IE Perspectives

MAGAZINE

Research and Leadership Insights from Informatics Europe

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INFORMATICS EUROPE

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IE Perspectives

Research and Leadership Insights from Informatics Europe

IE Perspectives is the flagship magazine of Informatics Europe and a platform where the community's **impact, visibility and shared resources** come together. Published twice a year, it brings together strategic reflections, forward-looking analyses, research insights and leading practices. By stimulating informed debate and collective empowerment, IE Perspectives strengthens the discipline and its societal impact in Europe.

IE is the collective voice of Informatics research and education in Europe. Uniting over 200 university departments, research labs and national associations, it empowers its community to create *impact* through shared positions and evidence-based policy engagement, strengthen *visibility* through a coherent European presence, and build *resources* through collaboration, peer exchange and shared knowledge.

Together, we turn shared challenges into collective progress, reinforcing Informatics as a core scientific discipline and contributing to Europe's technical and societal development.

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Call for Contributions

IE Perspectives invites contributions from across the Informatics Europe community. We particularly invite articles that align with one of the magazine's core sections: Foundations, Trends, Research Advances, Leading Practices and Voices.

Submission deadlines are the end of April for the June issue and the end of October for the January issue. Please refer to the full contribution guidelines as stated on the Informatics Europe website.

Advertising

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Honouring Foundations: The Enduring Impact of Curiosity in Informatics Research

Building on our inaugural issue, we are thrilled to present the second edition of ***IE Perspectives***, welcoming Simona Motogna, Informatics Europe Board Director (Diversity & Inclusion), as the new co-Editor-in-Chief.

Also new is the "Foundations" section, dedicated to sharing stories of European curiosity-driven research that has shaped disciplines, technologies and society. Some of the most transformative breakthroughs in informatics sprang from pure curiosity, yet society often overlooks the power driven by the simple desire to explore and understand. The new section celebrates groundbreaking ideas out of curiosity, not blueprints, by spotlighting stories behind curiosity-driven research that reshaped our world. We start with the origins of the World Wide Web, a perfect example of how a single spark of curiosity can ignite a global revolution, as presented in a recent IE publication advocating for better support of such research in public funding.

IE Perspectives continues to highlight forward-looking developments in the "Trends" section, including *the rise of AI-driven paradigms in software engineering* and *sustainable ICT frameworks*.

The "Research Advances" section features two contributions. One is about *Orthanc*, a groundbreaking open-source DICOM server enabling collaborative medical imaging research. Another presents *data-driven insights into urban epidemics*, including studies on non-compliance clustering in cities and epidemic modelling frameworks.

In the "Leading Practices" section, one article showcases *the DETAILLS Living Lab*, a model for participatory and interdisciplinary exploration of AI's societal impacts. Other showcases trends in Informatics education across Europe, such as retention and graduation rates, highlighting the evolving landscape of Informatics higher education as analysed in *IE's Informatics Higher Education Data Portal*.

Finally, the "Voices" section presents a visionary roadmap from the *SequoIA Cluster*, addressing trustworthy AI and cybersecurity to shape responsible and resilient digital futures.

IE Perspectives remains a platform for collaboration, advocacy and responsible practices in Informatics, committed to amplifying the diverse voices and collective achievements of our community. Your feedback and contributions are essential to its ongoing success.

Jean-Marc Jézéquel
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Extracted from the IE Report "The Impact of Curiosity-Driven Informatics Research" (April 2026).

The World Wide Web: How a Side Project Changed the Way We Access Information and Interact with Each Other

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World Wide Web is the name given by Tim Berners-Lee to his creation, which originated as a side project while at CERN. Frustrated with the difficulty of retrieving and organising relevant work information, he decided to create a software system in which information would be represented as entities connected by qualified links. He recalls, "I wrote it in my spare time and for my personal use, and for no loftier reason than to help me remember the connections among the various people, computers, and projects at the lab" [1]. The system soon caught the attention of his colleagues, and Berners-Lee was encouraged to seek institutional support to further develop it. His director at the time, Mike Sendall, famously labelled the project proposal "vague but exciting," and granted him the necessary resources to pursue it.

What began as a local information management tool at a European research laboratory quickly became a global phenomenon. Within a few years, the World Wide Web evolved from a set of interconnected hypertext documents into the backbone of modern communication and commerce. The release of the first popular browser, Mosaic, in 1993, and later the emergence of Netscape, Microsoft Internet Explorer, and open standards coordinated by the World Wide Web Consortium (W3C), transformed the Web into a ubiquitous platform. From the early academic pages of universities and research institutes, the Web expanded to host millions of websites, eventually reshaping how societies produce, distribute, and consume knowledge; while also profoundly changing commerce and even the foundation of social interactions.

Technologically, the Web's evolution reflects a continuous layering of innovation. The initial Web of information, a system for linking and reading documents, grew into a Web of software and business services, enabling interaction and transaction through protocols and languages such as HTTP, HTML, SOAP, and later REST. This, in turn, enabled e-commerce, online banking, and the emergence of digital economies. In the 2000s, the rise of social platforms and user-generated content led to what is often referred to as the social Web, which fundamentally altered media, education, and politics. Today, Web-based technologies underpin artificial intelligence, cloud computing, and the Internet of Things.

The Web's societal impact is difficult to overstate. Recent studies estimate that over five billion people, that is, roughly two-thirds of the world's population, use the Web daily. The economic value created by Web-based services exceeds trillions of euros annually, fuelling industries ranging from education to entertainment, logistics and finance. Yet, none of this was anticipated in Berners-Lee's original proposal. His goal was not to start a company or create a market, but simply to make knowledge easier to navigate. His motivation was intellectual curiosity and the pursuit of a more elegant way to manage information, not a plan for commercial transformation. The Web's extraordinary success thus stands as a compelling validation of Flexner's argument that freeing research from immediate utility is the most powerful path to societal progress. Furthermore, one can even dig further historically into the impact of basic research on the success of the Web. Similar to what Flexner claimed of Marconi regarding the radio [2, p.5], one could argue that Tim Berners-Lee was inevitable. The Web can be seen as the culmination of a lineage of visionary ideas: Vannevar Bush's concept of the Memex, a theoretical device for associative information storage; Douglas Engelbart's onLine System, which introduced hypertext and interactive computing; and Bill Atkinson's HyperCard environment for the Macintosh [3]. Each of these contributed essential elements that made the Web conceivable, yet it was Berners-Lee's curiosity, persistence, and belief in open source that turned them into a reality.

In hindsight, the World Wide Web stands as one of the clearest examples of how basic, curiosity-driven research and creative experimentation, pursued without commercial intent, can profoundly reshape the world [4].

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Contribution by Timo Kehrer, IE Board Director and member of the IE Software Research Working Group, and colleagues.

Perspectives in Software Engineering Research: Insights through the SE 2026 Lens

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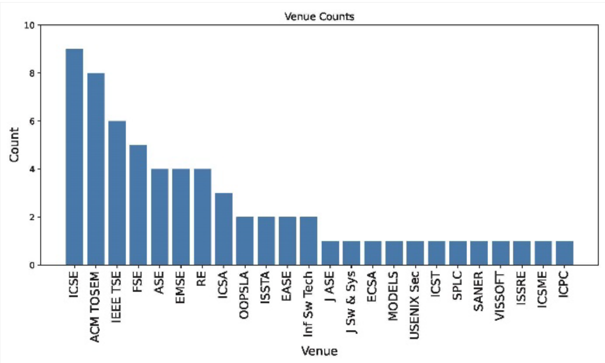
“From AI and cybersecurity to sustainability and healthcare, advances in software are driving innovation across all sectors of modern industry and society”. This is how the newly established Informatics Europe Working Group on Software Research[1] emphasises *software* as one of the pillars underpinning Europe's digital future, and therefore characterises *software engineering* as "the enabling technology and invisible infrastructure of the digital age" [Vos 2026].

At the same time, software engineering itself is undergoing profound transformation. Disruptive technologies such as Generative AI and quantum computing, increasing concerns about digital sovereignty, growing sustainability requirements, the ever-accelerating pace of software construction itself, the continuously increasing complexity of the constructed software-intensive systems, and many other driving forces are reshaping the discipline.

So, what are the current trends and perspectives in software engineering research in this period of transformation? There are certainly many answers and controversial discussions to this question. In this article, we take a brief and selective look at this question through the lens of the annual Software Engineering (SE) conference of the Software Engineering Division (SWT) of the German Informatics Society (GI)[2], organised in cooperation with the Swiss Informatics Society (SI) and the Austrian Computer Society (OCG). This year's edition, SE 2026[3], recently took place from 23–27 February in Bern, Switzerland, hosting around 250 participants from both academia and software engineering practice.

Scientific Program

The scientific program of the SE conference presented significant contributions to software engineering research that were accepted or published within the last two years at renowned international conferences or in leading journals. This year, there were 80 submissions for the main program, of which 64 were accepted with summaries published in the conference proceedings [Kehrer 2026]; the original publications are distributed across international software engineering venues as follows:



The SE 2026 conference program strongly reflected the ongoing paradigm shift towards "AI-first software engineering". Large Language Models (LLMs) and GenAI were touched across virtually all software engineering activities, from requirements engineering over software

1 https://www.informatics-europe.org/research/software-research.html

2 https://fb-swt.gi.de/

3 https://se2026.inf.unibe.ch/en/

construction to software analysis. In all of these activities, the research focus is no longer solely on the explorative usage of AI techniques and tools but also on understanding their reliability, explainability, risks, and integration into real-world development workflows.

