Title: Towards Selective Metal-based Photosensitizers for Anticancer Photodynamic Therapy

Topic number : ***2024_001***

Field : Chemistry, Physical chemistry and Chemical Engineering - Life and Health Science and Technology

Subfield: Bioinorganic Chemistry; Inorganic Medicinal Chemistry; Metals in Medicine; Photodynamic Therapy

ParisTech School: Chimie ParisTech - PSL
Research team : Laboratory for Inorganic Chemical Biology
Research team website: www.gassergroup.com
Research lab: I-CLEHS - Institute of chemistry for life and health
Lab location: Paris
Lab website: www.gassergroup.com

Contact point for this topic: Gasser - Gilles - gilles.gasser@chimieparistech.psl.eu

Advisor 1: Gilles Gasser - gilles.gasser@chimieparistech.psl.eu
Advisor 2: Kevin Cariou - kevin.cariou@chimieparistech.psl.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Photodynamic Therapy (PDT) is an approved medical technique to treat certain types of cancer.[1-2] It relies on the use of photosensitizer (PS) that is activated by light, producing reactive oxidative species (ROS) that kills cancer cells. However, most PSs are not selective for cancer cells, leading to some undesired side-effects. Our group has reported over the years that metal-based PSs were extremely effective, even in mice.[3-4] In this project, we envision to target some cancer-cell overexpressed enzymes such as carbonic anhydrases (CAs) to increase the selectivity of our metal-based PSs, as recently reported by our group.[5] At this end of this project, we hope to have unveiled a compound that works not only on cancer cells but also on mice tumor models.

Required background of the student:
The applicant should have a sound knowledge (theoretical and practical) in both inorganic and organic synthetic chemistry and be proficient with analytical techniques such as NMR and MS. The applicant must be fluent in English since it is the language spoken in the Gasser group. Practical knowledge in biology would be an asset.

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. G. Vigueras and G. Gasser,* Nature Chem., 2023, 15, 896-898.

2. J. Karges, F. Heinemann, M. Jakubaszek, F. Maschietto, C. Subecz, M. Dotou, R. Vinck, O. Blacque, M. Tharaud, B. Goud, E. Viñuelas Zahínos, B. Spingler, I. Ciofini, and G. Gasser, J. Am. Chem. Soc., 2020, 142, 6578-6587.

3. J. Karges, F. Heinemann, M. Jakubaszek, F. Maschietto, C. Subecz, M. Dotou, R. Vinck, O. Blacque, M. Tharaud, B. Goud, E. Viñuelas Zahínos, B. Spingler, I. Ciofini, and G. Gasser, J. Am. Chem. Soc., 2020, 142, 6578-6587.

4. A. Mani, T. Feng, A. Gandioso, R. Vinck, A. Notaro, L. Gourdon, P. Burckel, B. Saubaméa, O. Blacque, K. Cariou, J.-E. Belgaied, H. Chao,* and G. Gasser, Angew. Chem. Int. Ed., 2023, 62, e202218347.

5. Y. Wang, P. Mesdom, K. Purkait, B. Saubaméa, P. Burckel, P. Arnoux, C. Frochot, K. Cariou, T. Rossel, G. Gasser, Chem. Sci. 2023, 14, 11749-11760.

TITLE: NEW CLASS OF ELECTROCHEMICAL APTASENSORS FOR EARLY DISEASE DIAGNOSIS

Topic number : ***2024_002***

Field : Design, Industrialization - Design, Industrialization - Life and Health Science and Technology

Subfield:

ParisTech School: Chimie ParisTech - PSL
Research team : SEISAD
Research team website: https://iclehs.fr/research/seisad/
Research lab: I-CLEHS - Institute of chemistry for life and health
Lab location: Paris
Lab website: www.iclehs.fr

Contact point for this topic: cyrine.slim@chimieparistech.psl.eu

Advisor 1: Cyrine SLIM - cyrine.slim@chimieparistech.psl.eu
Advisor 2: Sophie GRIVEAU - sophie.griveau@chimieparistech.psl.eu
Advisor 3: Yvette TRAN - yvette.tran@espci.fr
Advisor 4:

Short description of possible research topics for a PhD:
Early diagnosis of diseases such as cancer, along with the urgent need to detect extremely low levels of tumor biomarkers, is driving the development of new biosensors dedicated to molecular recognition and the detection of biomarkers at very low concentrations in biological fluids. The goal of this project is to design biosensors using a novel class of grafted polymers, specifically surface-attached hydrogel thin films on conductive transducers, as a biocompatible matrix for biomolecule immobilization. Among biomolecules, aptamers represent an attractive alternative to antibodies due to their high affinity and excellent specificity for a particular target or group of selected targets. Additionally, aptamers can be functionalized with specific chemical groups or tags, allowing for their immobilization and facilitating their detection or analysis. Covalent immobilization of aptamers onto surface-attached hydrogel thin films offers a biodegradable, protective matrix, ensuring that the aptamers

maintain their active and functional structure while enabling sensitive biomarker detection. For enhanced sensor performance, a high density of immobilized aptamers is employed, improving both sensitivity and stability. As part of the continuous effort toward miniaturization, this work will be adapted for microfluidic electrochemical biosensors designed for real sample analysis. These microfluidic systems, characterized by their miniature, portable, and cost-effective design, also offer high throughput and automation. The project will explore integrating electrochemical sensors into microfluidic formats, incorporating advanced materials to improve detection. Developing these systems would offer significant advantages over current technologies, particularly in terms of sensitivity, speed, and cost-effectiveness for early diagnosis.

Required background of the student:
Knowledge of electrochemistry and physical chemistry

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. G. S. Kassahun, S. Griveau, F. Bedioui, C. Slim, Input of Electroanalytical Methods for the Determination of Diclofenac: A Review of Recent Trends and Developments. ChemElectroChem, 2022, 9. DOI:10.1002/celc.202100734

2. Y. Y. Zhang, F. -X. Guillon, S. Griveau, F. Bedioui, M. Lazerges, C. Slim, Evolution of nucleic acids biosensors detection limit III, 2022, 414, 943-968.

3. G. S. Kassahun, S. Griveau, S. Juillard, J. Champavert, A. Ringuedé, B. Bresson, Y. Tran, F. Bedioui, C. Slim. Hydrogel Matrix Grafted Impedimetric Aptasensor for the Detection of Diclofenac. Langmuir, 2020, 36, 4, 827–836

4. R. Oliveira, C. Sella, C. Souprayen, E. Ait-Yahiatene, C. Slim, S. Griveau, L. Thouin, F. Bedioui, Development of a flow microsensor for selective detection of nitric oxide in the presence of hydrogen peroxide, Electrochimica acta, 2018, 286, 365-373

TITLE: FLOWS OF CONCENTRATED DISPERSIONS OF FIBERS.

Topic number* : *2024_003

Field : Chemistry, Physical chemistry and Chemical Engineering - Material science, Mechanics and Fluids

Subfield: Rheology

ParisTech School: ESPCI Paris - PSL
Research team : MIE
Research team website:
Research lab: CBI - Chimie, Biologie et Innovation
Lab location: Paris
Lab website: https://mie.spip.espci.fr/spip.php?rubrique2

Contact point for this topic: COLIN Annie

Advisor 1: Annie COLIN - annie.colin@espci.fr
Advisor 2:
Advisor 3:
Advisor 4:

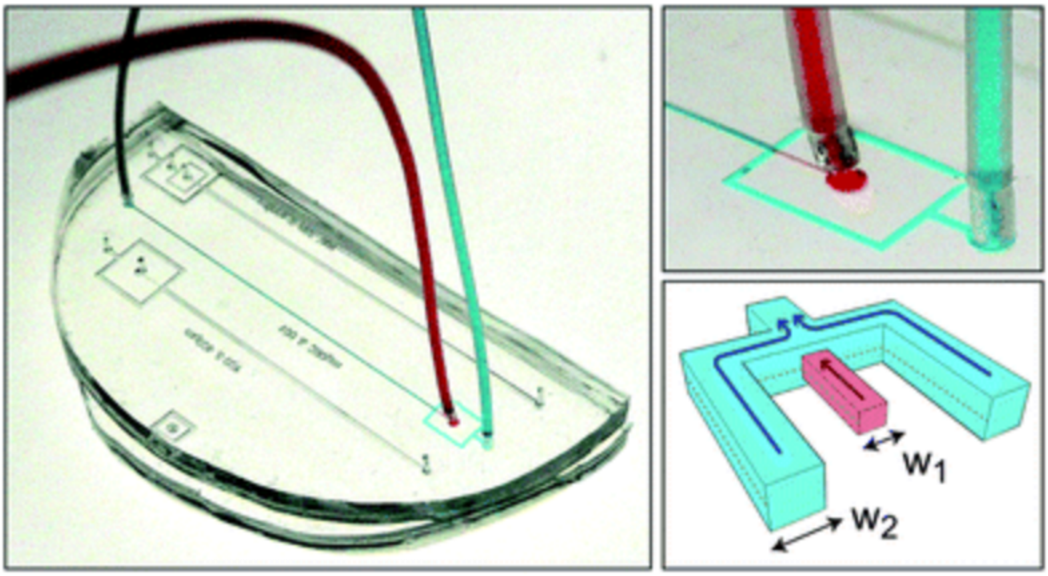
Short description of possible research topics for a PhD:
Suspensions are complex fluids composed of particles dispersed in a solvent. Paints, cement and industrial sludges are examples of suspensions we encounter every day. Controlling the flow properties of suspensions is a fundamental issue with many industrial applications. Studies on the rheology of spherical particle suspensions have been carried out in recent years (see ref 1-4) and have highlighted the importance of particle contacts. In this thesis, we focus on the rheology of concentrated fiber suspensions. PDMS or alginate fibers will be produced in large quantities using a microfluidic device. Their size and flexibility can be varied. They will then be dispersed in solvents where contacts between fibers will be non-existent due to repulsive forces, or very significant due to attractive forces. Preliminary experiments show that it is possible to form gels due to the entanglement of chains under shear. In this thesis, we propose to go a step further and study the rheology of these fiber dispersions in detail. In particular, the gelling behavior of

entangled chains will be studied as a function of the nature of the contacts and the length of the chains. The formation of gels will also be studied in the presence of oil or algae droplets. The question is whether these fiber dispersions can be used to flocculate oil droplets or algae. The gels produced may be systems of choice for revisiting questions concerning polymer mechanics (generation of model systems with entanglement, Mullins effect).

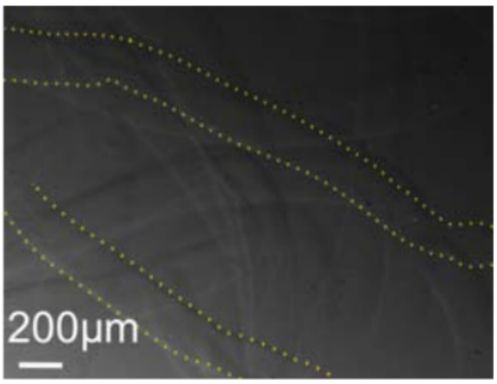
Required background of the student:
Complex fluids, rheology, material science.
A strong taste for experiments.

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Gauthier, A., Ovarlez, G. and Colin, A., 2023. Shear thickening in presence of adhesive contact forces: The singularity of cornstarch. Journal of Colloid and Interface Science, 650, pp.1105-1112.
2. Le, A. V. N., Izzet, A., Ovarlez, G., & Colin, A. (2023). Solvents govern rheology and jamming of polymeric bead suspensions. Journal of Colloid and Interface Science, 629, 438-450.
3. Ovarlez, G., Vu Nguyen Le, A., Smit, W. J., Fall, A., Mari, R., Chatté, G., & Colin, A. (2020). Density waves in shear-thickening suspensions. Science advances, 6(16), eaay5589.
4. Comtet, J., Chatté, G., Nigues, A., Bocquet, L., Siria, A., & Colin, A. (2017). Pairwise frictional profile between particles determines discontinuous shear thickening transition in non-colloidal suspensions. Nature communications, 8(1), 15633.
5. Bonhomme, O., Leng, J., & Colin, A. (2012). Microfluidic wet-spinning of alginate microfibers: A theoretical analysis of fiber formation. Soft Matter, 8(41), 10641-10649.



Schema of a microfluidic device allowing the preparation of fibers.



Observation of alginate fibers

TITLE: DEVELOPMENT OF ORGANOMETALLIC COMPOUNDS FOR ANTIBIOTIC APPLICATIONS

Topic number : ***2024_005***

Field : Chemistry, Physical chemistry and Chemical Engineering - Life and Health Science and Technology

Subfield: Bioorganometallic and Inorganic Chemistry, Chemical Biology and Medicinal Chemistry

ParisTech School: Chimie ParisTech - PSL
Research team : Inorganic Chemical Biology
Research team website: http://www.gassergroup.com/
Research lab: I-CLEHS - Institute of chemistry for life and health
Lab location: Paris
Lab website: http://www.gassergroup.com/

Contact point for this topic: kevin.cariou@chimieparistech.psl.eu

Advisor 1: Kevin Cariou - kevin.cariou@chimieparistech.psl.eu
Advisor 2: Gilles Gasser - gilles.gasser@chimieparistech.psl.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Antimicrobial resistance, whether for bacteria or for fungi, is a highly worrying topic that has been declared critical by the World Health Organization. Part of the solution is to explore new chemical space[1] to develop new drugs that can overcome the resistance. Our group is at the forefront of the development of organometallic anti-infectious compounds with a particular focus on antiparasitic and antifungal drugs. [2-5] In this project, we envision the development of organometallic antibiotic drugs, following the same successful approach. At this end of this project, we hope to have unveiled a compound that works on high priority resistant bacteria and mitigate the risk of new resistances emerging.

Required background of the student:

The applicant should have a sound knowledge (theoretical and practical) in both organic and organometallic synthetic chemistry and be proficient with analytical techniques such as NMR and MS. The applicant must be fluent in English since it is the language spoken in the Gasser group. Practical knowledge in biology would be an asset.

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. C. Mahe, O. Blacque, G. Gasser, V. Gandon and K. Cariou,* Org. Lett., 2023, 25, 4624–4629

2. Y. Lin, G. Scalese, C.A. Bulman, R. Vinck, O. Blacque, M. Paulino, A. Ballesteros-Casallas, L. Pérez Díaz, G. Salinas, M. Mitreva,* T. Weil,* K. Cariou,* J.A. Sakanari,* D. Gambino,* and G. Gasser,* ACS Infect. Dis., 2024, 10, 938-950.

3. Y. Lin, H. Jung, C.A. Bulman, J. Ng, R. Vinck, C. O'Beirne, S. Zhong, M.S. Moser, N. Tricoche, R. Peguero, R. Li, J.F. Urban Jr, P. Le Pape, F. Pagniez, M. Moretto, T. Weil,* S. Lustigman,* K. Cariou,* M. Mitreva,* J.A. Sakanari* and G. Gasser,* J. Med. Chem., 2023, 6, 15867-15882.

4. H.D. Betts, Y.C. Ong, N. Anghel, S. Keller, J. Karges, N. Voutsara, J. Müller, E. Manoury, O. Blacque, K. Cariou, A. Hemphill,* G. Gasser,* Organometallics, 2022, 41, 2035-2041.

5. R. Rubbiani,* T. Weil,* N. Tocci, L. Mastrobuoni, S. Jeger, M. Moretto, J. Ng, Y. Lin J. Hess, S. Ferrari, A. Kaech, L. Young, J. Spencer, A. L. Moore, K. Cariou,* R. Giorgia, L. Romani, M. Pariano and G. Gasser,* RSC Chem. Biol., 2021, 2, 1263-1273

TITLE: ENHANCED PASSIVITY AND CORROSION RESISTANCE OF MULTI-PRINCIPAL ELEMENT ALLOYS

Topic number* : *2024_006

Field : Chemistry, Physical chemistry and Chemical Engineering

Subfield:

ParisTech School: Chimie ParisTech - PSL
Research team : PCS
Research team website:
Research lab: IRCP - Institut de Recherche de Chimie de Paris
Lab location: Paris
Lab website: ircp.cnrs.fr

Contact point for this topic: Mercier Dimitri
dimitri.mercier@chimieparistech.psl.eu

Advisor 1: Dimitri Mercier - dimitri.mercier@chimieparistech.psl.eu
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Multi principal element alloys (MPEA), also called high entropy alloys (HEA), is a new class of metallic alloys (first elaborated in 2004) having a great interest as engineering alloys. Their mechanical properties have been widely studied and currently a detailed approach of the design of these alloys (microstructure, composition) allows elaborating specific alloys with excellent mechanical properties, that may outperform those of conventional alloys. In contrast to the mechanical properties, the surface reactivity of these materials, and particularly their corrosion resistance, has only been slightly studied. Different studies have shown that the original “Cantor” alloy does not provide good corrosion resistance, due to its high (equimolar) Mn content. Combining what we know of the origin of the corrosion resistance of Ni and Fe-based stainless alloys, and applying a thermodynamic approach for the composition optimization, our research group was able to design and synthesize two new single-

phase HEA/MPEA alloys containing molybdenum, which show excellent corrosion resistance. The purpose of this research program is to understand the detailed relationship between alloy composition, surface reactivity and corrosion behavior (passivity, passivity breakdown, localized corrosion resistance) of MPEA/HEA alloys with high Cr and Mo contents, and explore a range of compositions including single fcc phase and/or structured secondary phases improving the mechanical properties of theses alloys. The surface oxides (native and passive films), which are key factors for the corrosion resistance, will be characterized for the different alloy compositions by advanced surface analysis techniques, including X-ray Photoelectron Spectroscopy (XPS) and Time-of-Flight Secondary Ion Spectrometry (ToF-SIMS), combined with electrochemical measurements. A focus will be placed on the stability and the growth mechanisms of these layers using an original approach developed by our research group, using in situ isotopic labelling (18O2).

