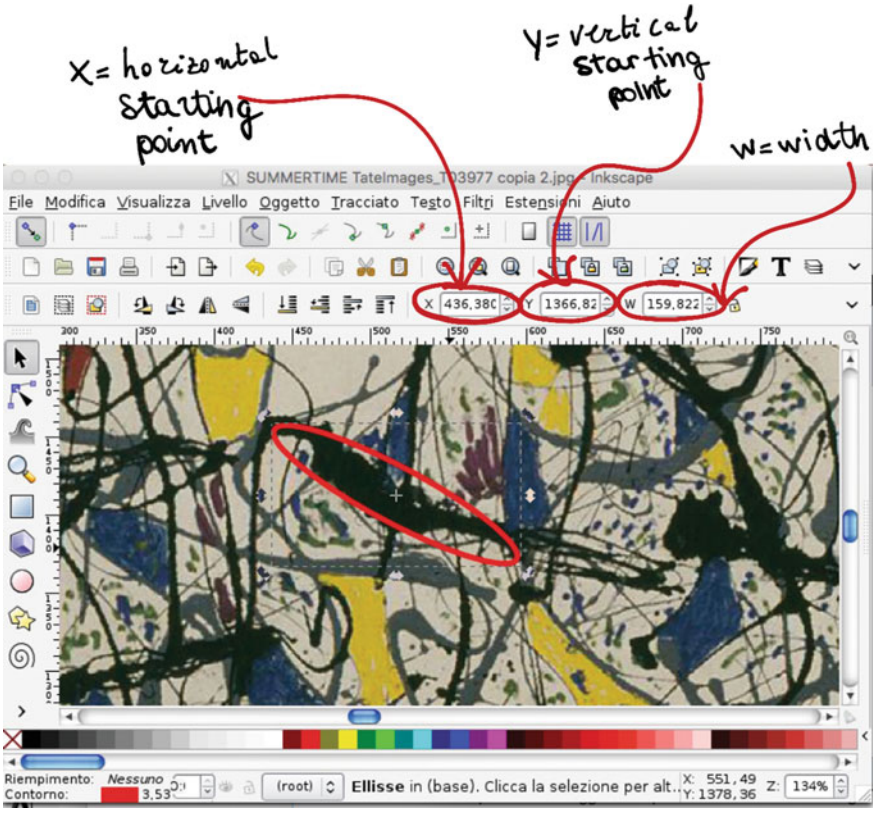

Fig. 2 Parameters of the ellipse obtained with Inkscape

of graphs that suggested themes and compositional patterns for the orchestration; the second takes into account the structure of the verse with its lines, indentations and enjambements which point a 3D interpretation through a cylindrical helix [6].

These researches where presented both at workshops on the spreading of mathematics, such as "Matematica e Cultura"(Istituto Veneto di Scienze, Lettere ed Arti) and Giornata per la Ricerca Artistica e Musicale (Fondazione Teatro alla Scala), and in public lectures and performances (e.g. Istituto Italiano di Cultura in London, Guggenheim Museum in Venice, "Your Future Festival", "Aperitivi Matematici"). The conference on "L'infinito" presented at Istituto Veneto di Scienze, Lettere ed Arti, was filmed, and it is now available on YouTube https://www.youtube.com/watch?v=cbuIJecLBO8.

Finally, on several occasions, we lectured to high schools students or professionals (engineers, architects) on the many links between mathematics, architecture and nature, with a particular focus on geometry (spirals, curves and surfaces, self-similarity, planar and spatial tesselations, regular and uniform polyhedra), making

Fig. 3 Deformations of yellow regions in Summertime n.9 by Jackson Pollock

a large use of applications such as Geogebra for creating drawings and animations which improved the comprehension of the audience.

In addition, we were engaged in teachers' education through workshops and series of lessons involving the use of softwares such as Geogebra, computational knowledge engines such as Wolfram Alpha, and learning management systems such as Moodle. The demonstration of Geogebra to first level secondary school (scuola media) teachers focused mainly on the use of sliders and the construction of polygonal figures in the plane and solid bodies in three-dimensional space, with special attention to projections and nets of polyhedrons.

Secondary school (liceo) professors received a more advanced training: Geogebra was used to deal with slider and animations, graphs of real functions of one real variable, planar and spatial curves, surfaces in three dimensional space, computations with Computer Algebra System; Wolfram Alpha was employed to work with rational and algebraic expressions, polynomial equations in one variable, systems of linear

equations in several variables, computation on vectors and matrices such as products, inverse, determinants. Through the test tool, Moodle gave the teachers the possibility to create an assignment for students in order to verify the comprehension of a subject explained during classhours; it was also used to get next year freshmen accustomed with the kind of quizzes they would have to pass in order to enter the university.

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