At the same time, the program also demonstrated the continued importance of classical software engineering topics. For example, formal verification, software architecture, variability management, and empirical software engineering remained strongly represented. We do not see this as a contradiction, as these areas continue to provide the methodological foundations required to build trustworthy, reliable, and maintainable systems, including those comprising AI components, those developed using AI-centric methods and tools, or both.

In sum, the scientific program of SE 2026 did not reflect a replacement of classical software engineering, but rather a convergence in which AI-centric approaches increasingly build upon and extend traditional software engineering foundations. This is in line with one of the grand challenges of computer science identified by the German Informatics Society (GI) in 2025[4].

Scientific Keynotes

The scientific program also featured two keynote talks, both of which reflected the interplay between AI and software engineering, though the main focus of this interplay was, arguably, on different directions, typically framed as "AI4SE" and "SE4AI", respectively:

"AI4SE": In his keynote entitled “Towards Human-like Software Testing” [Chen 2026], Chunyang Chen emphasised the importance of considering how software is actually used and assessed by humans when designing automated testing approaches. He presented several studies in which human-like testing was performed using LLM-driven testing agents, particularly for GUI testing of mobile applications. The goal of this human-centric testing approach is to explore AI-centric strategies, constraints, and intentions that more closely resemble those of end users.

"SE4AI": In her keynote entitled “Systematic Testing for Complex Systems in the Absence of Oracles” [Christakis 2026], Maria Christakis focused on metamorphic testing as a unifying foundation for testing complex systems in the absence of traditional test oracles. She demonstrated how metamorphic testing can uncover soundness and precision bugs in a variety of domains, including program analysers, cryptographic proof systems, and machine-learning models whose behaviour is based on learned representations. Her keynote illustrated how established verification principles continue to evolve towards new application domains shaped by AI and data-driven systems.

Co-located Events

The symbiosis between emerging paradigms and established software engineering foundations was also visible in the co-located events.

The 2026 CHOOSE Forum[5], organised by the Swiss (CH) Group for Original and Outside-the-box Software Engineering of the Swiss Informatics Society (SI), brought together experts from software engineering, artificial intelligence, and other scientific disciplines to explore the evolving intersections of these fields.

Similarly, the SEUH[6] conference (“Software Engineering im Unterricht der Hochschulen”) on software engineering education in the higher education sector, focused strongly on the impact of AI on teaching and learning. The SEUH participants interactively explored and discussed open questions related to programming education with and without AI support, software engineering education in the age of AI, and the opportunities and challenges of

4 https://gi.de/grand-challenges/vollautomatisierte-software-entwicklung

5 https://choose.swissinformatics.org/events/choose-forum-2026-software-engineering-ai-scientific-computing/

6 https://www.seuh.org/seuh2026/

AI-based tutoring systems in software engineering education.

The industry day[7], dedicated to the topic of digital sovereignty, critically examined the tension between dependence on AI providers and cloud infrastructures on the one hand, and maintaining control over training data, models, and infrastructures on the other. In her industry keynote entitled "Achieving Digital Sovereignty in Europe: Key Considerations for Success"[8], Amandine Le Pape, co-founder of Matrix/Element, reflected on the very concept of digital sovereignty, its growing importance, and the central role of open source and digital commons in achieving it. She also discussed potential pitfalls and shared best practices for successfully implementing digital sovereignty initiatives.

A similar picture was drawn by the seven accepted workshops[9], which together reflected both continuity and disruption within software engineering. On the one hand, highly established workshops represented long-standing software engineering domains, particularly in the German-speaking region. A prominent example is the 23rd edition of the Automotive Software Engineering workshop (ASE'26), where traditional concerns such as safety and security remained central, but also topics such as automated driving, cloud connectivity, and voice interaction highlighted the shift towards increasingly data-driven and AI-enabled software systems. On the other hand, several historically younger workshops focused explicitly on disruptive technologies and emerging paradigms, such as the 3rd Workshop on Generative and Neurosymbolic AI in Software Engineering (GenSE'26) and the 3rd International Workshop on Quantum Software Engineering Tools, Algorithms & Verification (Q-STAV'26).

Finally, the Software Engineering Division of the GI presented an award for the best PhD thesis[10]. Furthermore, as part of the student research competition[11], prizes were awarded to the best bachelor's and master's theses in software engineering. The excellent works that were nominated for presentation and awarded prizes covered a wide range of topics, demonstrating how young researchers are addressing current challenges and becoming integrated within the SE research community. With research topics ranging from neural bug detection to functional modelling of cyber-physical systems, it is particularly noteworthy that the early-career researchers' contributions reflect the current trends and perspectives within the community: The convergence of classical SE foundations with AI-driven and data-driven approaches, and the remarkable breadth of contemporary software engineering research.

Conclusion and Outlook

Overall, the SE 2026 conference program showcased a software engineering community undergoing a major paradigm shift while building on rigorous software engineering foundations. In particular, GenAI is no longer treated as an experimental topic, but has become deeply integrated into research. At the same time, the field continues to rely on its traditional foundations, such as formal modelling and analysis as well as empirical evaluation.

Looking ahead, the software engineering community will increasingly face the challenge of combining the productivity gains of AI-based development with the rigour required for engineering dependable and trustworthy modern software systems. We believe that this

7 https://se2026.inf.unibe.ch/en/tracks/industry-day/

8 https://se2026.inf.unibe.ch/en/program/keynotes/amandine-le-pape/

9 https://dl.gi.de/handle/20.500.12116/48241

10 https://se2026.inf.unibe.ch/de/tracks/dissertationspreis/

11 https://se2026.inf.unibe.ch/de/tracks/student-research-competition/

will require a deep understanding of how human expertise and intelligent automation can effectively complement each other. The SE conference series will continue to provide an important forum for shaping and critically reflecting on this evolution, and the community is already looking forward to the next edition in 2027 at the Technical University of Dortmund[12].

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12 https://se2027.cs.tu-dortmund.de/

Contribution by Anne-Cécile Orgerie, Keynote Speaker of ECSS 2025 Green ICT & ICT for Green Workshop.

Four Axes Driving Research on Sustainable ICT: Impacts Assessment, Efficiency, Sufficiency and Resilience

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Introduction

We are currently experiencing a serious environmental and climate crisis of proven anthropogenic origin [IPCC 2021]. We live in a finite world with limited resources in minerals, metals, water, land area, non-renewable resources, etc. This finite world relies on fragile equilibrium states, including biodiversity, which are severely threatened. In this context of environmental and climate crisis, objectives were set by the Paris Agreement, ratified in 2015. These objectives aim to limit global warming to 2°C above pre-industrial temperatures. We are currently deviating from the paths that would allow us to meet these objectives. One universal objective, however, prevails: to guarantee a decent and equitable standard of living.

In this environmental crisis, all industrial sectors are affected: all must reduce their impacts, and ICT is no exception. ICT is often presented as part of the solution to climate problems. Indeed, it allows for the optimisation of data transfers, storage, and calculations; the detailed modelling of complex system interactions; the simulation of large-scale problems with a very large number of parameters; and the calculation of trajectories and prospective scenarios. However, ICT is undeniably part of the climate problem, both through its direct and indirect effects [Freitag 2021]. Direct effects concern the resources used throughout the life cycle of ICT devices: embodied energy, water, metals, etc. Indirect effects include optimisation, induction, obsolescence, acceleration, social transformation, and rebound effects [Horner 2016]. In recent years, numerous research studies have been launched towards green ICT or sustainable ICT. In the following, we classify them into four complementary, and often intertwined, research axes. In particular, these axes are explored in the context of a French research and service network named EcoInfo [EcoInfo].

Impacts assessment

More and more studies are focusing on environmental impact assessment, meaning assessment methods for direct and indirect impacts, whether positive or negative, and on the development of indicators and methodologies for allocating these impacts. One can, for instance, cite the GHG protocol for assessing greenhouse gas emissions [GHG Protocol].

The impacts can be numerous and diverse: energy consumption, greenhouse gas emissions, water consumption, use of mineral resources, pollution, rebound effects, efficiency gains, conflicts of use, etc. This research axis notably covers issues related to energy consumption and carbon footprint in order to: understand the information conveyed by indicators, measure them on various IT equipment using software and hardware power meters, design attribution models for these indicators for digital services and shared digital infrastructures, and develop simulation tools to evaluate these indicators at a large scale for given digital applications. Research targeting other environmental and societal indicators, whether single-criterion or multi-criteria, remains less explored, as does research focusing on the non-use phases of the life cycle (end of life, for example, and electronic waste management), and research concerning indirect effects (obsolescence effects, direct and indirect rebound effects, systemic transformations) [Horner 2016].

Several methods exist for qualitatively or quantitatively estimating environmental and societal impacts. These methods either create a snapshot at a given moment (carbon footprint, material footprint, or attributional life cycle analysis), or answer questions about specific changes by identifying the difference with/without the targeted change (quantification of greenhouse gas emissions, project footprint, consequential life cycle analysis).