Required background of the student:
Corrosion Science, Surface Science, Materials Science, Electrochemistry

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Study of the surface oxides and corrosion behaviour of an equiatomic CoCrFeMnNi high entropy alloy by XPS and ToF-SIMS
L. Wang et al., Corrosion Science, 167 (2020)

2. Origin of enhanced passivity of Cr-Fe-Co-Ni-Mo multi-principal element alloy surfaces
X. Wang et al, npj Materials degradation, 7, 2023

3. Hydroxyl transport mechanisms upon passivation of Cr-Fe-Co-Ni-Mo multi-principal element alloy surfaces investigated by isotopic labelling
X. Wang et al., Applied Surface Science, 655, 2024

TITLE: MECHANICS AND RHEOLOGY OF STACKS OF GRANULAR CHAINS: NUMERICAL STUDY OF A MODEL ATHERMAL POLYMER SYSTEM

Topic number : ***2024_007***

Field : Material science, Mechanics and Fluids - Physics, Optics

Subfield: Discrete simulations, granular media, mechanics, statistical physics

ParisTech School: ESPCI Paris - PSL
Research team : MecaPhys
Research team website: https://blog.espci.fr/spatinet/
Research lab: PMMH - Physique et mécanique des Milieux Hétérogènes
Lab location: Paris
Lab website: https://www.pmmh.espci.fr/-Home-

Contact point for this topic: Sylvain Patinet <sylvain.patinet@espci.fr>

Advisor 1: Sylvain Patinet - sylvain.patinet@espci.fr
Advisor 2: Philippe Claudin - philippe.claudin@espci.fr
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
This thesis aims to numerically study the mechanical properties of an athermal analogue of polymers: a stack of granular chains. By taking advantage of the analogy, polymer/granular chain, we study the effect of the length of the chains and their concentration in this original system, allowing a direct comparison with the experiment. The first part of this thesis will be dedicated to determining the static mechanical properties of stacks, particularly the study of the jamming transition. The second objective of this thesis topic will focus on understanding the dynamic properties of granular chains. For this, two types of protocols will be investigated: the vibration of the stack and its shear for different deformation rates to study the variation of the effective viscosity of the system. The simulations will be carried out using a particle dynamics code we have just developed and validated. They will be compared with model experiments carried out by our collaborators.

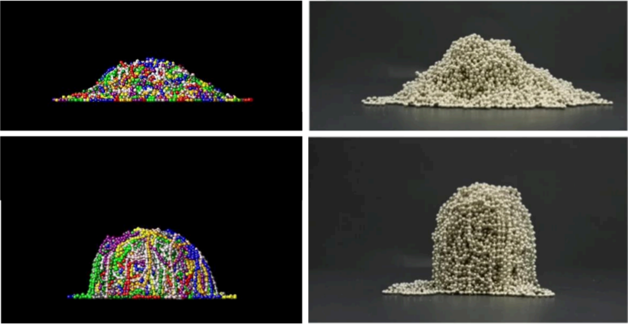
Required background of the student:
Master of Science — excellent level in science and general culture. A good level of English is required. The essential skills sought for this doctorate are: human qualities, communication, creativity, autonomy and adaptation, pedagogical qualities and a strong motivation for research. A good level of programming, data analysis, physics and mechanics of materials is particularly appreciated.

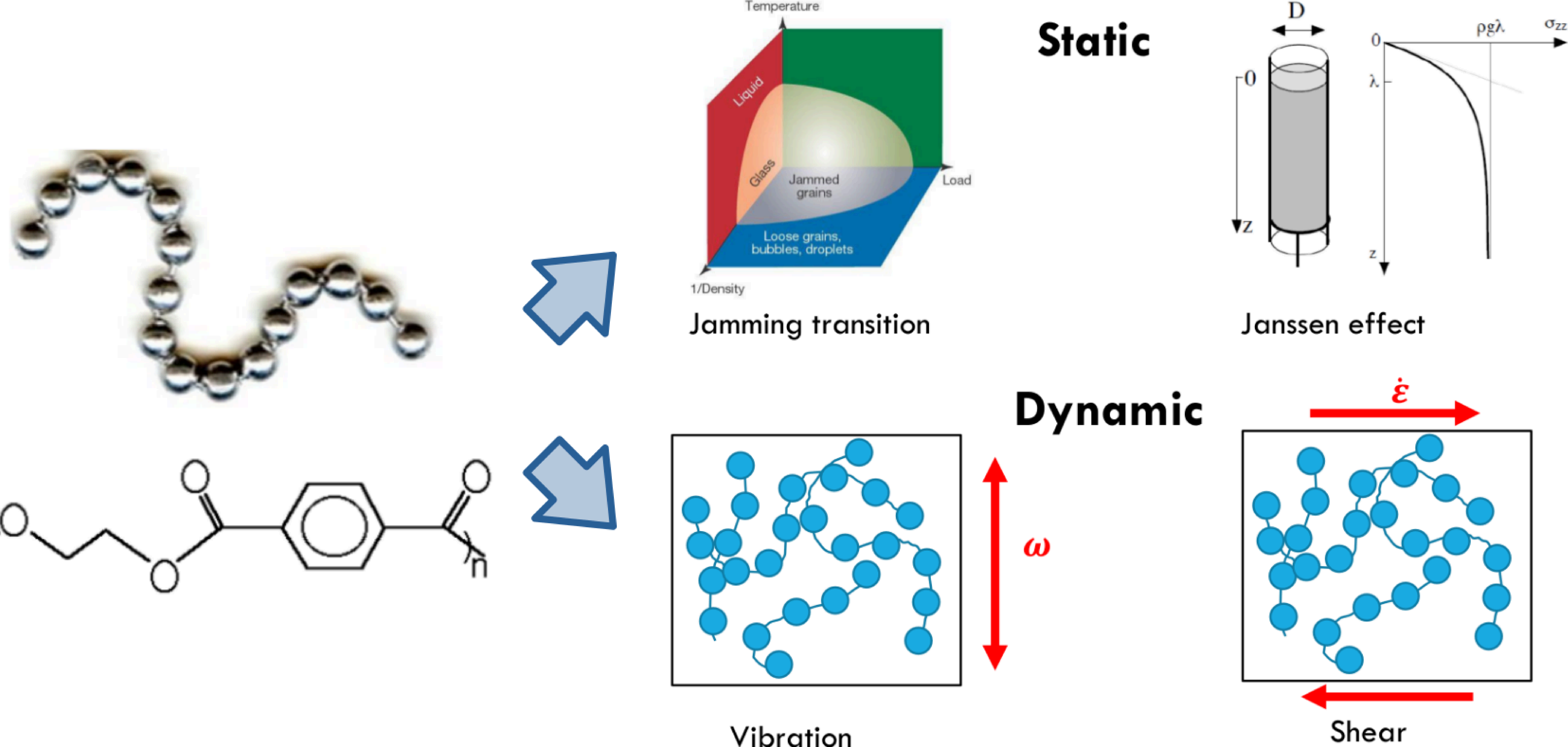
A list of (5 max.) representative publications of the group: (Related to the research topic)

1. D. Dumont, M. Houze, P. Rambach, T. Salez, S. Patinet and P. Damman, Phys. Rev. Lett. 120, 088001 (2018) [COVER, NEWS & VIEWS, PHYSICS, PRL EDITORS’ SUGGESTION]

2. Mehdi Bouzid, Martin Trulsson, Philippe Claudin, Eric Clément, and Bruno Andreotti, Phys. Rev. Lett. Nonlocal Rheology of Granular Flows across Yield Conditions 111, 238301 (2013)

3. D. Richard, M. Ozawa, S. Patinet, E. Stanifer, B. Shang, S. A. Ridout, B. Xu, G. Zhang, P. K. Morse, J.-L. Barrat, L. Berthier, M. L. Falk, P. Guan, A. J. Liu, K. Martens, S. Sastry, D. Vandembroucq, E. Lerner, M. L. Manning, Predicting plasticity in disordered solids from structural indicators, Phys. Rev. Mater. 4, 113609 (2020)




Static
Temperature
Liquid
Glass
Jammed grains
Load
Loose grains, bubbles, droplets
1/Density
Jamming transition
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Janssen effect
Dynamic
ω
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Vibration
Shear
n

The PMMH laboratory

- Web site: https://www.pmmh.espci.fr/
- 5th district of Paris

TITLE: TOWARD REALISTIC AND SYSTEMATIC ATOMISTIC MODELLING OF AMORPHOUS SOLIDS

Topic number : ***2024_008***

Field : Material science, Mechanics and Fluids - Physics, Optics

Subfield: Amorphous solids, dynamics, atomistic simulations, mechanics, statistical physics

ParisTech School: ESPCI Paris - PSL
Research team : MecaPhys
Research team website: https://blog.espci.fr/spatinet/
Research lab: PMMH - Physique et mécanique des Milieux Hétérogènes
Lab location: Paris
Lab website: https://www.pmmh.espci.fr/-Home-

Contact point for this topic: Sylvain Patinet <sylvain.patinet@espci.fr>

Advisor 1: Sylvain Patinet - sylvain.patinet@espci.fr
Advisor 2: Damien Vandembroucq - damien.vandembroucq@espci.fr
Advisor 3: David Richard - david.richard@espci.fr
Advisor 4:

Short description of possible research topics for a PhD:
Amorphous solids correspond to a broad class of materials disordered at the particle scale. Their properties differ significantly from crystalline solids, making it challenging to understand their physical properties. This PhD thesis aims to develop a methodological tool for studying the mechanical properties of amorphous materials via atomistic simulations. The first task is to build a database covering an extensive range of force fields for two-dimensional and three-dimensional systems. The project will also use machine-learning potentials to study amorphous models of polymers, amorphous silicon and metallic glass. The challenge is to obtain systems whose fictive temperatures spread over a range large enough to observe the brittle-ductile transition. The project will use a Swap Monte Carlo method to equilibrate liquids in the low-temperature regime efficiently. The synthesized systems will be characterized by various methods, such as geometric analysis of local atomic environments and

physical properties computed on the fly. The results will be shared via the GitHub platform with a CC-by 4.0 license for data reuse, integrity, and reproducibility of the project results. This project can accelerate discoveries and promote collaboration in the study of amorphous solids.

Required background of the student:
Master of Science — excellent level in science and general culture. A good level of English is required. The essential skills sought for this doctorate are: human qualities, communication, creativity, autonomy and adaptation, pedagogical qualities and a strong motivation for research. A good level of programming, data analysis, physics and mechanics of materials is particularly appreciated.

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. D. Richard, M. Ozawa, S. Patinet, E. Stanifer, B. Shang, S. A. Ridout, B. Xu, G. Zhang, P. K. Morse, J.-L. Barrat, L. Berthier, M. L. Falk, P. Guan, A. J. Liu, K. Martens, S. Sastry, D. Vandembroucq, E. Lerner, and M. L. Manning, Predicting plasticity in disordered solids from structural indicators, Phys. Rev. Mater. 4, 113609 (2020)

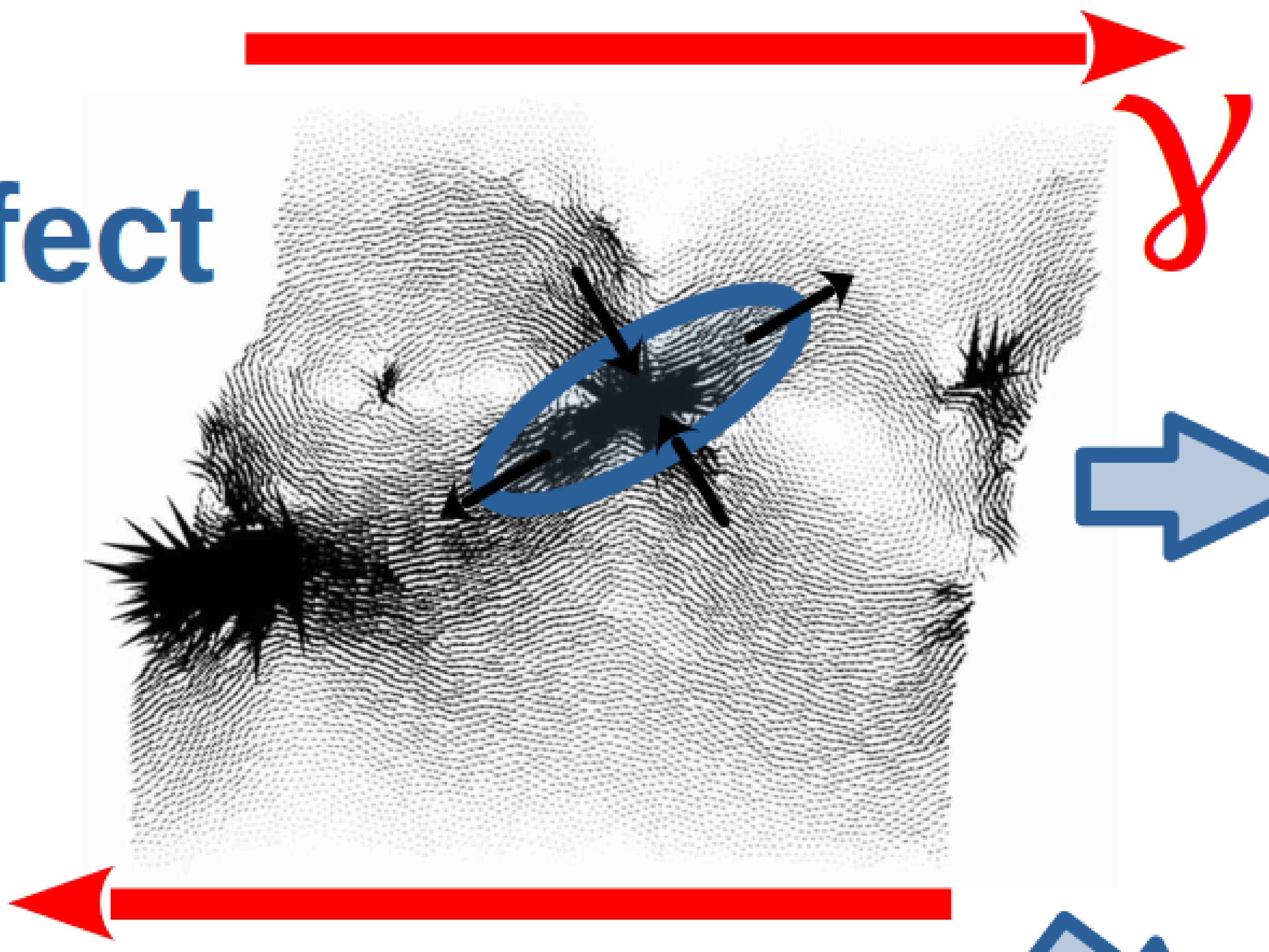
2. S. Patinet, D. Vandembroucq and M. L. Falk, Connecting Local Yield Stresses with Plastic Activity in Amorphous Solids, Phys. Rev. Lett. 117, 045501 (2016)

3. David Richard, Karina González-López, Geert Kapteijns, Robert Pater, Talya Vaknin, Eran Bouchbinder, and Edan Lerner, Universality of the Nonphononic Vibrational Spectrum across Different Classes of Computer Glasses, Phys. Rev. Lett. 125, 085502 (2020)