Currently, the energy consumption and greenhouse gas emissions of the digital sector are still the subject of debate regarding their quantification, but also regarding their trend (more or less pronounced increase). Research in this area is still recent and must nevertheless urgently address practical questions concerning the qualitative and quantitative assessment of impacts: of ICT on other sectors and other scientific disciplines, of the digitisation of services, of the introduction of new information technologies, and of research on ICT itself.

Efficiency

For several decades now, ICT research has also focused on efficiency, that is, achieving the same level of use with a reduced impact, optimising systems, and developing eco-design and repairability approaches to reduce resource waste. Efficiency concerns the optimisation of systems according to one or more criteria (resource consumption, greenhouse gas emissions, etc.). Efficiency issues concern both hardware and software aspects and their co-optimisation.

Historically, efficiency in terms of performance (e.g., computation time, memory space, silicon area, spectral efficiency) has been a concern since the start of ICT. However, except in some specific areas such as embedded systems, the targeted criterion was primarily economic and not environmental or societal. Increasingly, research is focusing on energy efficiency in various areas of computing: hardware architectures, programming languages, compilation, data lifecycle, algorithms, optimisation techniques, communication network management, distributed systems, computing and storage infrastructures, etc. Some research studies go beyond the use phase and beyond energy and carbon criteria by exploring, for instance, the efficient use of water throughout the entire lifecycle, or by reducing the use of some abiotic resources.

This research axis encompasses efficient approaches (during the use phase) and eco-design (upstream during the design phase) for both software and hardware, as well as research related to multi-criteria trade-offs between performance and environmental impacts.

Eco-design can aim, in particular, to extend the lifespan of digital equipment, increase its repairability, fight against software and hardware obsolescence, or make infrastructures and systems adaptable to dynamically adjust resource use to user needs.

Research in this area may focus on optimising existing systems or developing new technologies. Regarding the optimisation of existing systems, numerous techniques are being explored, such as standby modes, dynamic adaptation of voltage, frequency, or radio channel, data compression, heterogeneous architectures, approximate computing, etc.

Efficiency can also be achieved by optimising the carbon footprint of the electricity used by harnessing renewable energy sources, which are often intermittent, variable over time, and difficult to predict (e.g., wind power). This axis is gradually leading to questions about the role of ICT in the energy transition as a sector on its own (part of the problem), and not simply as a tool that may contribute to this transition (part of the solution).

Sufficiency

More recently, research studies have shifted towards sufficiency or sobriety, meaning redefining uses and reorienting needs in relation to global challenges. Sobriety is often associated with notions of frugality, absolute environmental sustainability, or sufficiency, and raises the question of needs in relation to that of planetary boundaries [Rockström 2009]. Who can define these needs? How can we guarantee a reduction in inequalities and the social justice that is necessary for self-limitation? How can we design a 'low-tech' ICT, or one limited by design? What should these limits be?

Some research studies in ICT are beginning to address these boundary issues by proposing, for example, to adapt existing systems, software, or algorithms to take into account predetermined budgets, whether in terms of energy consumption (energy budget), greenhouse gas emissions (carbon quota), or usage time. These restrictive budgets imply changes in users' habits. The challenges are therefore multifaceted: determining technically achievable limits (from both a theoretical and practical point of view), proposing adaptable mechanisms to reliably implement these limits, analysing their impacts (direct and indirect), determining desirable limits for each indicator to ensure compliance with planetary boundaries, and so on.

These limits can vary over time, for example, to smooth out peak usage (i.e., with peak/off-peak hour mechanisms) or, conversely, be fixed at the manufacturing stage (by design). In the case of time-varying limits, issues of flexible use arise, with potential rebound effects.

These limits can also be physical (low-tech) in terms of data volume, number of transistors, lifespan, etc. They can be defined at collective scales (a team, a company, an administration, a region, etc.) or individual scales. Digital sufficiency also raises the question of limiting usefulness and restricting usage, with major and inseparable implications: issues about social justice and fairness. The social effects of these limitations, whether stemming from regulations, incentives, or self-restraint practices, must be studied to avoid negative consequences (social inequalities, digital divide, etc.) and problematic behaviours (e.g., addictions). Adopting sober behaviours also raises questions about user appropriability and desirability.

Resilience

Finally, in parallel, studies have been conducted around resilience, meaning defining the kind of ICT that would help to cope with disruptive situations. It concerns both the resilience of digital technology itself in facing disruptions (e.g., intermittent electricity, shortages of materials or ICT components, water restrictions) and the resilience of other systems in facing ICT disruptions (e.g., outages, unavailability).

These two resilience directions seem orthogonal to reducing the environmental impacts of ICT. Indeed, the resilience of an ICT system is often characterised as its robustness and fault tolerance, and resource overallocation and redundancy methods are de facto standards to guarantee these two criteria. It is therefore necessary to propose other robustness methods that take planetary boundaries into account. These methods could, for example, explore much more decentralised architectures in the management of large ICT systems (communication networks, cloud infrastructures, etc.).

Foresight studies are a valuable tool for resilience research. Indeed, they allow us to anticipate in the face of uncertainty, and they provide methods for exploring future scenarios (rather than predicting them). These studies enable us to envision the future and, through the study of possible or desirable futures, to identify major trends, weak signals, or potential disruptions. Adapting hardware and software infrastructures to these potential disruptions or shortages remains a largely underexplored area.

The resilience of digital technology itself also raises questions of adaptability, repairability, and conviviality [Illich 1973], as well as issues of conflicting uses, and even user prioritisation in the event of very limited ICT resources or crisis management. Finally, resilience raises the question of the role of ICT in our future with increasingly tangible planetary boundaries and leads to research questions about dedigitalisation of other sectors.

Conclusion

Underlying these four axes is the question of the role of research in this environmental crisis and the individual and collective responsibility of higher education and research staff. How can we address these systemic challenges that raise ethical questions? What are our narratives about computer science? What kind of ICT do we dream of? What kind of ICT are we inventing? What kind of ICT are we telling in our research, development, teaching, and applications? Will this future ICT be sustainable, respectful of the environment, and of planetary boundaries? Will it contribute to guaranteeing a decent and equitable standard of living for all?

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Contribution from the Computing Science Department (INGI), UCLouvain, Belgium—an IE member institution since 2013.

Orthanc: a Lightweight, Open-Source DICOM Server for Medical Imaging Informatics

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The management and exchange of digital medical images are central to modern healthcare, supporting diagnosis, treatment planning, and follow-up in nearly all specialities, as well as clinical research. The volume of generated imaging data has grown rapidly in recent years, driven by two converging trends. The first is longitudinal imaging, in which patients are imaged repeatedly over time, whether to monitor disease evolution in routine care (e.g., oncology or cardiology) or to track biomarkers in long-term studies. The second is multimodal imaging, in which several complementary modalities (such as MRI, PET, and CT) are acquired for the same patient, in fields ranging from neurology to orthopaedics. The handling of this expanding data places considerable demands on the underlying IT infrastructure.

The Digital Imaging and Communications in Medicine (DICOM) standard provides the technical foundation for handling medical imaging data. DICOM specifies an exchange format for medical images and associated metadata (commonly referred to as “DICOM files”), as well as a network protocol for their transmission. This protocol, extensively used in hospitals worldwide, supports querying the content of a remote imaging device, sending images to it, or requesting a transfer between two remote devices. Hospitals typically deploy a central, large-scale database known as a Picture Archiving and Communication System (PACS), which stores and manages all DICOM images generated across their clinical departments.

Because DICOM is an open standard, a rich ecosystem of free and open-source software has matured around it. Such software broadly falls into three categories: libraries for processing DICOM files and handling DICOM networking (e.g., DCMTK, pydicom, GDCM, VTK, or dcm4che), viewers for displaying image content (e.g., OHIF, 3D Slicer, Horos, or Weasis), and servers for managing databases of medical images (e.g., dcm4chee, Dicoogle, or ConQuest). Free and open-source software plays a particularly significant role in medical imaging. It lowers the barrier to entry for clinics, research institutions, and low-resource settings that cannot afford commercial licensing fees. It supports knowledge sharing and auditability, which are important for clinical and industrial research. Beyond that, it allows healthcare institutions to build workflows that expand the features their central PACS offers. Indeed, proprietary PACS are often optimised for routine radiology and are rarely flexible enough to support clinical trials, multicenter studies, and the training and evaluation of artificial intelligence (AI) models on medical imaging data. Open-source DICOM tools enable institutions to build custom pipelines along with their existing infrastructure. This paper presents Orthanc, a free and open-source DICOM server that was developed to fill a gap in the open-source ecosystem for medical imaging [1].

The Orthanc project

Orthanc originates from the University Hospital of Liège (Belgium). It was first released in 2012 and is licensed under the GNU General Public License. The design of Orthanc reflects close observation of daily clinical and research practices. Indeed, it became clear that existing free and open-source PACS solutions, while powerful, required significant expertise and configuration effort before they could be put to use. Orthanc takes a different approach: It is distributed as a single executable with no external dependencies and runs out-of-the-box on all major operating systems, including commodity hardware such as standard desktop computers, as well as containerised environments. This is possible thanks to the fact that Orthanc is a standalone C++ software that embeds a SQLite database. Importantly, Orthanc exposes a RESTful API that wraps DICOM functionality over standard HTTP/HTTPS connections, enabling integration with contemporary Web technologies and lowering the barrier to programmatic interaction with medical imaging data, which was a feature no other open-source DICOM server offered at the time. The result is a server that is lightweight, pragmatic, interoperable, and accessible to users without deep DICOM expertise. Since 2021, the Orthanc project has been actively maintained and extended by UCLouvain University (Belgium) in an academic setting.

Orthanc is used in a wide range of applications. It often serves as an ancillary DICOM server in clinical environments, notably to support autorouting workflows, but it can also function as a full PACS in low-resource hospitals, as well as in industrial and research settings. It is widely used to support inter-site image exchange and to automate de-identification workflows, for example, in multicentre studies or AI data curation pipelines. Through its integration with multiple open-source viewers, it can also be used as a teleradiology platform, including for remote expertise and second opinions.

Beyond these use cases, Orthanc has attracted considerable interest for its extensibility. A plugin architecture allows the core server to be augmented with additional capabilities, ranging from advanced database backends (e.g., PostgreSQL) and cloud storage connectors to inference engines for AI-assisted image analysis. In particular, the automation of DICOM workflows can be implemented through Python scripts executed by a dedicated plugin. As illustrated in Figure 1, plugins have also been developed to serve popular open-source, Web-based DICOM viewers through the embedded Web server of Orthanc. Orthanc plugins also delivered the first open-source implementation of the DICOMweb protocol in 2015, as well as DICOM support for whole-slide pathology imaging in 2016. More recently, plugins have been developed to turn Orthanc into a teaching platform, including Moodle integration, or to distribute deep learning models, for instance, for the detection of masses in mammography.

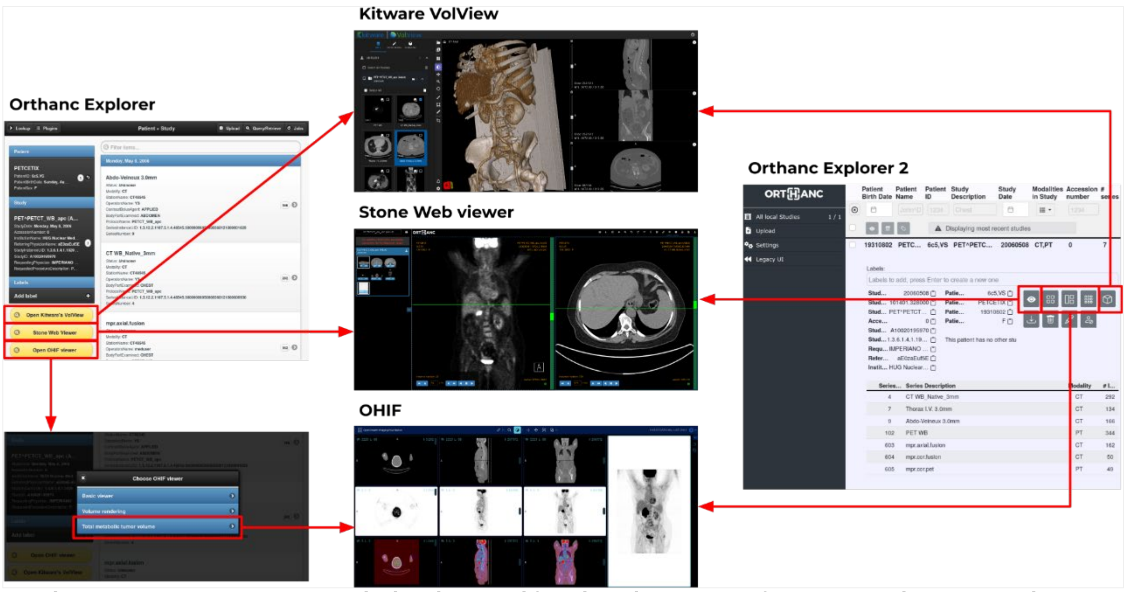

Figure 1: Three open-source DICOM viewers can be directly accessed from the Orthanc user interfaces: Kitware VolView, Stone Web Viewer, and OHIF.

As a companion project to its DICOM server, the Orthanc ecosystem also features a lightweight Web-based DICOM viewer designed specifically for teleradiology contexts, where network bandwidth efficiency is essential [2]. This viewer, named the Stone Web Viewer and depicted in Figure 2, is notable for being written primarily in C++ and compiled for Web browsers using the WebAssembly technology. This technological choice enables code reuse with desktop or mobile applications. The Stone Web Viewer additionally offers partial support for rendering DICOM structured reports, including those containing measurements or observations produced by AI algorithms, in line with the IHE "AI Results" profile.

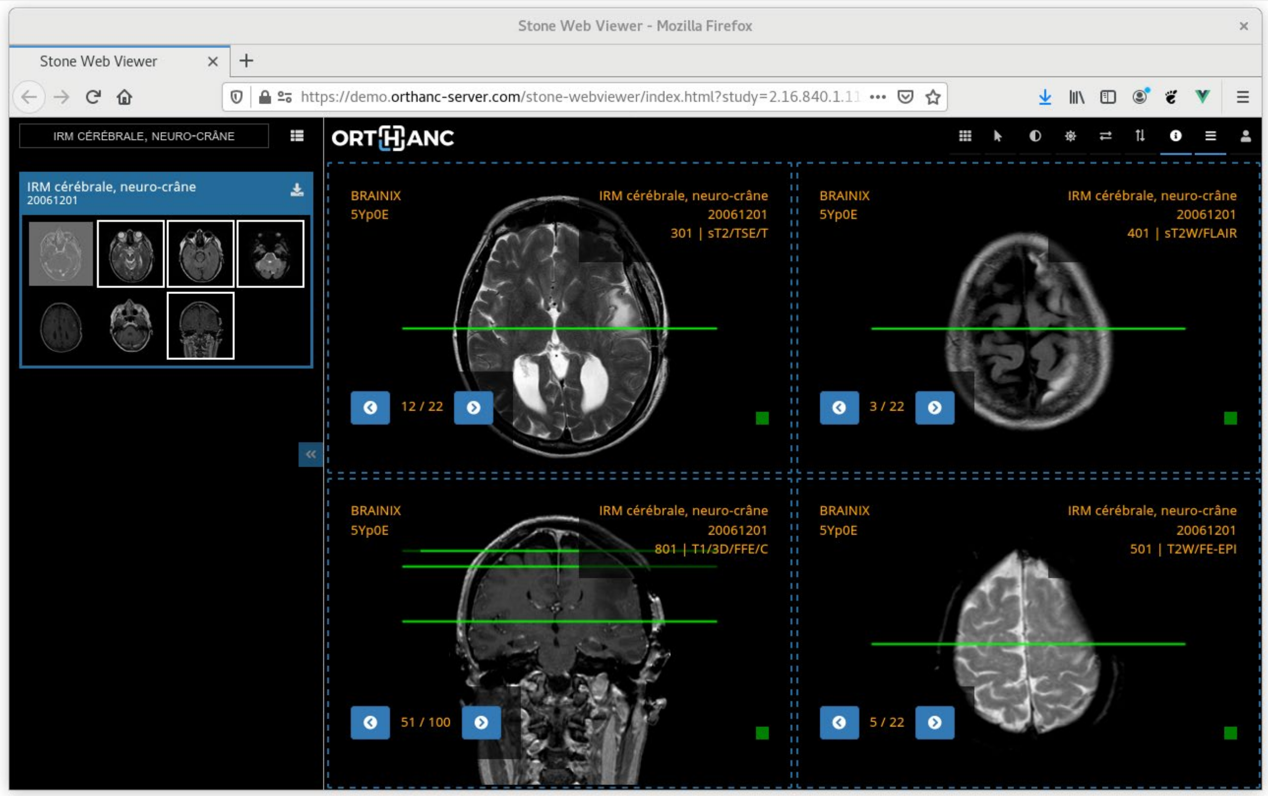

Figure 2: Stone Web Viewer displaying an MRI study (reproduced from [2]).

The Orthanc ecosystem is an established project with a worldwide community. It has been recognised as a Digital Public Good by the UN-endorsed Digital Public Goods Alliance (DPGA). Integrations with the GNU Health and OpenMRS free and open-source electronic health record (EHR) systems are available, linking patient records with medical images. Professional support is also provided by private companies.

Conclusion

The mission of the Orthanc project is to make technological knowledge about medical imaging freely accessible. By providing open, well-documented, and easy-to-deploy tools, Orthanc lowers the barriers that separate clinical practice, research, and software development. As medical imaging increasingly intersects with artificial intelligence, this mission extends to supporting the infrastructure needed to collect, curate, and process imaging data. The project is based on the conviction that such foundational tools should be a shared resource, available to any institution regardless of its size or means.

The homepage of the Orthanc project is available at: https://orthanc.uclouvain.be/.

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Contribution from the Department of Electronics Information and Bioengineering, Politecnico di Milano, Italy—an IE member institution since 2006.