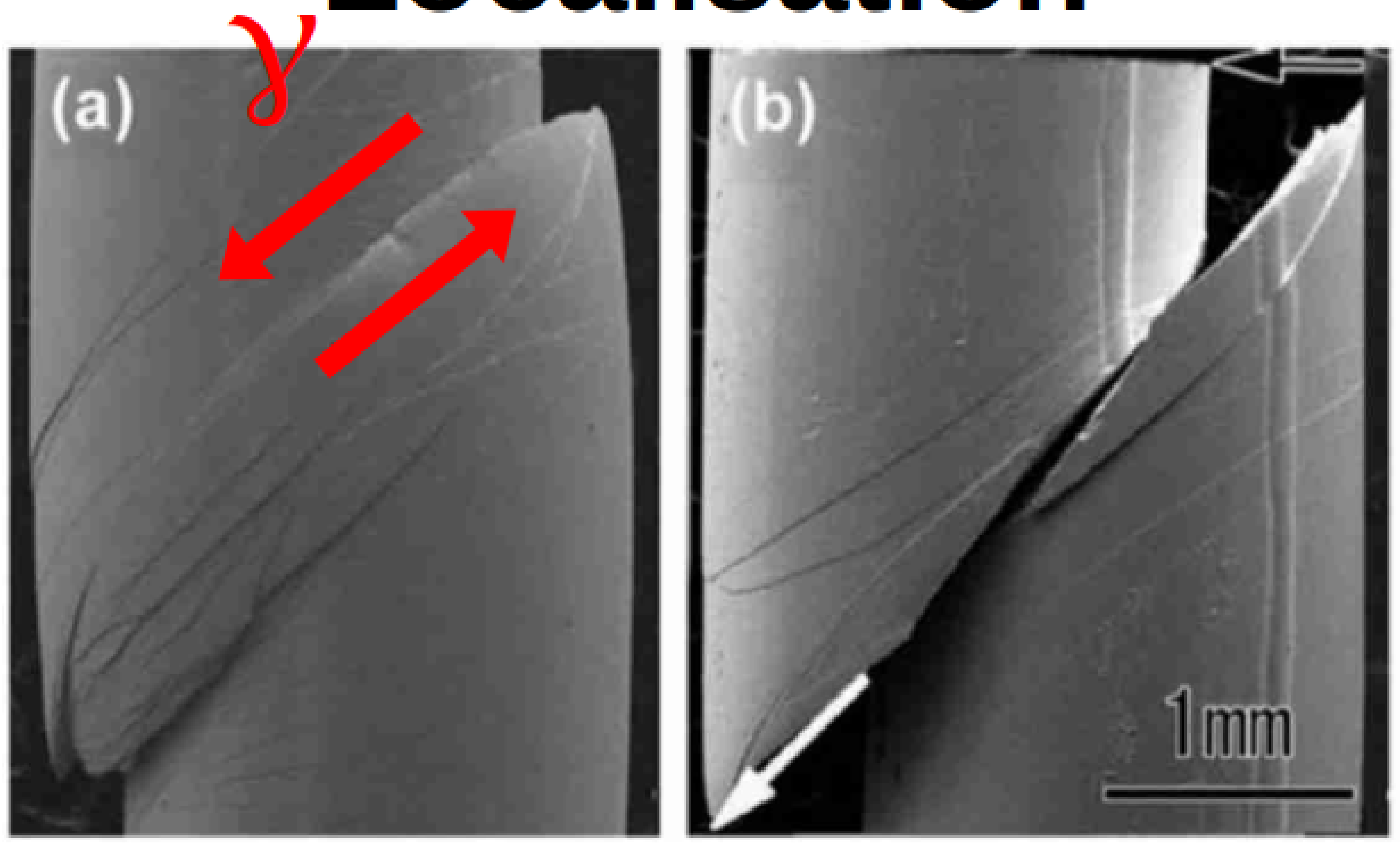
4. D. Fernández Castellanos, S. Roux and S. Patinet, History dependent plasticity of glass: a mapping between atomistic and elasto-plastic models, Acta Mater. 241, 118405 (2022)

Universal mechanical responses

Flow defect

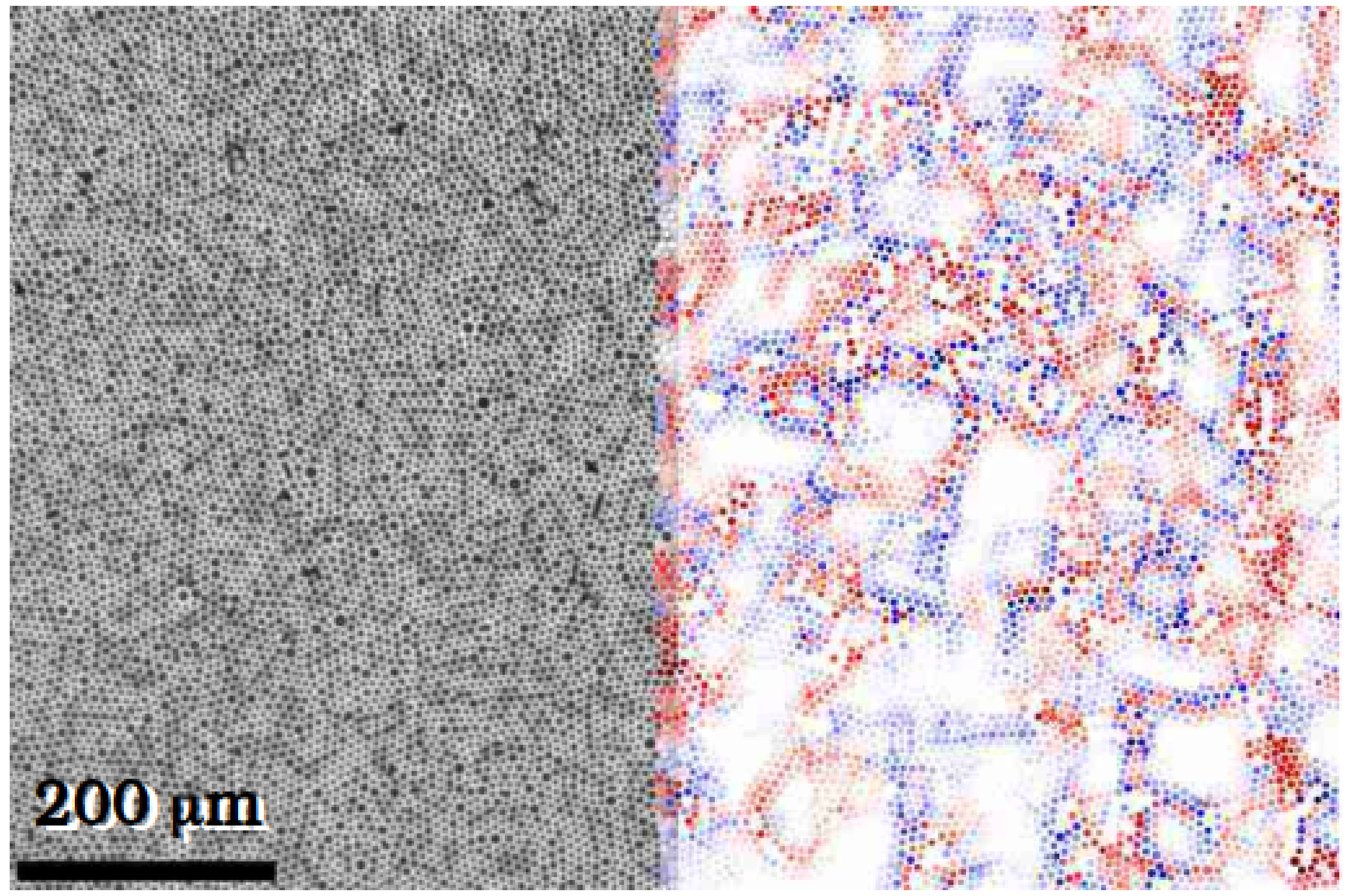


Localisation



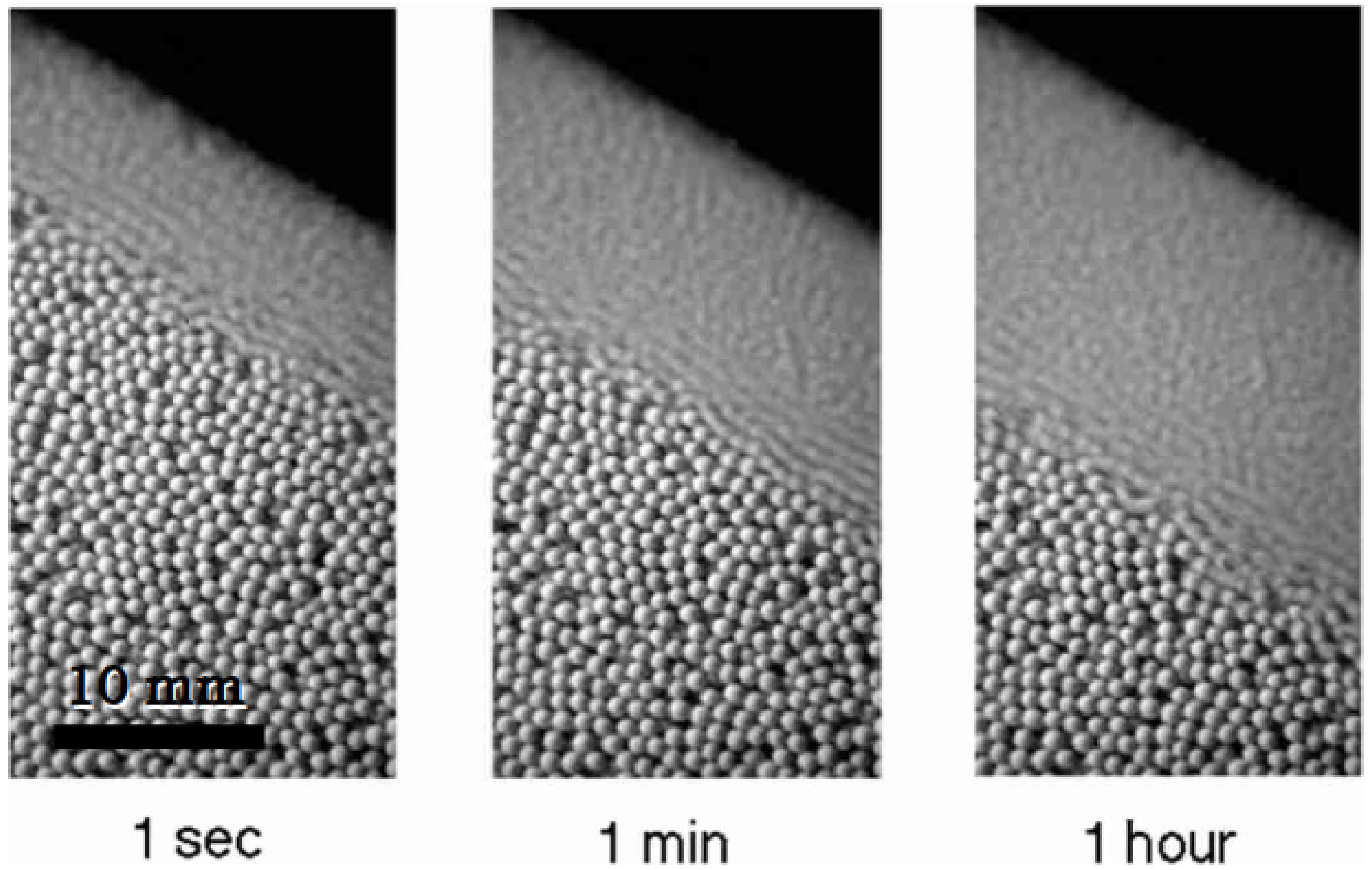
(metallic glass)

Stress fluctuation

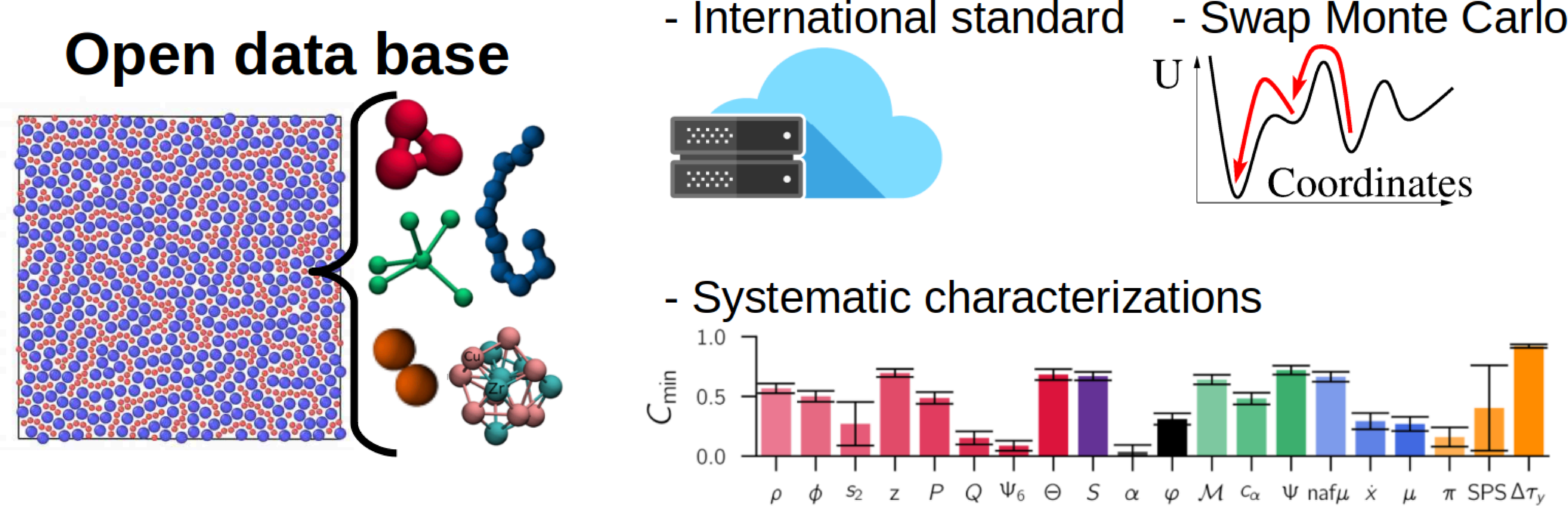


(colloid)

Flow



(granular pile)


Open data base
Cu
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- International standard
- Swap Monte Carlo
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- Systematic characterizations
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ρ ϕ s_2 z P Q Ψ_6 Θ S α φ $\mathcal{M}$ c_α Ψ nafμ $\dot{x}$ μ π SPS $\Delta\tau_y$

The PMMH laboratory

- Web site: https://www.pmmh.espci.fr/
- 5th district of Paris

Title: Multi-scale modelling of plasticity and damage in amorphous solids: from atomistic calculations to continuum mechanics

Topic number : *2024_009*

Field : Material science, Mechanics and Fluids - Physics, Optics - Mathematics and their applications

Subfield: Amorphous solids, atomistics, FTT, multi-scale, plasticity and damage

ParisTech School: ESPCI Paris - PSL
Research team : MecaPhys
Research team website: https://blog.espci.fr/spatinet/
Research lab: PMMH - Physique et mécanique des Milieux Hétérogènes
Lab location: Paris
Lab website: https://www.pmmh.espci.fr/-Home-

Contact point for this topic: Sylvain Patinet <sylvain.patinet@espci.fr>

Advisor 1: Sylvain Patinet - sylvain.patinet@espci.fr
Advisor 2: François Willot - francois.willot@minesparis.psl.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
The deformation of amorphous materials at the continuous scale (>mm) is primarily based on a phenomenological description of the mesoscopic scale (~mm). This multidisciplinary project, at the interface between physics and mechanics, aims to better ground these approaches by achieving a rigorous passage between the atomic and mesoscopic scales.