Why Small Pockets of Non-Compliance Can Reshape Urban Epidemics

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DOI: 10.5281/zenodo.20798369

In our research[1], we set out to study a question that became especially visible during the COVID-19 pandemic, but that is relevant to epidemics more broadly: what happens when compliance with public health measures is unevenly distributed across a city?

Epidemic dynamics are often described in terms of biological parameters such as transmissibility or recovery rates. Yet the spread of infection also depends strongly on behaviour. Measures such as vaccination, masking or distancing are effective only insofar as they are adopted. In practice, populations are never fully homogeneous. Some people consistently follow preventive recommendations, while others do not. We were interested in understanding how this behavioural heterogeneity—and in particular the presence of non-compliant individuals—can affect epidemic outcomes in realistic urban contexts.

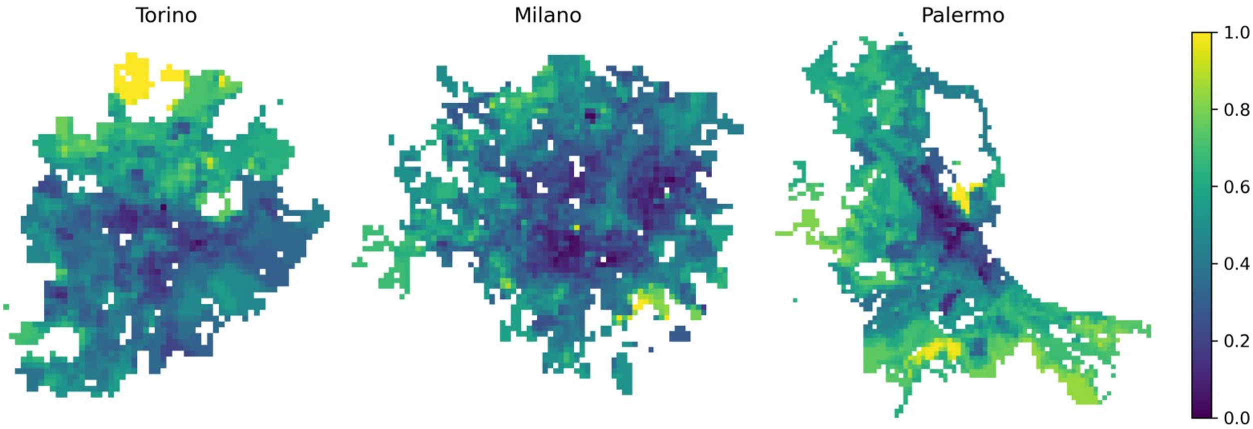
To address this question, we combined epidemic modelling with a data-driven representation of three Italian cities: Torino, Milano and Palermo. We chose these cities because they differ in size, structure and demographic composition, allowing us to explore whether our findings were robust across distinct urban settings. Using publicly available demographic and geographic information, we built synthetic contact networks that capture both household interactions and wider social contacts, while also considering spatial proximity and age structure.

On top of these networks, we implemented a heterogeneous extension of the classical susceptible-infected-recovered (SIR) model.[2] In our framework, the population is divided into compliant and non-compliant individuals. This distinction is intended to represent behavioural differences that influence exposure and transmission. Non-compliant individuals, in the model, are more likely both to contract the infection and to pass it on to others. Our goal was not to assign blame, but rather to examine how behavioural variability can shape collective outcomes.

What we found is that even a relatively small fraction of non-compliant individuals can have a substantial impact on epidemic diffusion. As the proportion of non-compliance increases, the epidemic tends to spread more rapidly, infect a larger share of the population, and reach its peak earlier. From a public health perspective, this is especially important because an earlier and higher peak means less time to respond and potentially greater pressure on healthcare systems.

1 Mazza, F., Brambilla, M., Piccardi, C., & Pierri, F. (2025). A data-driven analysis of the impact of non-compliant individuals on epidemic diffusion in urban settings. Proceedings of the Royal Society A, 481(2324), 20250511. https://doi.org/10.1098/rspa.2025.0511. This work was supported by the project 'CODE–Coupling Opinion Dynamics with Epidemics', funded under PNRR Mission 4 'Education and Research' - Component C2 - Investment 1.1 - Next Generation EU 'Fund for National Research Program and Projects of Significant National Interest' PRIN 2022 PNRR, grant code P2022AKRZ9, CUP B53D23026080001.

2 See also Mazza, F., Colaiori, F., Guarino, S., Meloni, S., Brambilla, M., Piccardi, C., Pierri, F., & Saracco, F. (2025). The impact of heterogeneity on epidemics: Insights from a modified SIR model. In Complex Networks & Their Applications XIII. https://doi.org/10.1007/978-3-031-82439-5_6.



Data-driven distribution of the proportion of non-compliant individuals, scaled such that 0 represents the minimum level and 1 the maximum level of non-compliance. Darker colours correspond to smaller values, using the same colour normalisation for the three cities.

One of the central insights from our work is that the effect of non-compliance is strongest in an intermediate transmissibility regime. If a disease is only weakly transmissible, outbreaks often fade out regardless of behavioural differences. If it is highly transmissible, large outbreaks can occur even under relatively high compliance. But when transmissibility lies near the epidemic threshold, behavioural heterogeneity becomes especially consequential. In this regime, a modest increase in risky behaviour can produce a disproportionately large change in epidemic size.

For us, this was a particularly interesting result because it points to the conditions under which interventions are most sensitive to social behaviour. It suggests that the success of public health measures cannot be assessed only through average compliance rates. Instead, one must consider how close the system is to a tipping point, where seemingly limited deviations in behaviour may trigger much broader effects.

We also wanted to go beyond city-level averages and examine the spatial dimension of the problem. In real cities, non-compliance is unlikely to be uniformly distributed. It may instead cluster in particular neighbourhoods or communities. To account for this, we estimated a geographically heterogeneous distribution of non-compliance by combining fine-grained electoral data with evidence from previous research on vaccine hesitancy. This allowed us to assign varying levels of non-compliance across different areas of each city.

At the aggregate level, the difference between a uniform and a spatially heterogeneous distribution of non-compliance is not always dramatic. However, once we looked at the local scale, the picture changed substantially. Areas with higher concentrations of non-compliant individuals displayed more intense epidemic activity, including stronger local peaks and higher infection burdens. In other words, localised hotspots emerged as a consequence of behavioural clustering.

We believe this is one of the most policy-relevant aspects of our study. A city may appear to be coping reasonably well when one looks only at average indicators, while still containing neighbourhoods where the epidemic is spreading much more aggressively. These local surges may place severe strain on nearby health and social services, and they may act as reservoirs that sustain wider transmission. For this reason, interventions should not focus solely on lowering non-compliance overall, but also on identifying where it is concentrated.

Another important element of our analysis concerns the role of network structure. Urban epidemics do not unfold in well-mixed populations. They move through highly structured systems of households, workplaces, schools and local communities. In our study, when we randomised the contact network while preserving the number of contacts per person, the hotspot effect associated with clustered non-compliance became much weaker. This result indicates that realistic urban contact patterns are essential for understanding how behavioural heterogeneity translates into epidemic risk.

From an informatics perspective, this is one of the broader messages we would like to emphasise. The integration of network science, computational modelling, behavioural data and spatial analysis can provide insights that are difficult to obtain from aggregate approaches alone. Our work illustrates how publicly available data can be used to build realistic models of urban systems and to explore scenarios that are directly relevant to public decision-making.

At the same time, our study has limitations. As in any model, some aspects of reality must be simplified. Behaviour is represented statically, whereas in real epidemics it can change over time in response to information, social influence or policy measures. Likewise, our proxy for spatial non-compliance can be refined further as richer behavioural datasets become available. We see these limitations not as weaknesses that undermine the main result, but as opportunities for future work at the intersection of informatics, computational social science and public health.

Overall, our findings support a simple but important conclusion: small behavioural minorities can generate large system-level effects, especially in cities. Epidemic preparedness therefore requires attention not only to average behaviour, but also to heterogeneity, clustering and network structure. By showing how local concentrations of non-compliance can amplify transmission, we hope to contribute to a more nuanced understanding of epidemic risk in urban environments.

For the informatics community, this opens a promising line of inquiry. Urban epidemics are not merely biomedical events; they are also data-rich, networked and spatial phenomena. Understanding them requires tools that can connect individual behaviour to collective dynamics. This, in our view, is precisely where informatics can make an important contribution.

Contribution from the IE Data Analysis and Reporting Working Group.

Notable Trends in Informatics Bachelor Students' Retention and Graduation Rates across Europe

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DOI: 10.5281/zenodo.20798984

Introduction

The landscape of European education in informatics, with its diversity, rich traditions and strong roots, has always been an object of interest at Informatics Europe (IE). Among the motivations was the shared need to get a broader, representative picture of this diverse landscape, where individual countries differ in both the structure and details of their higher education (HE) systems and in the ways data about these systems is being collected, categorised and made available. Given its wide coverage of European countries through its members, IE has the unique ability to provide a broader, representative picture.