Required background of the student:
Master of Science — excellent level in science and general culture. A good level of English is required. The essential skills sought for this doctorate are: human qualities, communication, creativity, autonomy and adaptation, pedagogical qualities and a strong motivation for research. A

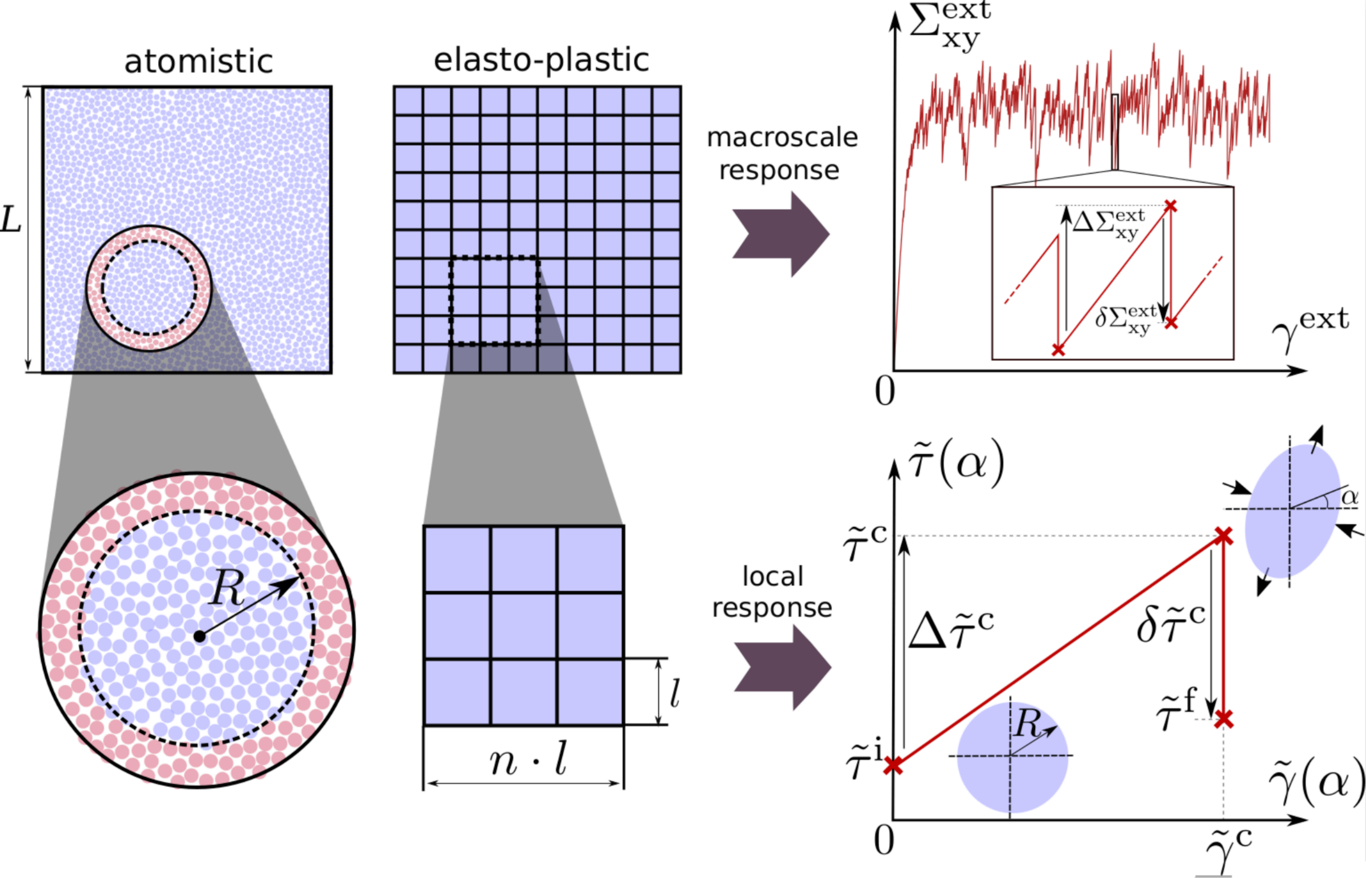
good level of programming, data analysis, physics and mechanics of materials is particularly appreciated.

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. S. Patinet, D. Vandembroucq and M. L. Falk, Connecting Local Yield Stresses with Plastic Activity in Amorphous Solids, Phys. Rev. Lett. 117, 045501 (2016).

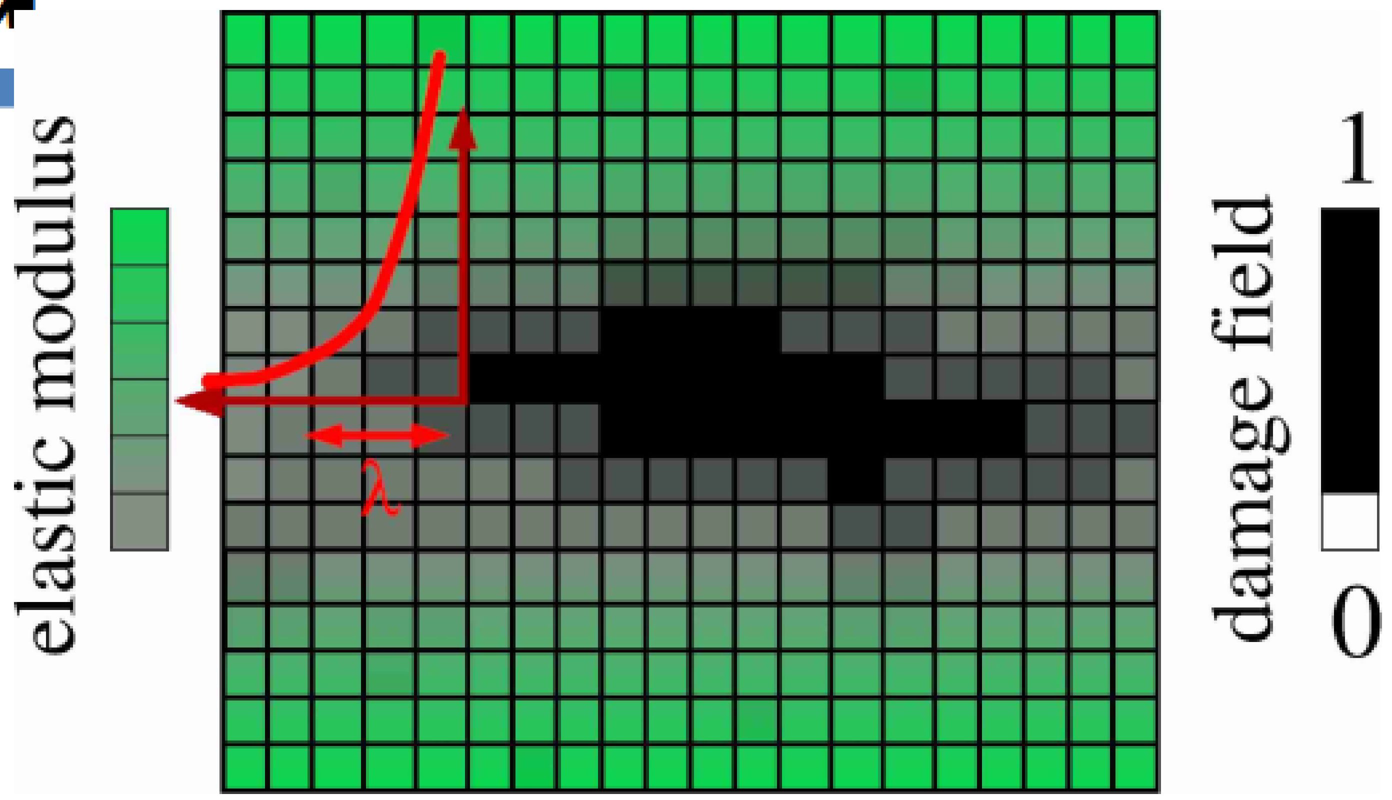
2. F. Willot, Fourier-based schemes for computing the mechanical response of composites with accurate local fields, C. R. Meca. 343 (3), 232-245 (2015).

3. D. Fernández Castellanos, S. Roux and S. Patinet, History dependent plasticity of glass: a mapping between atomistic and elasto-plastic models, Acta Mater. 241, 118405 (2022)

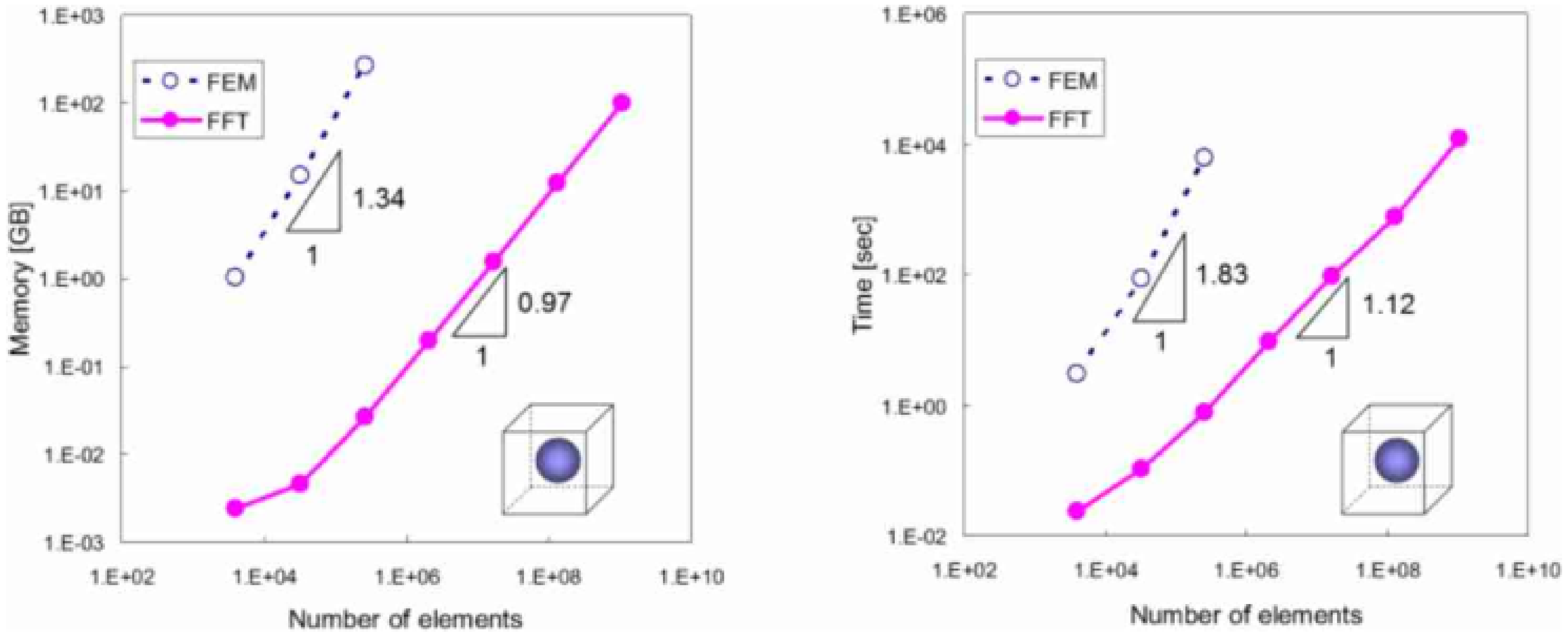


atomistic
elasto-plastic
L
R
$n \cdot l$
l
macroscale response
local response
$\Sigma_{\mathrm{xy}}^{\mathrm{ext}}$
$\Delta\Sigma_{\mathrm{xy}}^{\mathrm{ext}}$
$\delta\Sigma_{\mathrm{xy}}^{\mathrm{ext}}$
γ^{ext}
0
$\tilde{\tau}(\alpha)$
$\tilde{\tau}^{\mathrm{c}}$
$\Delta\tilde{\tau}^{\mathrm{c}}$
$\delta\tilde{\tau}^{\mathrm{c}}$
$\tilde{\tau}^{\mathrm{f}}$
$\tilde{\tau}^{\mathrm{i}}$
α
$\tilde{\gamma}(\alpha)$
$\tilde{\gamma}^{\mathrm{c}}$

Physical upscaling: FFT-based method

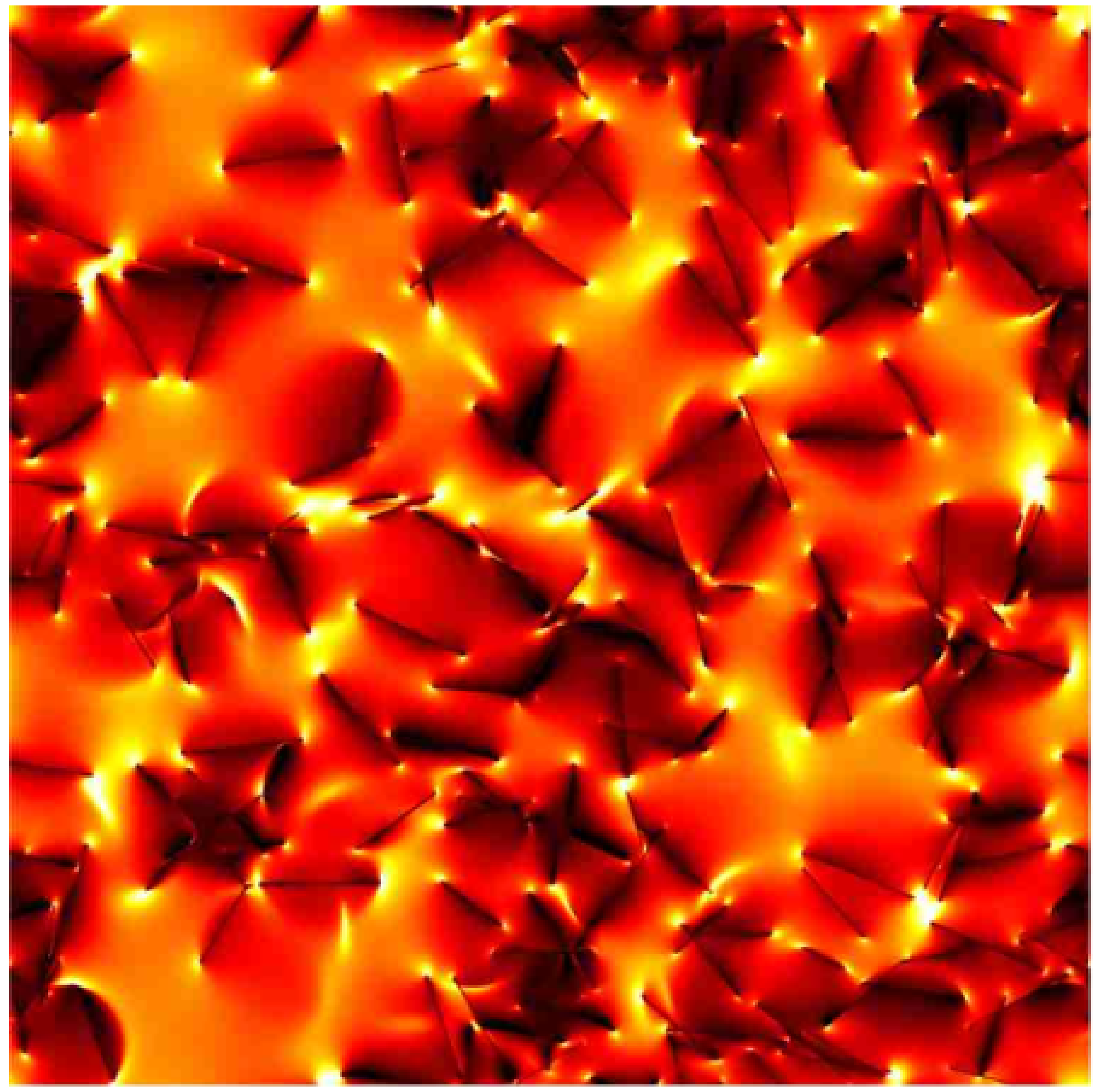


Performance



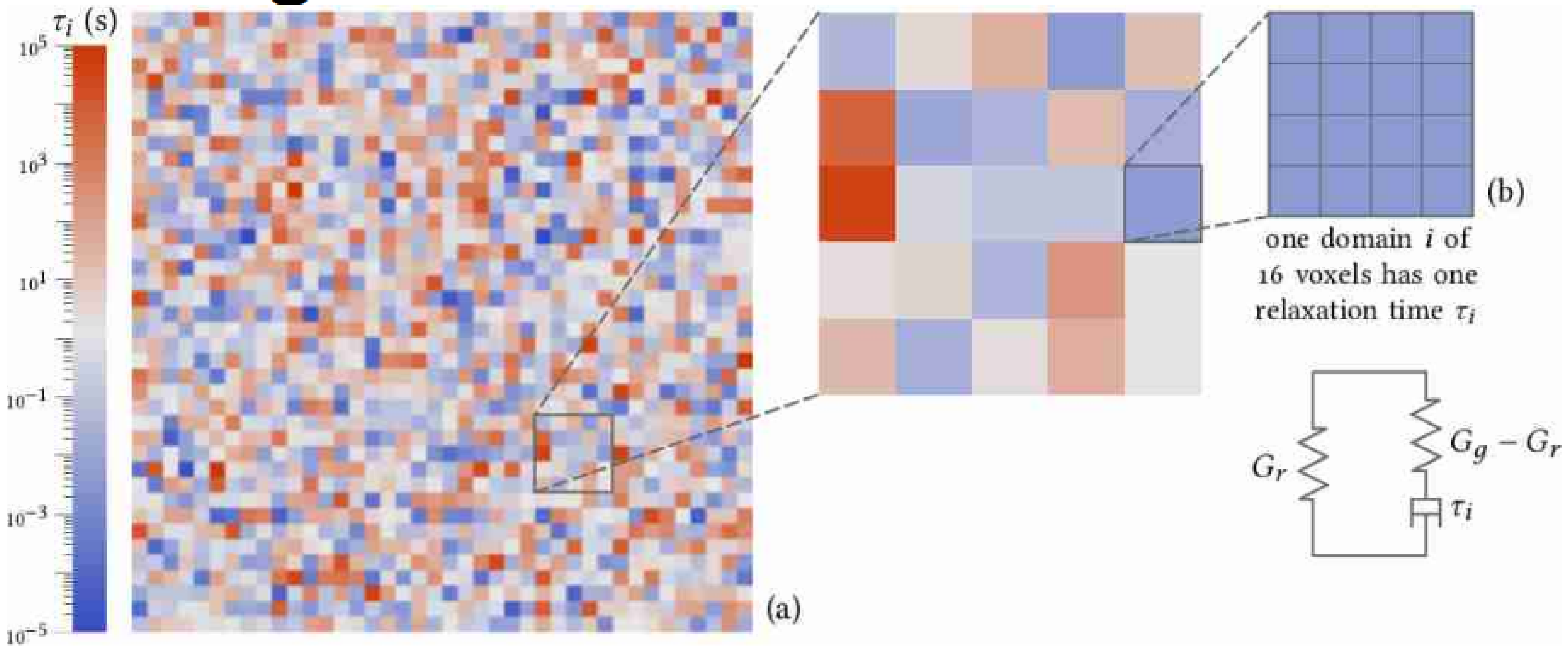
M. Koishi et al. 10th European Conference on Constitutive Models for Rubbers (ECCMR) (2017)

Elastic singularities



J. B. Gasnier et al., *International Journal of Solids and Structures*, ***155***, 248 (2018)

Heterogeneous solids



André et al., Journal of Theoretical, Computational and Applied Mechanics (2021)

The PMMH laboratory

- Web site: https://www.pmmh.espci.fr/
- 5th district of Paris

TITLE: EVALUATING, EXPANDING, AND APPLYING EXCITED STATES DYNAMICS WITH TIME-DEPENDENT DENSITY FUNCTIONAL THEORY

Topic number : ***2024_010***

Field : Chemistry, Physical chemistry and Chemical Engineering

Subfield:

ParisTech School: Chimie ParisTech - PSL
Research team : Chemical Theory and Modelling
Research team website: www.quanthic.fr
Research lab: I-CLEHS - Institute of chemistry for life and health
Lab location: Paris
Lab website: https://iclehs.fr/

Contact point for this topic: Davide - Avagliano - davide.avagliano@chimieparistech.psl.eu

Advisor 1: Davide Avagliano - davide.avagliano@chimieparistech.psl.eu
Advisor 2: Carlo Adamo - carlo.adamo@chimieparistech.psl.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Light is the initiator of numerous and crucial natural and artificial processes like photosynthesis, energy conversion, or both essential and detrimental biological reactions. Simulating the dynamics happening on the excited states after light irradiation is a powerful computational technique, which allows to obtain unique insights in terms of electronic and geometrical evolution of the chromophore not easily accessible by other means. However, the high computational demand of these simulations imposes finding a balance between accuracy and cost, if the dynamics of chromophores of biological interest want to be studied. Time-Dependent Density Functional Theory (TD-DFT) has been successfully used to simulate excited states dynamics of medium and big-size chromophores. However, very little theoretical and methodological development of TD-DFT has been focused to first understanding and then improving the performances of this theory in excited states dynamics. In

this project, a first comprehensive study of the effect of the approximations of TD-DFT in excited states dynamics will be carried out. This will allow to determine the parameters needed to optimize the methods in terms of accuracy and computational cost. After that, the project will focus on applications. The dynamics of the bacteriophytochromes will be investigated, an important family of chromophores of natural origin with great potential in the applications in optogenetics and fluorescent probes. Solvent and environmental effects will be considered by evolving the nuclei on mixed quantum-mechanics/molecular-mechanics (QM/MM) potentials, as employed in state-of-the-art computational protocols and software.

Required background of the student:
Knowledge of Physical and Theoretical Chemistry

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. D. Avagliano, M. Bonfanti, A. Nenov, M. Garavelli, “Automatized protocol and interface to simulate QM/MM time-resolved transient absorption at TD-DFT level with COBRAMM”, J. Comput. Chem. 2022, 43(24), 1641

2. D. Avagliano, M. Bonfanti, M. Garavelli. L. González, “QM/MM nonadiabatic dynamics: The SHARC/COBRAMM approach”, J. Chem. Theory Comput. 2021, 17, 8, 4639–4647

3. D. Avagliano, E. Lorini, L. González,”Sampling effects in quantum mechanical/molecular mechanics trajectory surface hopping non-adiabatic dynamics” Phil. Trans. R. Soc. A.38020200381, 2022

4. C. Adamo, D. Jacquemin, “The calculations of excited-state properties with Time-Dependent Density Functional Theory”, Chem. Soc. Rev., 2013,42, 845-856

5. D. Jacquemin, B. Mennucci, C. Adamo, “Excited-state calculations with TD-DFT: from benchmarks to simulations in complex environments”, Phys. Chem. Chem. Phys., 2011,13, 16987-16998

TITLE: VIRTUAL ARCHEOLOGICAL ARTEFACTS ASSEMBLY THROUGH GEOMETRICAL FEATURES

Topic number : ***2024_011***

Field : Information and Communication Science and Technology - Mathematics and their applications

Subfield: Computer graphics, Virtual Reality, Geometric modeling

ParisTech School: Arts et Métiers
Research team : Virtual reality teams
Research team website: https://institutchalon.ensam.eu/
Research lab: LISPEN
Lab location: Chalon-sur-Saône
Lab website: https://lispen.artsetmetiers.fr/

Contact point for this topic: LOU Ruding ruding@ensam.eu

Advisor 1: Ruding LOU - ruding.lou@ensam.eu
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Archaeology is a fascinating field that involves the study of human history and prehistory through the excavation and analysis of material remains such as artifacts. Archaeology today often employs an interdisciplinary approach, for more comprehensive and precise analysis of archaeological finds. It covers Geographic Information Systems, databases and ontologies, geometries, points clouds or images processing, big data and machine learning. High-resolution 3D scanning and photogrammetry techniques have become standard tools in archaeology to create detailed 3D models of excavation sites, artifacts, and architectural structures. The analyze of geometrical features in 3D models of archaeological assemblies can provide valuable insights into the construction techniques, design, and organization of ancient structures or artifacts [1-3]. An international contest, “Forma Urbis Romae” project is still active, pushing the scientists to the limits, to be able to reassemble a complete

map of Ancient Rome, based on digitized fragments [4]. Another usage of these 3D models are Virtual Reality (VR) and Augmented Reality (AR). There can be a powerful tool for the reconstruction and presentation of cultural heritage. It allows people to explore and experience historical sites, artifacts, and cultural contexts, in an immersive and interactive manner. Archaeologists can also use VR/AR to overview and analyze archaeological sites before physical excavation. This helps in planning excavations, understanding site layouts, and identifying potential research areas [5-6]. In this PhD thesis an innovative digital tool based on VR/AR will be designed and prototyped to allow archeologists exploring the different geometrical features of 3D artefacts and assembling them in order to reconstruct historical heritage; The research questions are: what is the best computer – human interface for the archeologists in virtual artefacts assembly tasks, and how to let them to perceive and interact with the geometrical features.

Required background of the student:

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Le Tien, M., Tan, K. N., & Raffin, R. Matching correspondence between images and 3D model in a reconstruction process. Journal of Science and Technology, 2(1), 64-69. 2016.

2. Le Tien, M., Tan, K. N., & Raffin, R. Analysis of geometrical features of 3D model based on the surface curvature of a set of point cloud. In ICFNDS 2021.

3. Qi-Xing Huang, Simon Flöry, Natasha Gelfand, Michael Hofer, and Helmut Pottmann. 2006. Reassembling fractured objects by geometric matching. ACM Trans. Graph. 25, 3 (July 2006), 569–578.

4. Emmanuel Durand, Frederic Merienne, Christian Pere, and Patrick Callet. Ray-on, an On-Site Photometric Augmented Reality Device. J. Comput. Cult. Herit. 7, 2, Article 7, 2014.

5. LANDRIEU J., Père C., Rollier J., Castandet S. and SCHOTTÉ G. Digital Rebirth of the Greatest Church of Cluny maior Ecclesia: From Optronic Surveys to Real Time Use of the Digital Model. ISPRS, 2012.

TITLE: DESIGN OF A NEW COUNTER-ROTATING AXIAL TURBINE TO BE COUPLED WITH A PUMP AS TURBINE

Topic number : ***2024_012***

Field : Energy, Processes

Subfield: fluid machinery, fluid mechanics, optimization

ParisTech School: Arts et Métiers
Research team :
Research team website:
Research lab: LIFSE - Laboratoire Ingénierie des Fluides Systèmes Energétiques
Lab location: Paris
Lab website: https://lifse.artsetmetiers.fr/

Contact point for this topic: Capurso Tommaso
tommaso.capurso@ensam.eu

Advisor 1: Tommaso Capurso - tommaso.capurso@ensam.eu
Advisor 2: Florent Ravelet - florent.ravelet@ensam.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Hydraulic energy demonstrates to be one of the trustworthy solution to fight climate change. In the past, pumps as turbines (PaT) have been used in industry as a cheap solution to convert hydraulic energy in mechanical and electrical energy. Recently, they have found place in pumped storage systems and in water distribution networks to recover energy from pressurized flows in place of pressure reducing valves. However, since these machines are design as pumps, when they are used as turbines, their BEP is shifted towards higher values of flow rate. This means that at the exit of the runner, there is a flow characterized by a tangential component (swirling flow). Namely, there is still energy that can be recovered. The idea is to design an axial turbomachinery, which rotates on the opposite direction of the first impeller with the aim to recover energy still present in the fluid guaranteeing an absolute tangential

velocity of the flow equal to zero. Numerical simulations will be performed to study the 3D flows exiting from the runner. This input will be used to design the axial turbine blades. The shape of the joined turbine draft tube will be designed to maximize the matching between the 2 turbines. The resulting configuration will allow to maximize the exploitation of hydraulic energy. Finally, the new turbomachinery will be tested to assess its performance.

Required background of the student:
Fluid dynamics, Turbomachinery, Computational fluid dynamics

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Capurso, T., Bergamini, L., Torresi, M. (2019). Design and CFD performance analysis of a novel impeller for double suction centrifugal pumps. Journal of Nuclear Engineering and Design. Vol. 341 Pages 155-166 Elsevier. https://doi.org/ 10.1016/j.nucengdes.2018.11.002.
2. Capurso, T., Stefanizzi, M., Pascazio, G., Ranaldo, S., Camporeale, S.M., Fortunato, B., Torresi, M. (2019). CFD analysis of the slip factor at the outlet of centripetal turbomachineries. Water. 11(3), 565. MDPI. https://doi.org/10.3390/w11030565
3. Martin Bourhis, Michaël Pereira, Florent Ravelet, Ivan Dobrev. Experimental Thermal and Fluid Science, 2022, 130, pp.110504. ⟨10.1016/j.expthermflusci.2021.110504⟩
4. Florent Ravelet, F. Bakir, C. Sarraf, J. Wang. Experimental Thermal and Fluid Science, 2018, 96, pp.101. 10.1016/j.expthermflusci.2018.03.004

TITLE: DESIGN OF PASSIVE CAVITATION INDUCTION SYSTEM TO CONTROL THE TEMPERATURE OF CRYOGENIC FLUIDS

Topic number : ***2024_013***

Field : Energy, Processes - Material science, Mechanics and Fluids

Subfield:

ParisTech School: Arts et Métiers
Research team :
Research team website:
Research lab: LIFSE - Laboratoire Ingénierie des Fluides Systèmes Energétiques
Lab location: Paris
Lab website: https://lifse.artsetmetiers.fr

Contact point for this topic: Capurso Tommaso
tommaso.capurso@ensam.eu

Advisor 1: Tommaso Capurso - tommaso.capurso@ensam.eu
Advisor 2: Michael Deligant - michael.deligant@ensam.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
In order to contrast climate crisis, hydrogen has been indicated as a solution for energy storage by converting electrical energy, produced by Renewable Energy Sources, to chemical energy, know as power-to-gas. Since hydrogen is characterized by low density, many solutions are under development, e.g., compressed H2, cryogenic H2 and adsorption. Among them, cryogenic H2 will be preferred in the long distance transportation, especially by shipping. This is possible by reducing its temperature at 20 K at ambient pressure. Hence, it is important to control the temperature of the piping system to avoid hydrogen boil-off, which will undermine the proper functionality of the apparatus. For this reason, in this project a new passive system to induce localized cavitation will be developed. Differently from other liquids, as water, cryogenic fluids are thermal sensible to phase-change. In particular, under flashing operating

condition, such as cavitation, energy for phase-change is picked up from surrounding liquid. This process leads to a localized temperature reduction, which can be used to control hydrogen temperature in delivering systems. Furthermore, the introduction of a passive system will reduce global cost of the system. On the other hand, it is demonstrated the hazardous presence of cavitation in fluids. Thus, it is paramount to optimize this component to trigger cavitation without inducing vibration and hazardous working conditions. The aim is to find a good compromise between life-length and costs of cryogenic components.

Required background of the student:
Computational fluid dynamics, thermodynamics

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Capurso, T., Lorusso, M., Camporeale, S.M., Fortunato, B., Torresi, M. (2018) Implementation of a passive control system for limiting cavitation around hydrofoils. IOP Conf. Ser.: Earth Environ. Sci. 240 032025. https://doi.org/10.1088/1755-1315/240/3/032025

2. Koffi Samuel Koulekpa, Michael Deligant, Hélène Elias-Birembaux, Frédéric Rossi, Gérard Poulachon (2023). Analysis of CO2 Jet’s Temperature by BOS Method for Applications in Cryogenic Machining. Proceedings of the Machining Innovations Conference for Aerospace Industry (MIC), http://dx.doi.org/10.2139/ssrn.4657853

3. Bergamini, L., Torresi, M., Capurso, T. (07-05-2018). IT201600111763 (A1) - HIGH EFFICIENCY DOUBLE SUCTION IMPELLER. https://patents.google.com/patent/US20210190073A1/en

4. Capurso, T., Bergamini, L., Torresi, M. (2019). Design and CFD performance analysis of a novel impeller for double suction centrifugal pumps. Journal of Nuclear Engineering and Design. Vol. 341 Pages 155-166 Elsevier. https://doi.org/ 10.1016/j.nucengdes.2018.11.002.

TITLE: FROM THE GLOBAL TO THE LOCAL HEAT TRANSFER COEFFICIENT FOR SINGLE AND TWO-PHASE FILM FLOWS

Topic number : ***2024_014***

Field : Energy, Processes - Mathematics and their applications

Subfield: Computational fluid dynamics, thermodynamics

ParisTech School: Arts et Métiers
Research team :
Research team website:
Research lab: LIFSE - Laboratoire Ingénierie des Fluides Systèmes Energétiques
Lab location: Paris
Lab website: https://lifse.artsetmetiers.fr

Contact point for this topic: Capurso Tommaso
tommaso.capurso@ensam.eu

Advisor 1: Tommaso Capurso - tommaso.capurso@ensam.eu
Advisor 2: Michael Deligant - michael.deligant@ensam.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Energy transition pushed the employment of systems based on electro-chemical processes. However, their life is linked to the management of both heat production and dissipation. For this reason, many systems have been developed to reduce and control the temperature of electric, electronic and electrochemical components during their operation. To name few, immersion cooling system, cold plated systems and spray applications. Even though, in order to quantify the mass flow rate of each system it is important to know the heat transfer coefficient of the specific application. The latter is characterized by many factors as fluid chemical-physical properties, regime and configuration. Moreover, the cooling system can be designed to work with two-phase flows. For this reason, it is always tough to define in advance the correct value of “h”, the so called heat transfer coefficient. In this project, fluid dynamics simulations will

be run to investigate the development of the thermal boundary layer of different types of refrigerants flowing around hot surfaces under different regimes (laminar and turbulent). Finally, experiments will be carried out on a test bench to validate numerical simulations. The results fo this work will be valuable to advance in the conceptualization of more efficient and reliable cooling systems.

Required background of the student:
Computational fluid dynamics, thermodynamics

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Capurso, T., Laera, D., Riber, E., Cuenot, B., (2023). NOx pathways in lean partially premixed swirling H2-air turbulent flame. Combustion and Flame https://doi.org/10.1016/j.combustflame.2022.112581

2. Beaux, J.-H., Girardeau, J., Khelladi, S., Deligant, M., Perilhon, C. Numerical Investigations of Flows and Heat Transfer in Turbine Disk Cavities Journal of Engineering for Gas Turbines and Power, 2024, 146(10), 101016

3. Specklin, M., Deligant, M., Sapin, P., Moises Solis, Marc Wagner, Markides, C.N., Bakir, F. Numerical study of a liquid-piston compressor system for hydrogen applications. Applied Thermal Engineering, 2022, 216, 118946

4. Chen, L., Deligant, M., Specklin, M., Khelladi, S. Validation and Application of HEM for Non-ideal Compressible Fluid Dynamic. ERCOFTAC Series, 2023, 29, pp. 156–165

ParisTech

TITLE: NEW METHOD TO PREDICT THE VIBRATION CHARACTERISTICS OF NANOPARTICLES IN BIOLOGICAL TISSUE USING A HIGHER-ORDER NONLOCAL ELASTICITY AND STRAIN GRADIENT THEORIES : AN EMERGING AVENUE IN BIOMECHANICS.