The results of this interest range from data collection activities through analyses to policy recommendations. Early pivotal examples include the annual series of reports "Informatics Education in Europe: Institutions, Degrees, Students, Positions, Salaries — Key Data Report" [2] and the "Europe cannot afford to miss the boat" report [1]. The data collection efforts took an important step with the creation of the Informatics Europe Higher Education Data Portal[1], launched in 2019 in collaboration with the Software Institute at Università della Swizzera Italiana and later presented in a comprehensive paper [3].

In this article, we briefly cover the Data Portal's features and then present key findings from a recent analysis using its data — trends in retention and graduation rates among European bachelor-level informatics students.

Informatics Europe Data Portal

The Informatics Europe Higher Education Data Portal, part of the IE public website, provides both statistical and descriptive information on various aspects of higher education in informatics across Europe. The portal contains data on informatics student and graduate numbers (at all three levels of higher education) starting from the academic year 2010/2011, as well as lists of informatics HE institutions and factual information on HE systems in individual countries (focusing on the specifics of the Informatics field), currently covering 25 European countries.

This dataset is curated and updated by the IE office every year with new student and graduate statistics and at appropriate moments with revised descriptive parts. While the IE office plays a key role in this process, collaboration with national contacts (representatives from IE member institutions) is essential as they provide clarifications of locally specific aspects of the data, point to reliable national sources, and supply data updates for countries where it is not available from official institutions.

A major part of the portal's dataset is available exclusively to logged-in users, as part of the services provided to IE members. A useful feature of the portal is the online data

[1] https://www.informatics-europe.org/data/higher-education

visualisation tool, which depicts cross-country and time-series comparisons directly on the European map and bar-chart graphs. By specifying the topic of interest (i.e. first-year students, students from all semesters, degrees awarded), the level of education according to the Bologna system – bachelor, master, or doctoral (Ph.D.), institution type (Research Universities abbreviated as RU or Universities of Applied Science (UAS) for the countries where these institutions exist), country, and year, users can generate custom maps and graphs to view recent trends in informatics HE in Europe.

Recent Trends in Student Retention and Graduation Rates

This dataset enabled us in the past year to undertake new analytical studies of retention and graduation rates among European bachelor-level informatics students. By *retention* rate, we mean the proportion of students from a cohort entering a given year of study who remain enrolled and make progress toward their degree, and by *graduation* rate, we mean the ratio between the number of students who graduated in a given year and the size of the cohort of corresponding first-year students. Further details on the methodology for computing retention and graduation rates, including the set of countries selected[2], are provided in the "European Informatics Retention and Graduation Rate Report" [4].

Our studies on these two features are an important contribution to understanding the patterns of informatics students' progress through studies, since no dataset from any European country provides this information explicitly. It should be noted, however, that this also means the reported

Regarding the **gender differences** in retention rates, there is no uniform pattern across Europe. In most countries, women

figures are approximations. Among the reasons are the simplifying assumption that the duration of bachelor programmes is 3 years, as is typical (though not universal) in many Bologna system countries, and that all bachelor students in their final year complete their studies and graduate from the informatics programme in the given country of study.

One of the main challenges in preparing the dataset was ensuring that the country data was sufficiently mutually harmonised, particularly regarding the definition of "Informatics" as a discipline and its reflection in the nomenclatures used in the available statistics, which vary across national systems.

Below, we present several illustrative findings from these studies, highlighting patterns in retention and graduation rates at the bachelor's level.

The calculated retention rates vary across countries, ranging from 75% to 100%, and the overall trend in the last decade is that of a moderate increase: among the 13 countries studied, 7 show increasing retention (see Figure 1 below) and four a stable trend (Bulgaria, Italy, Portugal, United Kingdom), while retention is decreasing in only 2 countries (Switzerland and the Netherlands) which have one of the highest rates in the studied set.

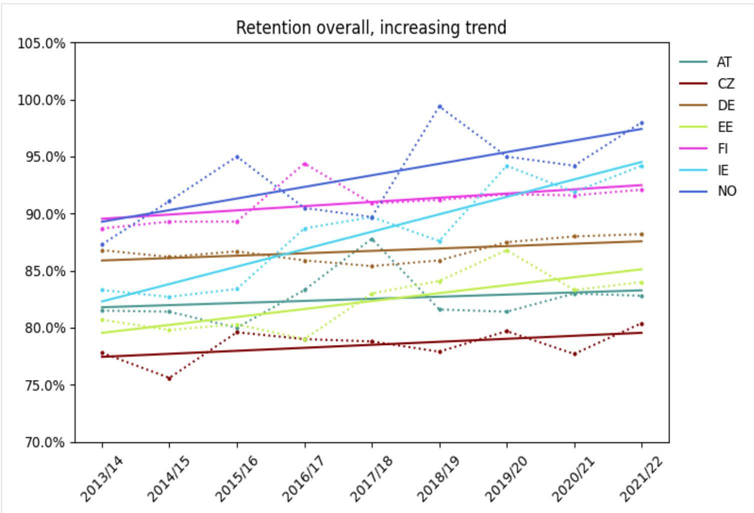

Figure 1: Bachelor-level retention data and trends in informatics – countries with increasing rates.

[2] AT = Austria, BG = Bulgaria, CH = Switzerland, CZ = Czech Republic, DE = Germany, EE= Estonia, FI = Finland, IE = Ireland, IT = Italy, NL = the Netherlands, NO = Norway, PT = Portugal, UK = United Kingdom

exhibit slightly higher retention rates (cf. Figure 2), while in others, men show higher retention, notably in Austria, Switzerland, and Germany. In a further group of countries, the gender differences are small and not statistically clear (Italy, Portugal). Overall, gender gaps are small compared to differences across countries.

Graduation rates show a similar pattern in terms of gender comparison, see Figure 3. An interesting observation is that male graduation rates are higher only in predominantly German-speaking countries.

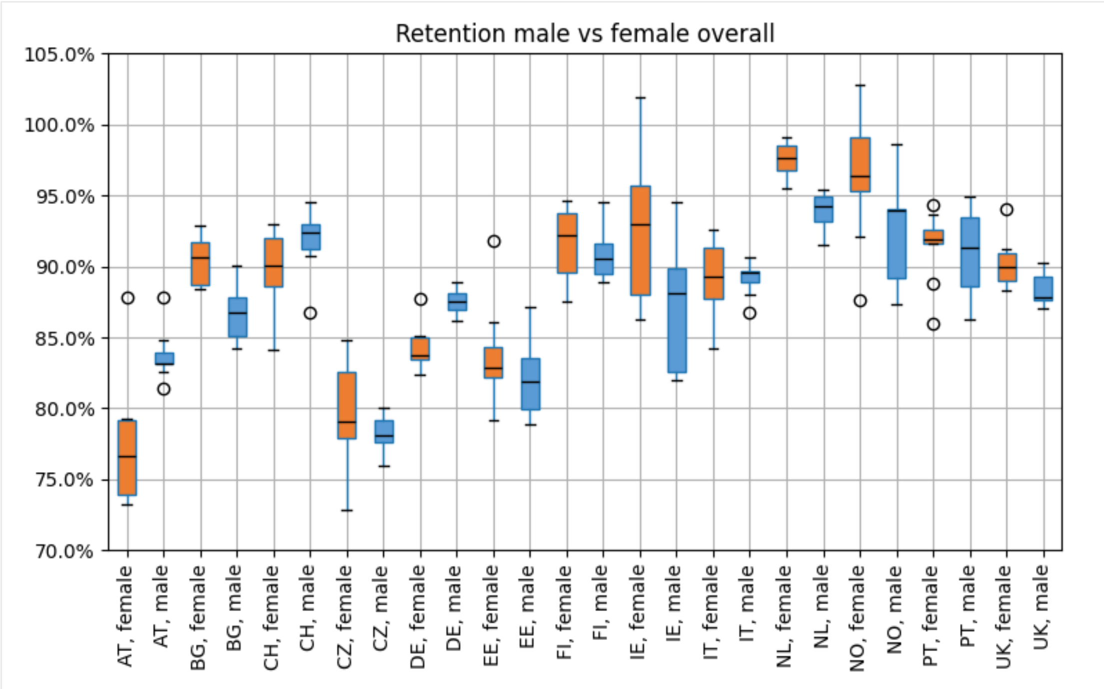

Figure 2: Gender differences in bachelor-level retention rates in informatics.