Topic number : ***2024_015***

Field : Material science, Mechanics and Fluids - Mathematics and their applications - Life and Health Science and Technology

Subfield: Fluid-structure interaction, Viscoelastic properties of biological materials, Mathematical modeling of nanoparticles vibration in biological tissues.

ParisTech School: Arts et Métiers
Research team : DIPPE - Structures et Ecoulements Complexes
Research team website: https://lampa.ensam.eu/equipe-dippe-134463.kjsp?RH=1415871394252&RF=1478611690252
Research lab: LAMPA - Laboratoire angevin de mécanique, procédés et innovation
Lab location: Angers
Lab website: https://lampa.ensam.eu/accueil-lampa-100748.kjsp

Contact point for this topic: EL BAROUDI Adil
adil.elbaroudi@ensam.eu

Advisor 1: Amine AMMAR - amine.ammar@ensam.eu
Advisor 2: Adil EL BAROUDI - adil.elbaroudi@ensam.eu
Advisor 3: Jean Yves LE POMMELLEC - jeanyves.lepommellec@ensam.eu
Advisor 4:

Short description of possible research topics for a PhD:
Interest in nanomaterials has continued to grow over the past twenty years. The work carried out to date has made it possible to understand and use these new materials which have physical and chemical properties completely different from those known until now thanks to their small size. This work gave birth to nanotechnology, a vast disciplinary field which deals with the synthesis, characterization and exploitation of

nanostructured materials. Nanomedicine, still at the development stage, is part of nanotechnology. In particular, gold nanoparticles are used in many applications such as catalysis, biology and medicine. In oncology, these nanoparticles are the subject of growing interest. Three applications are currently being developed: aid in diagnosis and radiotherapy, transport of therapeutic molecules (vectorization) and photothermal therapy. The interest in nanoparticles in oncology is linked to the fact that nanoparticles injected through the bloodstream concentrate on tumors. In addition, these particles are chemically inert and therefore biocompatible. The network of blood vessels around the tumors promotes this concentration. Moreover, these nanoparticles are also used as nanovectors for the delivery of therapeutic molecules. Otherwise, the fixation of gold particles on tumors has given rise to another very promising application, the photothermal therapy. Finally, another solution is to vibrate the nanoparticles using a magnetic field. This vibration activates the cell death mechanisms of cancer cells without affecting healthy tissues. This perspective makes it necessary to study resonance frequencies and quality factor.

Required background of the student:
Mechanics and Mathematics

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. X. Huang, A. El Baroudi, J. Y. Le Pommellec and A. Ammar (2024). On the importance of modified continuum mechanics to predict the vibration of an embedded nanosphere in fluid, Zeitschrift für angewandte Mathematik und Physik.

2. X. Huang, A. El Baroudi and B. Wu (2023). Vibration properties of an elastic gold nanosphere submerged in viscoelastic fluid, Modern Physics Letters B.

3. S. Ducottet and A. El Baroudi (2023). Small-scale effects on the radial vibration of an elastic nanosphere based on nonlocal strain gradient theory, Nanotechnology.

4. Y. Wu, M. R. K. Ali, K. Chen, N. Fang and M. A. El-Sayed (2018). Gold nanoparticles in biological optical imaging, Nano Today.

5. A. Ahmed, M. Pelton and J. R. Guest (2017). Understanding How Acoustic Vibrations Modulate the Optical Response of Plasmonic Metal Nanoparticles, ACS Nano.

ParisTech

TITLE: DESIGN AND CONTROL OF AN HYDROGEN INJECTOR WITH THE AID OF REINFORCEMENT MACHINE LEARNING

Topic number* : *2024_016

Field : Energy, Processes - Material science, Mechanics and Fluids

Subfield: Fluid mechanics, Computational fluid dynamics, thermodynamics, Machine Learning

ParisTech School: Arts et Métiers
Research team :
Research team website:
Research lab: LIFSE - Laboratoire Ingénierie des Fluides Systèmes Energétiques
Lab location: Paris
Lab website: https://lifse.artsetmetiers.fr

Contact point for this topic: Capurso Tommaso
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Advisor 1: Tommaso Capurso - tommaso.capurso@ensam.eu
Advisor 2: Sofiane Khelladi - sofiane.khelladi@ensam.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
In the energy transition from fossil fuels to renewable energies sources, hydrogen plays the role of main actor. With the objective to decarbonize the transport sector, hydrogen needs to be used more and more. For instance, hydrogen can be used in many fields, such as gas turbines (power generation and aviation), Internal combustion engines, fuel cells, etc. In the field od combustion, one of the main concern is its mixing with oxidants in order to guarantee a good level of homogeneity and stratification. Nonetheless, there are a lot of issues due to its high flammability, high adiabatic flame temperature and diffusivity. In this work, a new hydrogen injector will be developed with the purpose to create an homogeneous mixture avoiding hot spots and thus reducing the risk of high emission level (NOx). The injector will be designed by

introducing adjustable components able. Machine learning will be used to develop a control strategy to avoid injection and flame frequencies matching with natural frequencies of the environmental. The results will be useful to extend the operating range of the combustion system. Nonetheless, it will be useful to limit the emission due to hydrogen combustion.

Required background of the student:
Fluid mechanics, Computational fluid dynamics, thermodynamics, Machine Learning

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Anaclerio, G., Capurso, T., Torresi, M., (2023) Gas-dynamic and mixing analysis of under-expanded hydrogen jets: effect of the cross section shape. Journal of Fluid Mechanics

2. Capurso, T., Laera, D., Riber, E., Cuenot, B., (2023). NOx pathways in lean partially premixed swirling H2-air turbulent flame. Combustion and Flame https://doi.org/10.1016/j.combustflame.2022.112581

3. Ceglie, V., Stefanizzi, M., Capurso, T., Fornarelli, F., Camporeale, S.M., (2023). Thermoacoustic Combustion Stability Analysis of a Bluff Body-Stabilized Burner Fueled by Methane–Air and Hydrogen–Air Mixtures. Energies. https://doi.org/10.3390/en16073272s

4. Dimola N., Stefanizzi M., Capurso T., Shuller T., Torresi M., Camporeale S.M. (2022). Cost-Effective Cfd Analysis of the Acoustic Response of a Perforated Plate. ASME Turbo Expo 2020: Turbomachinery Technical Conference and Exposition, GT 2022.

5. Capurso, T., Stefanizzi, M., Torresi, M., Camporeale, S.M. (2022). Perspective of the role of hydrogen in the 21st century energy transition. Energy Conversion and Management. https://doi.org/10.1016/j.enconman.2021.114898

ParisTech

CHINA SCHOLARSHIP COUNCIL

TITLE: ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY IN HIGH PRECISION MANUFACTURING BASED ON ADAPTIVE TOLERANCE OPTIMIZATION

Topic number : ***2024_017***

Field : Design, Industrialization - Environment Science and Technology, Sustainable Development, Geosciences

Subfield: Sustainabilty in smart manufacturing

ParisTech School: Arts et Métiers
Research team :
Research team website:
Research lab: LCFC - Laboratoire de conception, fabrication, commande
Lab location: Metz
Lab website: http://lcfc.ensam.eu/

Contact point for this topic: HOMRI - Lazhar - lazhar.homri@ensam.eu

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Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Sustainable and smart manufacturing has become a strategic focus as industries have begun exploring new ways to use resources efficiently, improve product quality, and reduce energy consumption. Integrating environmental considerations into every stage of product development in manufacturing industries plays a crucial role in reducing energy and resource consumption and improving quality. The efficiency of the resulting products is ultimately influenced by the conditions in which they are designed, manufactured, and assembled. The convergence of advanced technologies and new data analytics provide real-time feedback for smart manufacturing process control and adaptive product development for parts tolerance allocation as key element, ultimately leading to improved manufacturing efficiency and reduced scrap rates by integrating principles of reusing and remanufacturing. A tradeoff

between cost, quality, energy consumption and material, aims to better meet the requirements. With the introduction of precision manufacturing technology, traditional tolerance optimization models that only consider cost and quality can no longer meet the requirements. The issue of optimizing energy consumption in the manufacturing process should be more considered. Therefore, the tradeoffs between manufacturing cost, quality loss, and energy consumption during processing are considered as objective functions. A multi-objective optimization model for tolerance allocation is defined based on cost, quality, and energy consumption, that aims to serve as a surrogate model.

Required background of the student:
Mechanical Engineering, Sustainability, Mathematics, Computer science

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Khezri, A., Homri, L., Etienne, A., & Dantan, J. Y. (2023). Hybrid cost-tolerance allocation and production strategy selection for complex mechanisms: simulation and surrogate built-in optimization models. Journal of Computing and Information Science in Engineering, 23(5), 051003.

2. Hoffenson, S., Dagman, A., & Söderberg, R. (2015). Visual quality and sustainability considerations in tolerance optimization: A market-based approach. International Journal of Production Economics, 168, 167-180

3. Dantan, J.-Y. and Eifler, T., 2021, Tolerance allocation under behavioural simulation uncertainty of a multiphysical system. CIRP Annals, 70, 127-130.

4. Wang, Y., Huang, A., Quigley, C. A., Li, L., & Sutherland, J. W. (2021). Tolerance allocation: Balancing quality, cost, and waste through production rate optimization. Journal of Cleaner Production, 285, 124837.

5. Natarajan, J., Sivasankaran, R., & Kanagaraj, G. (2018). Bi-objective optimization for tolerance allocation in an interchangeable assembly under diverse manufacturing environment. The International Journal of Advanced Manufacturing Technology, 95, 1571-1595.

Research Topic for the ParisTech/CSC PhD Program

Field: Design, Industrialization

Subfield: Mechanical Eng., Industrial Eng., Process Eng.

Title: Environmental and Economic Sustainability in High Precision Manufacturing based on Adaptive Tolerance Optimization

ParisTech School: Arts et Métiers Sciences et Technologies

Advisor(s) Name: Lazhar HOMRI, Jean-Yves DANTAN
Advisor(s) Email: *lazhar.homri@ensam.eu*
Research group/Lab: *LCFC*
Lab location: *Arts et Métiers Institute of Technology, Campus of Metz*
(Lab/Advisor website): *http://lcfc.ensam.eu/*

Short description of possible research topics for a PhD:

Sustainable and smart manufacturing has become a strategic focus as industries have begun exploring new ways to use resources efficiently, improve product quality, and reduce energy consumption. Integrating environmental considerations into every stage of product development in manufacturing industries plays a crucial role in reducing energy and resource consumption and improving quality. The efficiency of the resulting products is ultimately influenced by the conditions in which they are designed, manufactured, and assembled.

The convergence of advanced technologies and new data analytics provide real-time feedback for smart manufacturing process control and adaptive product development for parts tolerance allocation as key element, ultimately leading to improved manufacturing efficiency and reduced scrap rates by integrating principles of reusing and remanufacturing. A tradeoff between cost, quality, energy consumption and material, aims to better meet the requirements.

With the introduction of precision manufacturing technology, traditional tolerance optimization models that only consider cost and quality can no longer meet the requirements. The issue of optimizing energy consumption in the manufacturing process should be more considered. Therefore, the tradeoffs between manufacturing cost, quality loss, and energy consumption during processing are considered as objective functions. A multi-objective optimization model for tolerance allocation is defined based on cost, quality, and energy consumption, that aims to serve as a surrogate model.

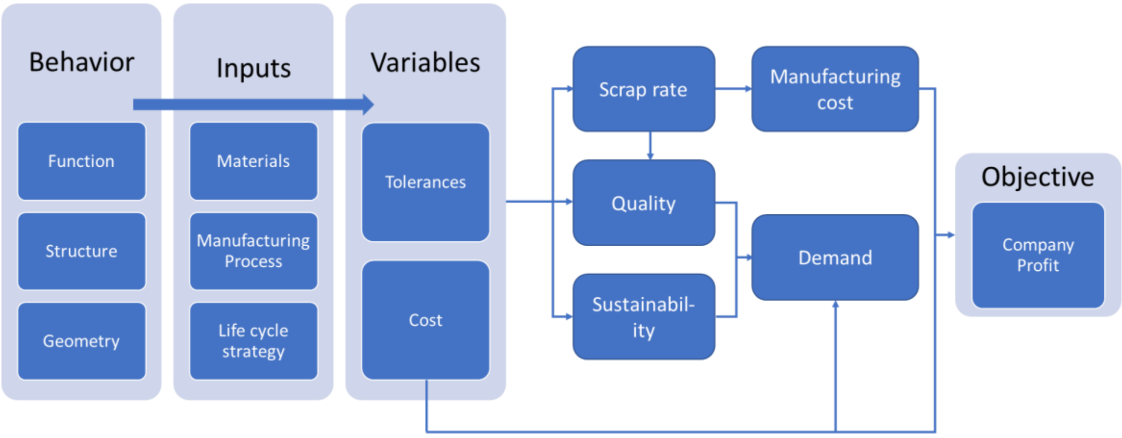

Figure 1. Sustainability and design decisions impacts

Required background of the student: Mechanical Engineering, Sustainability, Mathematics, Computer science

Key words: Sustainability, reusing, tolerancing, Cost, Energy, Optimization, AI.

A list of 5 (max.) representative publications of the group:

1. Khezri, A., Homri, L., Etienne, A., & Dantan, J. Y. (2023). Hybrid cost-tolerance allocation and production strategy selection for complex mechanisms: simulation and surrogate built-in optimization models. Journal of Computing and Information Science in Engineering, 23(5), 051003.
2. Hoffenson, S., Dagman, A., & Söderberg, R. (2015). Visual quality and sustainability considerations in tolerance optimization: A market-based approach. International Journal of Production Economics, 168, 167-180.
3. Dantan, J.-Y. and Eifler, T., 2021, Tolerance allocation under behavioural simulation uncertainty of a multiphysical system. CIRP Annals, 70, 127-130.
4. Wang, Y., Huang, A., Quigley, C. A., Li, L., & Sutherland, J. W. (2021). Tolerance allocation: Balancing quality, cost, and waste through production rate optimization. Journal of Cleaner Production, 285, 124837.
5. Natarajan, J., Sivasankaran, R., & Kanagaraj, G. (2018). Bi-objective optimization for tolerance allocation in an interchangeable assembly under diverse manufacturing environment. The International Journal of Advanced Manufacturing Technology, 95, 1571-1595.

ParisTech

CHINA SCHOLARSHIP COUNCIL

TITLE: ARTIFICIAL INTELLIGENCE REINFORCED MATERIALS AND PROCESSING OPTIMIZATION FOR POWDER BED FUSION-LASER BEAMS

Topic number : ***2024_018***

Field : Material science, Mechanics and Fluids

Subfield: Smart Manufacturing

ParisTech School: Arts et Métiers
Research team :
Research team website:
Research lab: MSMP - Laboratoire Mécanique, Surface, Matériaux et Procédés
Lab location: Châlons-en-Champagne
Lab website: https://www.msmp.eu/

Contact point for this topic: Nan KANG, nan.kang@ensam.eu

Advisor 1: Nan KANG - nan.kang@ensam.eu
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Powder bed fusion-laser beam (PBF-LB) additive manufacturing (AM) holds immense promise for the fabrication of complex, high-performance components across various industries. However, the optimization of materials and processing parameters remains a critical challenge, impacting the final quality, mechanical properties, and efficiency of manufactured parts. This project focuses on an innovative approach that integrates artificial intelligence (AI) techniques to enhance PBF-LB processes by optimizing material selection and processing parameters. First, the utilization of AI algorithms, such as machine learning and neural networks, enables the identification and characterization of suitable materials for PBF-LB, considering factors such as chemical composition, powder morphology, and solidification properties. By analyzing vast datasets encompassing material properties and AM process parameters, AI models can predict material behavior during

processing, aiding in the selection of materials with desirable properties for specific applications. Second, AI-driven optimization algorithms facilitate the tuning of processing parameters in real time, ensuring enhanced part quality and performance. Through iterative learning and feedback mechanisms, these algorithms adaptively adjust the laser power, scan speed, hatch spacing, and other process variables to minimize defects, such as porosity, warping, and residual stresses, while maximizing the build speed and energy efficiency. Overall, the synergistic combination of AI and PBF-LB technology offers unprecedented opportunities for accelerating the adoption of additive manufacturing in various industries by facilitating the production of high-quality, complex components with superior mechanical properties and performance.