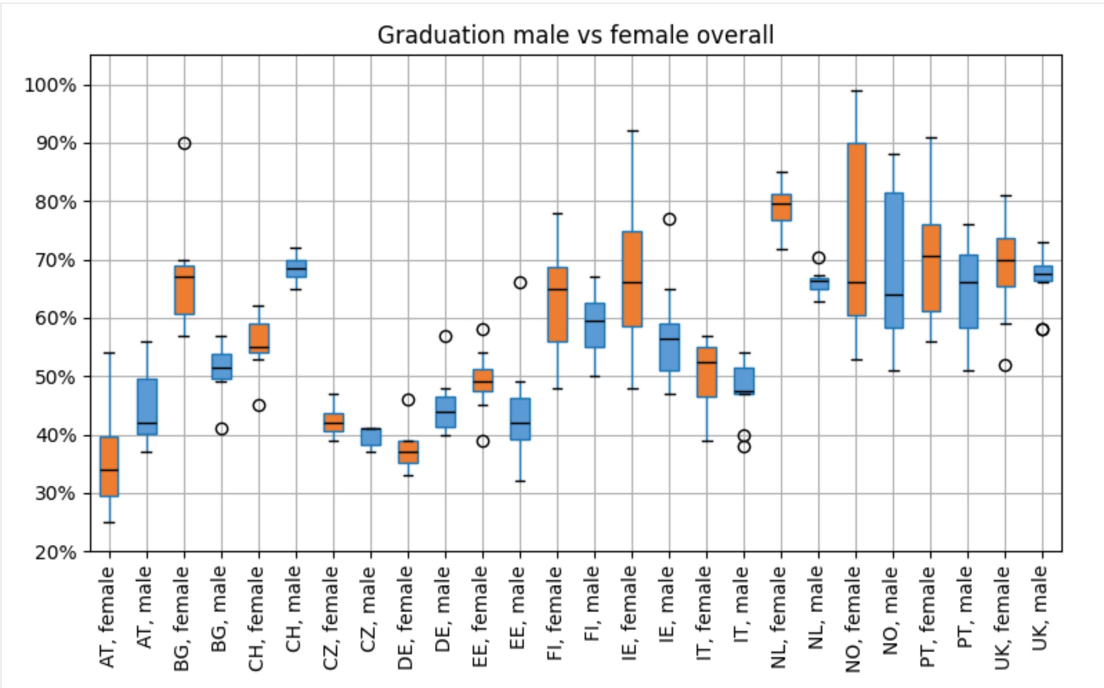

Figure 3: Gender differences in bachelor-level graduation rates in informatics.

Regarding the types of universities, our studies uncovered high variability in retention rates at universities of applied sciences (UAS) in countries with very small UAS enrolments. On the other hand, UAS contribute to about ½ of informatics bachelor graduates in 7 countries studied (i.e., in ½ of our sample), see Figure 4, which highlights the need for appropriate policies to cover both research and applied science universities.

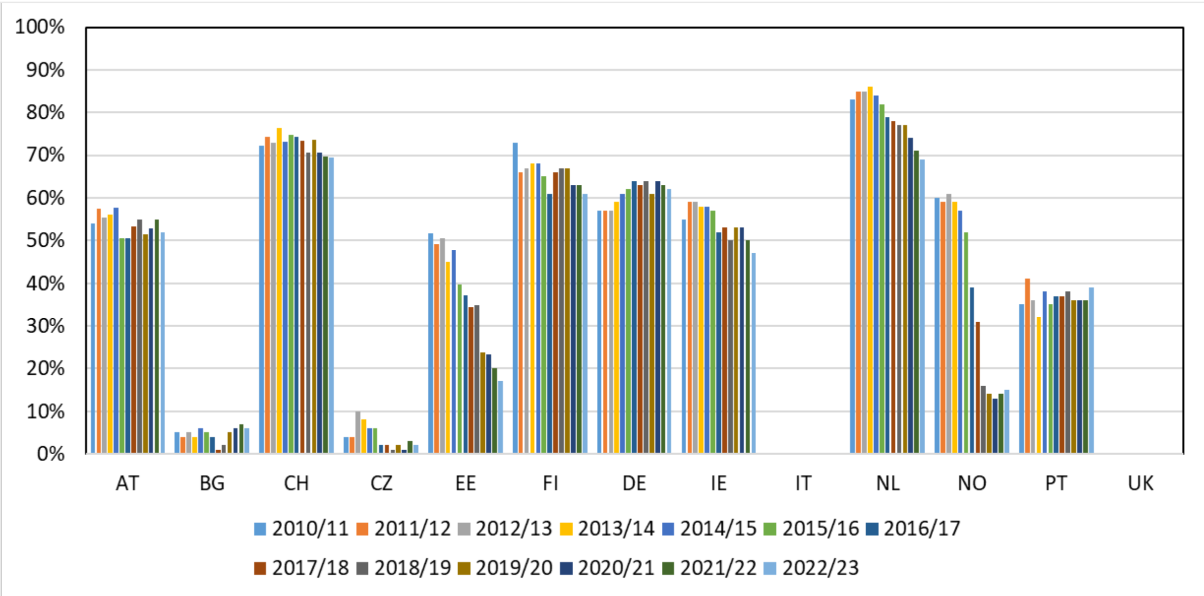

Figure 4: Percentage of UAS informatics bachelor's students enrolled in all semesters.

Conclusion

Our studies of bachelor-level retention and graduation rates in Informatics reveal that, overall, the situation across Europe is gradually improving in both metrics, perhaps as a result of many targeted measures at the institutional, country, and EU levels. The findings also support the "common knowledge" that higher education systems exhibit both commonalities and unique national characteristics.

Further work will be needed to understand the causes of the particular values and/or trends in selected countries, e.g., the rapid improvement in graduation rates in Norway and Ireland. Regarding the data available for studies like ours, the national statistics (and the underlying field-of-study definitions) need to be better understood and aligned across Europe.

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Contribution from the Department of Computer Science, University of Pisa, Italy—an IE member institution, rejoining in 2025 to continue its support for our mission.

AI as a Socio-Technical System: DETAILLS Living Lab for Sustainable Innovation

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DOI: 10.5281/zenodo.20798730

Context and Objectives

Artificial Intelligence (AI) is rapidly reshaping societies, economies, and everyday life. More than a technical tool, it functions as a **socio-technical system** intertwined with human behaviour, institutions, and culture [1]. Addressing AI therefore requires moving beyond technical solutions toward participatory, interdisciplinary, and reflective approaches.

This perspective calls for new ways of designing, studying, and communicating AI: approaches that actively involve diverse stakeholders and foster collective understanding. **Living Lab methodologies** offer a promising response. First introduced as experimental environments to study technology in everyday contexts and later defined by ENoLL (European Networks of Living Labs) as user-centred, open innovation ecosystems based on co-creation and real-life settings [2], Living Labs create spaces where users, researchers, and practitioners collaboratively explore, experiment, and co-design solutions, bridging the gap between innovation and societal needs.

Within this framework, the **Erasmus+ project DETAILLS** (DEsign Tools of Artificial Intelligence in Sustainability Living LabS) (https://www.detaills.eu/) brought together European universities and organisations to explore how AI-driven design methodologies can contribute to sustainability goals.

One of the most tangible results of the project has been the establishment of a **Living Lab in Pisa, Italy,** at one of the partner universities involved in the Erasmus+ project. Its objective is to communicate AI as a socio-technical system and to explore its impacts through participatory, interactive, and interdisciplinary practices.

From Research to Design: Identifying Living Lab Practices

The design of the Pisa Living Lab was **grounded in a structured research phase** aimed at identifying effective Living Lab practices. Two complementary research activities informed our approach: a **systematic literature** review and a **validation workshop** with experts. For more in-depth information about the research phase, please refer to the documents “Living Lab Practices Desk Research” and “Workshop protocol for validating good practices in training activities” available for download here: https://www.detaills.eu/results/.

Literature Review on Living Lab Practices

The literature review identified key Living Labs practices from 154 documents in Scopus and Web of Science. It highlighted the importance of **participatory and multi-stakeholder approaches** to support inclusive and context-sensitive innovation.

It also emphasised **co-creation, experimentation, and iterative processes**, alongside the value of **interdisciplinary collaboration** for addressing complex challenges such as AI.

Finally, the review emphasised experiential and **project-based learning**, effective **stakeholder**

engagement, and the integration of **sustainability** and **systems thinking**. These principles informed the design of activities that combine learning, experimentation, and reflection in real-world contexts.

Validation Workshops on Good Practices

The validation workshops, involving 16 international experts, reinforced the importance of **experimental learning techniques** and **collaborative learning strategies**, particularly through prototyping and interdisciplinary teamwork.

They also emphasised **aligning skill development with industry needs**, especially by integrating AI, sustainability, and engagement with external organisations.

Overall, these research activities provided a solid foundation for translating theoretical principles into concrete practices. The insights gained directly shaped the structure and methodologies of the Pisa Living Lab, ensuring that its activities were both evidence-based and contextually relevant.

From Principles to Practice: DETAILLS Living Lab

Building on these insights, the **DETAILLS Living Lab in Pisa**, Italy (https://share.google/7GxO9MYQaPO5XmI8Y) was designed as an open and collaborative environment where diverse stakeholders can engage with AI and its societal implications. The aim was not only to transfer knowledge but to create conditions for dialogue, experimentation, and co-creation.

The Living Lab brings together a wide community (researchers, students, companies, educators, artists, and citizens) reflecting the **multi-stakeholder approach** identified in the research phase. Activities have been organised into five main formats.

Talks provide structured moments of knowledge sharing, where experts address topics such as AI ethics, language and creativity, and the social impacts of technology. These events are open to both academic audiences and the wider public, supporting dissemination while encouraging dialogue.

Thematic roundtables create horizontal spaces for discussion on issues such as AI and discrimination, gender and technology, and sustainability. Using participatory methods, these sessions enable open exchanges between academia and society, supporting collective sense-making and imagination.

Artistic events, including film screenings and live performances with AI, offer alternative perspectives on AI. By engaging creative communities, they expand the conversation beyond technical and academic domains, revealing how AI shapes cultural imaginaries and practices, and showcasing how artists experiment with and reinterpret AI through unconventional and alternative uses.