Required background of the student:
1. Candidates should have a master’s degree in the field of artificial intelligence;
2. A background in additive manufacturing will be a clear advantage;
3. Candidates should be able to work in a multidisciplinary environment and be fluent in English (both oral and written)

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Machine learning in additive manufacturing: State-of-the-art and perspectives, Additive Manufacturing, Volume 36, December 2020, 101538, https://doi.org/10.1016/j.addma.2020.101538

2. Smart additive manufacturing: Current artificial intelligence-enabled methods and future perspectives. Sci. China Technol. Sci. 63, 1600–1611 (2020). https://doi.org/10.1007/s11431-020-1581-2

3. Laser powder bed fusion of a novel high strength quasicrystalline Al–Fe–Cr reinforced Al matrix composite, Advanced Powder Materials, Volume 2, Issue 2, , April 2023, 100108, https://doi.org/10.1016/j.apmate.2022.100108

TITLE: CONSTRUCTION OF CERAMIC MATRIX COMPOSITES WITH STRUCTURAL PROGRAMMING FOR STEREOLITHOGRAPHY ADDITIVE MANUFACTURING

Topic number : ***2024_019***

Field : Energy, Processes - Material science, Mechanics and Fluids

Subfield: Additive Manufacturing

ParisTech School: Arts et Métiers
Research team :
Research team website:
Research lab: MSMP - Laboratoire Mécanique, Surface, Matériaux et Procédés
Lab location: Aix-en-Provence
Lab website: https://www.msmp.eu/

Contact point for this topic: Nan KANG, nan.kang@ensam.eu

Advisor 1: Mohamed EL MANSORI - mohamed.elmansori@ensam.eu
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Stereolithography (SLA) additive manufacturing has gained prominence for its ability to produce complex geometries with high resolution and accuracy. However, the application of SLA to ceramic matrix composites (CMCs) has been limited due to challenges in material selection, processing, and postprocessing. This project employs programming techniques tailored for SLA-based fabrication of CMCs to obtain high-density and high-dimensional accuracy components. It then delves into the specific challenges associated with SLA-based fabrication of CMCs, such as material viscosity, photopolymerization kinetics, and ceramic particle dispersion. The programming strategies encompass material formulation techniques for achieving homogenous ceramic dispersion within photopolymer resins, as well as process parameter optimization methodologies to enhance the build quality, dimensional accuracy, and

mechanical properties of CMC parts. Finally, the thermal treatment processes for ceramic phase formation and matrix densification demonstrate the feasibility of producing fully densified CMC components with tailored microstructures and superior mechanical performance. The objective of this project is to advance the capabilities of SLA-AM, paving the way for the widespread adoption of CMCs in diverse industrial sectors.

Required background of the student:

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. A comprehensive review of the photopolymerization of ceramic resins used in stereolithography, Additive Manufacturing, Volume 35, October 2020, 101177, https://doi.org/10.1016/j.addma.2020.101177

2. Stereolithography-based additive manufacturing of lightweight and high-strength Cf/SiC ceramics, Additive Manufacturing, Volume 35, October 2020, 101177, https://doi.org/10.1016/j.addma.2020.101177

3. A review on the progress and challenges of binder jet 3D printing of sand moulds for advanced casting, Additive Manufacturing, Volume 40, April 2021, 101889, https://doi.org/10.1016/j.addma.2021.101889

TITLE: INVESTIGATION ON THE RESIDUAL STRESS AND MULTI-SCALED STRUCTURE IN LASER POWDER BED FUSION ADDITIVE MANUFACTURED H13 STEEL

Topic number* : *2024_020

Field : Material science, Mechanics and Fluids - Energy, Processes

Subfield: Additive Manufacturing

ParisTech School: Arts et Métiers
Research team :
Research team website:
Research lab: MSMP - Laboratoire Mécanique, Surface, Matériaux et Procédés
Lab location: Châlons-en-Champagne
Lab website: https://www.msmp.eu/

Contact point for this topic: Nan KANG, nan.kang@ensam.eu

Advisor 1: Nan KANG - nan.kang@ensam.eu
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
This work focuses on a detailed investigation into the formation of residual stress and defects, as well as their multi-scale effects, in the Laser Powder Bed Fusion (LPBF) additive manufacturing processed H13 steel. LPBF, a widely used technique for fabricating complex metal structures with high precision, encounters significant challenges due to the non-uniform thermal gradients that arise during rapid heating and cooling cycles. These thermal fluctuations lead to the accumulation of residual stress and the development of various defects, including porosity, lack of fusion, keyhole defects, and microcracks. Residual stress can cause distortions, reduce fatigue life, and compromise the overall mechanical performance of the manufactured components, while defects can serve as stress concentrators that further weaken the structure. The mechanisms responsible for the development of residual stress and

defects at multiple scales: micro-scale (grain boundaries, phase transformations), meso-scale (layer-by-layer heat accumulation, melt pool dynamics), and macro-scale (overall part deformation and warping) will be considered. By using advanced characterization techniques and simulations, the work will highlights the interactions between thermal stresses, material properties, and defect formation. These insights provide a comprehensive understanding of how residual stress and defects evolve during the LPBF process, enabling strategies for optimizing process parameters and improving the quality and reliability of additively manufactured parts.

Required background of the student:

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. A review on the multi-scaled structures and mechanical/thermal properties of tool steels fabricated by laser powder bed fusion additive manufacturing. Int J Miner Metall Mater 31, 1048–1071 (2024). https://doi.org/10.1007/s12613-023-2731-5

2. Study on the in situ strengthening and toughening mechanism of H13 tool steel/WC-12Co composite using laser-based directed energy deposition, Composites Part B: Engineering, Volume 266, , November 2023, 111011. https://doi.org/10.1016/j.compositesb.2023.111011

3. Impact of applied loads on wear mechanisms in H13 steel at various preheating temperatures during laser powder bed fusion additive manufacturing, Wear, Volumes 556–557, 15 November 2024, 205538. https://doi.org/10.1016/j.wear.2024.205538

TITLE: VIRTUAL REALITY FOR PHYSICAL VAPOR DEPOSITION

Topic number : ***2024_021***

Field : Information and Communication Science and Technology - Material science, Mechanics and Fluids - Design, Industrialization

Subfield: Computer graphics, Geometric modelling, Virtual reality, Physical simulation, PVD

ParisTech School: Arts et Métiers
Research team : Virtual reality team
Research team website: https://institutchalon.ensam.eu/
Research lab: LISPEN
Lab location: Chalon-sur-Saône
Lab website: https://lispen.artsetmetiers.fr/

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Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Sputtering is one of the technic grouped under the denomination of Physical Vapor Deposition (PVD). The objective of these processes is to deposit matter on the surface of a piece by the mean of a vapor generated physically (i.e. thermally or mechanically). The deposition results in a film, or coating, few micrometres thick and from centimetre to meter in lateral dimension. The deposited film changes the surface properties of the piece. The applications are found in microelectronics, optics, data storage devices, energy (photovoltaic solar panel, batteries, fuel cells), medical devices (implants, prosthesis, tools), cutting tools and many others. In the context of Industry 4.0, Mixed reality (MR) plays a crucial role by merging the physical and digital worlds, providing immersive and interactive experiences. MR in Industry 4.0 enhances productivity, efficiency, and innovation by bridging the gap between the physical and digital realms, enabling new ways of working, training, and problem-

solving in the industrial context. MR allows engineers and designers to visualize complex 3D models and data in a realistic environment. This aids in designing, prototyping, and optimizing products and processes. MR enables the integration of digital twins, allowing real-time monitoring, simulation, and analysis of physical assets and processes. MR supports predictive maintenance by providing real-time data visualization and analytics. The aim of this project is to develop a new interactive MR application for PVD based on scientific data obtain by experimental measurements and numerical computations. • Process Visualization: MR can overlay relevant data, such as temperature, pressure, and deposition rates, onto the physical PVD equipment in real-time. This enables operators to monitor the process parameters more effectively and make informed decisions for process optimization. • Maintenance and Troubleshooting: MR can assist maintenance personnel in identifying and addressing issues with PVD equipment. By overlaying digital information on the physical equipment, maintenance procedures can be guided step by step, reducing downtime and improving the overall reliability of the system. • Customization and Design: MR can aid in the design and customization of coatings. By visualizing virtual prototypes and simulations in the physical environment, engineers and designers can make informed decisions about the composition and thickness of coatings, leading to improved product performance. The following research questions will be addressed during the proposed PhD : • What is the best interaction metaphor to let user visualize the virtual coating film ? o Under different representations: point cloud (for atoms) or surface mesh (for volume) o Through different scales: macroscope (coating pièce) or microscope (column-like structure) • How to design the augmented reality visualization for virtual PVD process in real machine ? o When the real PVD is stopped, how to visualize the simulated PVD results o During the real PVD process, how to synchronize the virtual PVD with which data ? • How to real-time and imprecisely simulate the PVD process in mixed reality application ? o Using scientific simulation software to simulate multiple cases o Using AI to train a black box model that can predict simulation result in MR

Required background of the student:

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. B. Li, F. Segonds, C. Mateev, R. Lou, F. Merienne, "Design in context of use: An experiment with a multi-view and multi-representation system for collaborative design", Computers in Industry, 103: 28 - 37, 2018.

2. Watiez, N. et al. (2023). Finite Element Mesh Generation for Nano-scale Modeling of Tilted Columnar Thin Films for Numerical Simulation. In: Noël, F., Nyffenegger, F., Rivest, L., Bouras, A. (eds) Product Lifecycle

Management. PLM in Transition Times: The Place of Humans and Transformative Technologies. PLM 2022. IFIP Advances in Information and Communication Technology, vol 667. Springer, Cham
3. Watiez, N., Cotton, D., Besnard, A., Lou, R., Birembaux, H., & Outeiro, J, Augmented reality representation for the investigation of simulated inclined chromium thin films, In PLATHINIUM, Antibes, France, September 2023

ParisTech

CHINA SCHOLARSHIP COUNCIL

Title: Exploring Human-AI collaboration models in industrial Processes: A frugal approach to define the optimal collaboration balance for enhanced performance.

Topic number : ***2024_022***

Field : Design, Industrialization

Subfield: Industrial engineering, Information system, Artificial intelligence.

ParisTech School: Arts et Métiers
Research team : Kenza AMZIL, Nathalie Klement, Esma YAHIA, Lionel ROUCOULES
Research team website:
Research lab: LISPEN - Laboratoire d'ingénierie des systèmes physiques et numériques
Lab location: Aix-en-Provence
Lab website: https://lispen.artsetmetiers.fr/

Contact point for this topic: AMZIL - Kenza - kenza.amzil@ensam.eu

Advisor 1: Kenza AMZIL - kenza.amzil@ensam.eu
Advisor 2: Esma Yahia - esma.yahia@ensam.eu
Advisor 3: Nathalie Klement - nathalie.klement@ensam.eu
Advisor 4: Lionel Roucoules - lionel.roucoules@ensam.eu

Short description of possible research topics for a PhD:
This PhD program will investigate and evaluate different modes of human-AI collaboration in industrial environments to determine the optimal balance between human and AI involvement. The objective is to assess how varying degrees of AI autonomy—from fully autonomous AI to human-controlled processes—impact key performance indicators such as task efficiency, cost optimization, transparency, user acceptability, etc. Intermediate collaboration models, such as AI-assisted decision-making, shared task responsibilities, and human supervision of AI, will also be examined. A comprehensive evaluation framework will be developed based on four critical dimensions: • Efficiency: Examining task performance improvements, resource optimization, reduction of human

errors, and the speed of execution in different collaborative configurations. • Transparency: Ensuring that the AI’s processes are interpretable, roles between human and AI are clearly defined, and interactions are smooth and intuitive for users. • Adaptability: Assessing how human-AI systems adjust to new contexts, evolving tasks, and varying user preferences, as well as their ability to improve through learning and continuous interaction. • Ethics and Security: Assessing the system's adherence to ethical standards, prevention of biases, data privacy, and robustness against security threats. The research will employ both qualitative and quantitative methods, combining interviews, simulations, and performance evaluations to identify best practices in human-AI interaction in order to build a framework for recommending the best mode of Human-AI collaboration depending on the specific situation and its characteristics. Experiments will be conducted in simulated industrial settings to validate these collaboration models, with a focus on determining the minimum viable AI involvement required to maintain optimal task performance and user satisfaction. This approach aligns with frugal innovation principles, which emphasize the need for resource-efficient solutions that deliver maximum value while minimizing complexity and costs. This PhD project will provide valuable insights into how human-AI collaboration can be best structured in industrial processes to achieve superior performance in a cost-effective, resource-efficient manner while maintaining flexibility and transparency in decision-making.

Required background of the student:
Industrial engineering, Information system, Artificial intelligence.

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Song, Binyang, Qihao Zhu, et Jianxi Luo. « Human-AI Collaboration by Design ». Proceedings of the Design Society 4 (mai 2024): 2247-56. https://doi.org/10.1017/pds.2024.227.

2. Heinzl, B., Silvina, A., Krause, F., Schwarz, N., Kurniawan, K., Kiesling, E., ... & Moser, B. (2024, April). Towards Integrating Knowledge Graphs into Process-Oriented Human-AI Collaboration in Industry. In International Conference on Software Quality (pp. 76-87). Cham: Springer Nature Switzerland.

3. Fragiadakis, George, Christos Diou, George Kousiouris, et Mara Nikolaidou. « Evaluating Human-AI Collaboration: A Review and Methodological Framework ». arXiv, 9 juillet 2024. http://arxiv.org/abs/2407.19098.

4. Amzil K., Yahia E., Klement N., Roucoules L. (2021) Causality Learning Approach for Supervision in the Context of Industry 4.0. In: Roucoules L., Paredes M., Eynard B., Morer Camo P., Rizzi C. (eds) Advances on Mechanics, Design Engineering and Manufacturing III. JCM 2020. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-70566-4_50

5. Hartikainen, M., Spurava, G., & Väänänen, K. (2024). Human-AI Collaboration in Smart Manufacturing: Key Concepts and Framework for Design. HHAI 2024: Hybrid Human AI Systems for the Social Good, 162-172.

Title: Gradient damage approach: Application to cementitious composites failure

Topic number : ***2024_023***

Field : Material science, Mechanics and Fluids - Material science, Mechanics and Fluids - Material science, Mechanics and Fluids

Subfield:

ParisTech School: Arts et Métiers
Research team : DIPPE
Research team website: https://lampa.ensam.eu/equipe-dippe-axe-sec-144046.kjsp?RH=1478611690252
Research lab: LAMPA - Laboratoire angevin de mécanique, procédés et innovation
Lab location: Angers
Lab website: https://lampa.ensam.eu/le-laboratoire-100789.kjsp?RH=1478611690252&RF=1415870871805

Contact point for this topic: EL AREM - Saber - saber.elarem@ensam.eu

Advisor 1: Amine Ammar - amine.ammar@ensam.eu
Advisor 2: Saber EL AREM - saber.elarem@ensam.eu
Advisor 3: Karim Miled - karim.miled@enit.utm.tn
Advisor 4:

Short description of possible research topics for a PhD:
The degradation of quasi-brittle materials such as concrete and cementitious composites are generally brittle at the microscopic scale and ductile at the macroscopic scale (damage). Moreover, this quasi-brittleness is depending on the heterogeneous microstructure of the material (volume fraction, shape and size of the inclusions as well as their nature and the contrast in rigidity between the cementitious matrix and the inclusions), which often generates a different failure modes. This often results in a transition from a brittle failure mode to a more ductile mode or vice versa, and generates a size effect on the compressive strength of cementitious materials whose apprehension and modeling are

complex. Indeed, several types of inclusions with different physical and mechanical properties can be incorporated into a cementitious matrix depending on the desired application. In ordinary concrete of common density, these inclusions are natural aggregates of sand and gravel which are more rigid than hardened cement paste. On the other hand, in a light concrete, the inclusions are very flexible light aggregates or even air bubbles assimilated to pores. Furthermore, these inclusions can have different shapes and sizes and can be regularly or randomly distributed in the cementitious matrix. Despite the abundance of scientific literature on the subject of compressive failure of quasi-brittle cementitious materials, this subject remains topical. In fact, there are several ways to model it. Some are purely empirical since they are based on tests on real materials in which the microstructure is varied. This approach is costly because it requires a very large number of tests to be able to correctly understand the failure mechanisms and predict all the effects of the microstructure of the material studied on its compressive strength. Other approaches are purely numerical and are based first on the modeling of the real or idealized microstructure of these materials and then on the adoption of a nonlinear constitutive law modeling the behavior of the cementitious matrix placed between the inclusions which are generally assumed to be elastic or perfectly rigid. This approach is efficient but costly in terms of numerical implementation and computation time. Moreover, certain local numerical models exhibit problems of pathological localization of the damage or concentration of the stresses in points of the cracks leading to problems of nonconvergence of computation or mesh dependence of the results. Recently, alternative methods for the numerical simulation of brittle fracture phenomena have appeared and where discontinuities are not explicitly introduced into the solid. The major advantage of using a phase field is that the evolution of the fracture surfaces stems from the resolution of a coupled system of PDE. It is not necessary to explicitly follow the topology of the crack nor to constrain its path a priori. Thus, this approach will be adopted in the PhD proposal to simulate the complete failure process of cementitious composites containing different types of inclusions.