Training workshops focus on developing practical skills related to AI, including generative AI, trust in automation, and sustainability. These sessions rely on hands-on, experiential learning methods such as group work, case studies, and peer learning, with activities adapted to the specific contexts and needs of participants, directly reflecting the principles identified in the research phase.

Co-design workshops represent the most direct application of Living Lab methodologies. In these sessions, participants from different backgrounds work together on a shared project. Using approaches such as Design Thinking, Design Fiction, and prototyping, they collaboratively develop solutions that leverage AI. The project-based approach proved particularly effective in aligning diverse participants around common goals.

Through these interconnected activities, the Living Lab translates research principles into practice. It becomes a space where knowledge is not only shared but co-created and continuously refined.

Photos of activities organised by DETAILLS Living Lab in Pisa, Italy.

Reflections and Transferable Takeaways

The experience of designing and implementing the DETAILLS Living Lab offers several insights that may be transferable to other contexts.

A first lesson concerns **interdisciplinarity**. Working with AI requires integrating perspectives from multiple domains, as its impacts extend far beyond technology. Our experience showed that interdisciplinarity enriches both understanding and design processes. For example, discussions involving artists and citizens revealed perspectives that would not emerge in purely technical settings, highlighting alternative ways of thinking about AI and its uses.

However, interdisciplinarity also carries risks, particularly the tendency for discussions to remain at a superficial level. Addressing this requires creating opportunities for **deeper engagement** and **specialised learning**, especially in technically AI domains such as natural language processing and text analysis. In our experience, complementing Living Lab activities with more structured formats helps bridge this gap by combining methodological depth with hands-on engagement, as exemplified by initiatives such as the annual summer school "*Text Analysis and Large Language Models for Innovation Management*" (https://www.unipi.it/didattica/corsi/summer-schools/text-analysis-large-language-models-for-innovation-management/).

A second insight relates to the value of **project-based approaches**. Co-design workshops demonstrated that working on shared, concrete problems helps align diverse participants and fosters collaboration. This approach proved particularly effective in bridging academia and industry, allowing participants to jointly explore how AI can address real-world challenges.

A further reflection concerns the relationship between understanding, imagination, and action. Given the complexity and rapid evolution of AI, participatory and interdisciplinary practices in Living Labs help develop a **shared understanding** of current challenges. This in turn enables **collective imagination**, the ability to envision shared, desirable futures grounded in diverse perspectives, which can ultimately **drive change**. As Sarah Housley argues, "*a coherent and collective vision of achievable futures can inspire people to bring about change. These visions act as motivators and engines of imagination*" [3].

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Contribution by Guillaume Gravier, Panellist of ECSS 2025 Leaders Workshop.

An Overview of Challenging Topics in AI for Trust and Security

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This short paper highlights the challenges in trustworthy AI for critical security domains, building on the scientific roadmap of the Cluster SequoIA, standing for "security, confidence, AI", an excellence centre in AI labelled by the French national strategy on AI. The overall goal of the Cluster SequoIA, federating higher education and research (HER) institutions under the leadership of the Université de Rennes, is to promote research, education and innovation on the general theme of AI for trust and security in and by digital systems. In particular, the scientific roadmap, combined with an innovation strategy based on a strong synergy between the HER institutions of the consortium and a large set of partners, mostly private sector companies and national agencies, significantly contributes to accelerating the diffusion of AI technology in priority domains such as cybersecurity[1].

The vision of the Cluster SequoIA lies in the definition of well-understood, mastered and accepted AI solutions that address the general challenge of trust and security by and in digital systems, with a particular focus on cybersecurity, defence and environmental security. This vision encompasses an interdisciplinary perspective, ranging from fundamental challenges in trustworthy AI science to applied AI in key domains –cybersecurity, environmental observation, intelligence – and human and social research on usage, acceptability, regulation, or social transformation. This vision translates into a number of scientific challenges schematically articulated around three pillars briefly detailed hereunder from an informatics science standpoint.

First, the *core AI* pillar addresses the foundations of trustworthy machine learning (ML), with challenges in secure, frugal, embedded, hybrid and explainable AI. From a theoretical standpoint, a better understanding of the empirical success of recent neural architectures in many domains, better formalizing the necessary conditions for a model to successfully learn and/or infer trustworthy knowledge on unseen data, e.g., by defining statistical bounds [1], is paramount. Similarly, progress is required in the design of learning procedures where data are rare or even absent in the long-tailed distributions [2] – e.g., as in novel cybersecurity attacks or extreme climate events – and in the construction of lifelong learning systems that adapt to changes in data distributions [3], including conceptual drifts, noise and outliers, and ill-specified learning sets. Formal assessment of machine learning also constitutes a raising fundamental challenge in trustworthy AI: This is a new frontier for formal methods and model checking, that drastically need adaptation of existing tools [4] to assess the robustness of general classifiers [5]. Finally, hybrid AI models, harnessing common-sense and interpretable knowledge representation with the power of data-driven machine learning

[1] A detailed version of the scientific roadmap and more information on the consortium, the partners and the actions supported can be found at https://cluster-sequoia.univ-rennes.fr/.

and multi-agent systems, are also instrumental to improve trustworthy AI systems and their adoption. Yet, opening the “black-box” of machine learning raise challenges to handle and quantify uncertainty, provide human control on the system design and operation. The recent raise of LLM-based multi-agent systems offer tremendous opportunities in this direction, yet raising concerns to address regarding their controllability.

The second pillar addresses *AI, cybersecurity and defence*, with noteworthy applications in the security of systems, infrastructures, and information. Many challenges appear in the security and audit of AI systems and, in a dual manner, in the field of cybersecurity. On the first aspect, vulnerabilities of ML models arise at both learning and inference stages [6], and current approaches are mostly based on oversimplified scenarios considering a static ML pipeline: The risk of attacks already existing in training and inference – adversarial evasion [7], data poisoning and data attacks [8] – is thus underestimated as the potential attack surface extends in real-world AI systems. We advocate for a paradigm shift to secure AI systems at scale, better characterising the roots of the vulnerabilities, shifting from model to system security, encompassing hardware issues and the full life-cycle of dynamical AI systems. In the field of cybersecurity, AI-based approaches to core cybersecurity tasks – e.g., detection of vulnerabilities and intrusions – remain a challenge due to the complex nature of the data and the specifics of the events to detect [9, 10], requiring specific models and realistic data that are still in infancy. A different approach lies in the optimal and dynamic deployment of AI-based security policies according to operational constraints or under attack, leveraging LLMs and their extension to agentic AI systems. These models are, however, also used to lower the cost of attacks, as evidenced by the recent controversy on Claude Mythos, challenging cybersecurity in a way that is yet to be fully apprehended. Lastly, information security is also being challenged by generative AI [11], calling for clear solutions, e.g., to track and characterise content and models, and facilitate fact-checking: watermarking content and models at scale, auditing LLMs for factual behaviour, or combining ML with knowledge-based reasoning are key research.

Finally, the third pillar focuses on *AI, environment and ocean*, focusing on the observation and modelling of the earth’s systems to address societal and scientific challenges on environmental security, climate change, and underwater defence. Many core ML challenges from the first pillar straightforwardly extend to the observation and modelling of complex systems such as the Earth or the ocean. Very large-scale, possibly chaotic, systems involving global physical equilibrium, however, require suitable AI frameworks to establish surrogate data-driven physical models [12]. Such systems remain highly sensitive to uncertainties in initial conditions and errors in training samples. They require better statistical robustness of predictions and the assessment of confidence intervals, e.g., leveraging conformal prediction [13] and bridging variational data assimilation, meta-learning and uncertainty quantification [14]. Also, integrating heterogeneous and noisy data acquired from diverse sensors [15] with multiple spatial and temporal resolutions remains a challenge for today’s ML paradigms, calling for new approaches and foundation models. Remote sensing also features challenges in the detection and identification of weak signals and abnormal behaviour, sharing common fundamental issues with cybersecurity that deviate from mere statistical modelling and require embedding knowledge – physical priors, ontologies – into AI models [16].

As highlighted, the three pillars are strongly intertwined, with core AI challenges that arise from and drive research in the application areas. They also need to rely on transversal research that spans all pillars. On the technology side, continuum computing is a key enabler, with specific hardware and embedded AI systems – that raise new security threats – to HPC frameworks for efficient and as frugal as possible data processing and machine learning. Continuous integration and test in AI system deployment, known as MLOps, is also a new challenge facing security, stability and backward compatibility issues. But the main transversal research topics are non-technical and relate to usage at large. We argue that, in critical domains such as cybersecurity or defence, AI technologies should be at the service of users, ultimately responsible for the decisions and actions they take. Users' perception and appropriation of AI-based technology must be addressed through real-life user studies encompassing most of these aspects. Involving ethical factors (bias, application autonomy) and legal aspects right from the design stage rises important challenges [17, 18]. It is also important to reinforce and adapt the legal framework driving usage, taking into account *lato sensu* users – individuals, professionals, companies, administrations and, broadly, any human organisation [19] – and the central question of AI responsibility [20].

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