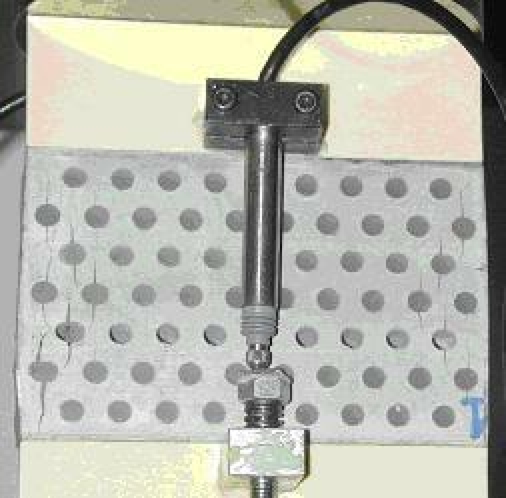
Required background of the student:

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. K Miled, K Sab, R Le Roy - "Particle size effect on EPS lightweight concrete compressive strength: Experimental investigation and modelling" - Mechanics of Materials, 2007

2. K Miled, K Sab, R Le Roy - "Effective elastic properties of porous materials: Homogenization schemes vs experimental data", Mechanics Research Communications, 2011

3. A Naija, K Miled - " Numerical study of the influence of W/C ratio and aggregate shape and size on the ITZ volume fraction in concrete"-CoConstruction and Building Materials, 2022nstruction and Building Materials, 2022
4. H Gmati, C Mareau, A Ammar, S El AremH Gmati, C Mareau, A Ammar, S El Arem - "A phase-field model for brittle fracture of anisotropic materials"-International Journal for Numerical Methods in Engineering, 2020



Title: Dynamic crack propagation in multidirectional functionally graded materials under mechanical and thermal loadings

Topic number : ***2024_024***

Field : Material science, Mechanics and Fluids - Material science, Mechanics and Fluids - Material science, Mechanics and Fluids

Subfield: Mechanics of solids

ParisTech School: Arts et Métiers
Research team : DIPPE
Research team website: https://lampa.ensam.eu/les-equipes-de-recherche-100787.kjsp?RH=1415871756377&RF=1415871394252
Research lab: LAMPA - Laboratoire angevin de mécanique, procédés et innovation
Lab location: Angers
Lab website: https://lampa.ensam.eu/accueil-lampa-100748.kjsp

Contact point for this topic: saber EL AREM saber.elarem@ensam.eu

Advisor 1: AMINE AMMAR - amine.ammar@ensam.euami
Advisor 2: Saber EL AREM - saber.elarem@ensam.eu
Advisor 3: Mohammad-Javad KAZEMZADEHPARSI - javad.kazem@ensam.eu
Advisor 4:

Short description of possible research topics for a PhD:
Functionally Graded Materials (FGM) are new class of composite materials that their mechanical properties evolve continuously in space. In traditional composite materials, the mechanical properties change sharply at the interface of different phases and this leads to high interfacial stresses and in many times the origin of failure. Whereas, the gradual variation of material properties in FGM materials prevents from such behaviors. This feature makes the FGM as the ideal choice in severe thermal environments and make it possible to have a part with pure metallic phase at one point to satisfy strength and pure ceramic phase at other point to resist again high temperature. One example application of

FGM materials is heat barrier in spacecrafts. Optimal design of FGM materials consists of accurate determination of spacial distribution of concentration (or volume fraction) of constituents. Recent technologies use additive manufacturing to produce FGM materials and consequently the FGM parts with multi directional material variations are realistic today. Failure analysis is the inseparable part of any engineering design and crack propagation is the inseparable part of any failure analysis. Therefore, analysis of crack propagation in FGM materials are highly important in optimal design of such products. Phase field approach is the most accurate and versatile technique in moving boundary problems specially crack propagations. The main objective of the present project is to establish a general approach for accurate dynamic crack propagation and failure in components made of FGM materials in the framework of gradient damage approach.

Required background of the student:
Master in Mechanics and Material sciences; Applied mechanics, numerical methods

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. MJ Kazemzadeh-Parsi, A Ammar, F ChinestaMJ Kazemzadeh-Parsi, A Ammar, F Chinesta "Parametric analysis of thick FGM plates based on 3D thermo-elasticity theory: a proper generalized decomposition approach", Materials, 2023

2. MJ Kazemzadeh-Parsi, F Chinesta, A Ammar, "Proper generalized decomposition for parametric study and material distribution design of multi-directional functionally graded plates based on 3D elasticity solution", Materials, 2021

3. H Gmati, C Mareau, A Ammar, S El Arem H Gmati, C Mareau, A Ammar, S El Arem , " A phase-field model for brittle fracture of anisotropic materialsA phase-field model for brittle fracture of aniotropic materials", International Journal for Numerical Methods in Engineering, 2020

ParisTech

TITLE: ENGINEERING OF MULTIMODAL MAGNETIC RESONANCE AND OPTICAL IMAGING USING THERANOSTIC FORMULATIONS AGAINST CANCER AND INFLAMMATION

Topic number* : *2024_025

Field : Life and Health Science and Technology - Chemistry, Physical chemistry and Chemical Engineering - Material science, Mechanics and Fluids

Subfield: Bioimaging

ParisTech School: Chimie ParisTech - PSL
Research team : Synthesis, Electrochemistry, Imaging and Analytical Systems for Diagnosis
Research team website: https://iclehs.fr/research/seisad/
Research lab: I-CLEHS - Institute of chemistry for life and health
Lab location: Paris
Lab website: https://iclehs.fr/research/seisad/

Contact point for this topic: DOAN Bich-Thuy, bich-thuy.doan@chimieparistech.psl.eu

Advisor 1: Bich Thuy Doan - bich-thuy.doan@chimieparistech.psl.eu
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Cancer is a major public health problem worldwide. Inflammatory diseases such as osteoarthritis is the leading cause of disability. Clinical therapy therefore could benefit from image-guided therapy which needs the development of both: i) sensitive imagings diagnostic methods and ii) effective tolerated new therapies. In this context, the research for innovative and efficient systems to effectively diagnose and treat diseases is highly active: we propose the development of new multifunctional nanoformulations with bioimaging features. These theranostic probes will enable to be vectorized to target diseased tissues and bring medicine. More precisely, we propose to develop quantitative multimodal and

multiscale molecular bioimaging methods based on MRI and optical imaging to codevelop, characterize and evaluate innovative nanomedicine with bimodal fluorescent magnetic, and photoactive therapeutical properties, and incorporated them in hydrogels matrix for sustained release, in collaboration with chemists team at the Université PSL and University Paris Cité. The task is to gather multiparametric imaging data (molecular, functional…) to identify new diagnostic imaging features applied to the study of cancer and inflammation in preclinics.

Required background of the student:
Basics in chemistry, biomedical engineering, Bioimagings

A list of (5 max.) representative publications of the group: (Related to the research topic)

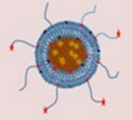
1. Boumati S. , … BT Doan, Three in One: Anti Cancer Activity in vitro and in vivo Evaluation of a Theranostic Agent that Combines Magnetic Resonance Imaging, Optical Bioimaging and Photodynamic Therapy Capabilities ACS Appl Bio Mater. 2023 ;6(11):4791-4804. doi: 10.1021/acsabm.3c00565

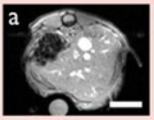
2. Zhang Y, Doan BT and Gasser G. Metal-Based Photosensitizers as Inducers of Regulated Cell Death Mechanisms Chemical Reviews 2023 123 (16), 10135-10155 DOI: 10.1021/acs.chemrev.3c00161

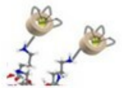
3. Do HD, Ménager C, Michel A, Seguin J, Korichi T, Dhotel H, Marie C, Doan BT, Mignet N. Development of Theranostic Cationic Liposomes Designed for Image-Guided Delivery of Nucleic Acid. Pharmaceutics. 2020 ;12(9):854. doi: 10.3390/pharmaceutics12090854

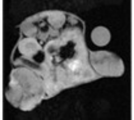
4. Thébault CJ, Ramniceanu G, Boumati S, Michel A, Seguin J, Larrat B, Mignet N, Ménager C, Doan BT. Theranostic MRI liposomes for magnetic targeting and ultrasound triggered release of the antivascular CA4P. J Control Release. 2020. pii: S0168-3659(20)30150-4. doi: 10.1016/j.jconrel.2020.03.003

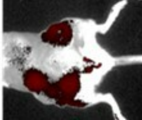
5. Piraquive J, Leporq B, Wan JH, Lambert SA, Mignet N, Doan BT, Lotersztajn S, Garteiser P, Van Beers BE In vitro distinction between proinflammatory and antiinflammatory macrophages with gadolinium-liposomes and ultrasmall superparamagnetic iron oxide particles at 3.0T. J Magn Reson Imaging. 2019;49(4):1166-1173. doi: 10.1002/jmri.26331




a
b







ParisTech

TITLE: SMART AND MULTIPHYSICS SOLID-SHELL FINITE ELEMENTS FOR THE 3D SIMULATION OF THIN STRUCTURES

Topic number : *2024_026*

Field : Material science, Mechanics and Fluids

Subfield: Mechanical Engineering

ParisTech School: Arts et Métiers
Research team : Numerical Methods, Instabilities and Vibrations
Research team website:
Research lab: LEM3 - Laboratoire d'étude des microstructures et de mécanique des matériaux
Lab location: Metz
Lab website: https://lem3.univ-lorraine.fr/

Contact point for this topic: CHALAL Hocine
[hocine.chalal@ensam.eu]

Advisor 1: Farid ABED-MERAIM - Farid.Abed-Meraim@ensam.eu
Advisor 2: Hocine CHALAL - Hocine.chalal@ensam.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
In nowadays manufacturing industry, thin structures are widely designed and employed to reduce weight of products, while improving their mechanical performances (strength, crashworthiness …). The simulation of these thin structures using the finite element method has become more and more important in the design and manufacture processes. In our research group, we have recently developed a family of solid‐shell finite elements, which are capable of modeling most 3D thin structural problems using only a single element layer, while accurately describing the various through-thickness phenomena. The purpose of the present PhD thesis is to pursue the previous works on the development of solid‐shell elements, by extending their formulations to advanced and multiphysics constitutive laws for the simulation of smart devices. More specifically, coupled magnetic‐elastic‐plastic constitutive laws will be

combined with the developed solid‐shell elements for the simulation of magnetic pulse forming processes. Also, hard-magnetic soft materials, consisting of an elastomer matrix filled with high remnant magnetic particles, can be efficiently modeled by combining magneto-mechanical behavior with the developed solid‐shell elements. These specific materials can exhibit controlled flexibility and rapid shape change under non-contact activation, showing promising potential applications in soft robotics, biomedical devices and flexible electronics. Moreover, for the piezoelectric formulations of the solid‐shell elements, more advanced piezoelectric laws will be investigated in order to enhance the active control of smart devices. In addition, the formulation of the solid‐shell elements will be extended to Functionally Graded Materials (FGM) and Functionally Graded Piezoelectric Materials (FGPM), for which the material properties exhibit a gradual change along the thickness direction.

Required background of the student:
- Solid background in solid mechanics and numerical methods;
- Good analytical and programming skills (e.g. C/C++, Fortran, Matlab);
- Experience with Finite Element modeling would be an asset.

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Chalal H, Abed-Meraim F (2018). Quadratic solid-shell finite elements for geometrically nonlinear analysis of functionally graded material plates. Materials, 11(6), art. no. 1046.

2. Wang P, Chalal H, Abed-Meraim F (2017). Quadratic prismatic and hexahedral solid–shell elements for geometric nonlinear analysis of laminated composite structures. Composite Structures, 172:282–296. 1.

3. Wang P, Chalal H, Abed-Meraim F (2017). Quadratic solid–shell elements for nonlinear structural analysis and sheet metal forming simulation. Computational Mechanics, 59:161–186.

4. Abed-Meraim F, Trinh VD, Combescure A (2013). New quadratic solid–shell elements and their evaluation on linear benchmark problems. Computing, 95:373–394.

5. Abed-Meraim F, Combescure A (2009). An improved assumed strain solid‒shell element formulation with physical stabilization for geometric non-linear applications and elastic–plastic stability analysis. International Journal for Numerical Methods in Engineering, 80:1640–1686.

TITLE: ECO-EFFICIENT PROCESSES FOR THE SYNTHESIS OF SUSTAINABLE POLYMERS

Topic number : **2024_027**

Field : Chemistry, Physical chemistry and Chemical Engineering

Subfield:

ParisTech School: Chimie ParisTech - PSL
Research team : COCP
Research team website: https://www.ircp.cnrs.fr/equipes-recherche-ircp/equipe-cocp/
Research lab: IRCP - Institut de Recherche de Chimie de Paris
Lab location: Paris
Lab website: https://www.ircp.cnrs.fr/

Contact point for this topic: regis.gauvin@chimieparistech.psl.eu

Advisor 1: Régis Gauvin - regis.gauvin@chimieparistech.psl.eu
Advisor 2: Christophe Thomas - christophe.thomas@chimieparistech.psl.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
The development of new methods to transform biomass into resources suitable for polymer production remains a crucial obstacle on the way to a more sustainable chemical economy.[1] In this regard, the creation of renewable polymers through one-pot catalysis represents an important tool to support more sustainable plastics production.[2,3] In this project, hydrogen borrowing, a clean atom-economical technology, will be harnessed in a first step to synthesize lactones or lactames monomers from biosourced raw materials.[4] These will then be polymerized through stereoselective ring opening polymerization, providing novel polyesters or polyamides.[5] An intense emphasis will be placed on the design of new organometallic catalysts based on Earth-abundant metals, as well as on establishing the physicochemical properties of the polymers.

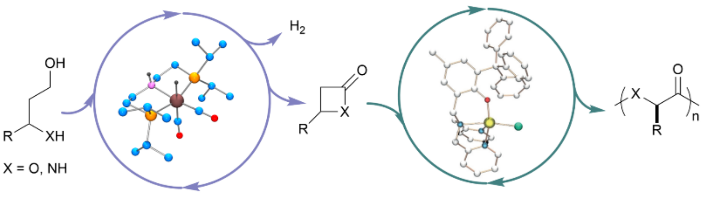
Required background of the student:
The student should be familiar with molecular synthesis and characterization techniques (organic, organometallic and/or polymer chemistry).

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Fouilloux, H.; Rager, M.-N.; Ríos, P.; Conejero, S.; Thomas, C. M. Angew. Chem., Int. Ed. 2022, 61, e202113443.
2. Upitak, K.; Thomas, C. M. , Acc. Chem. Res. 2022, 55, 2168.

3. a) Robert, C.; De Montigny, F.; Thomas, C. M., Nat. Commun. 2011, 2, 586. b) Fouilloux, H.; Qiang, W.; Robert, C.; Placet V.; Thomas, C. M. Angew. Chem., Int. Ed. 2021, 60, 19374.

4. Nguyen, D. H.; Trivelli, X.; Capet, F.; Paul, J.-F.; Dumeignil, F.; Gauvin R. M., ACS Catal., 2017, 7, 2022.


OH
XH
R
X = O, NH
H_2
O
X
R
X
O
R
n

TITLE: DESIGN OF BIOCOMPATIBLE AND BIODEGRADABLE POLYMER-COATED NANOPARTICLES AS VECTORIZING AGENTS

Topic number* : *2024_028

Field : Chemistry, Physical chemistry and Chemical Engineering - Material science, Mechanics and Fluids

Subfield:

ParisTech School: Chimie ParisTech - PSL
Research team : COCP
Research team website: https://www.ircp.cnrs.fr/equipes-recherche-ircp/equipe-cocp/
Research lab: IRCP - Institut de Recherche de Chimie de Paris
Lab location: Paris
Lab website: https://www.ircp.cnrs.fr/

Contact point for this topic: regis.gauvin@chimieparistech.psl.eu

Advisor 1: Régis Gauvin - regis.gauvin@chimieparistech.psl.eu
Advisor 2: Christophe Thomas - christophe.thomas@chimieparistech.psl.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
The design of efficient vectorizing agents is at the cornerstone of modern pharmaceutical agents. In this view, the tailoring of specific (molecular) objects by covalent bonding with polymer chains is of major interest, to confer them significant compatibility with physiological environments.[1] In this view, biocompatible and biodegradable polymers are ideal candidates as components within such advanced formulations. These can be most efficiently prepared using ring opening polymerization (ROP) of lactones or lactides into polyesters or polylactic acid mediated by organometallic initiators.[2,3] On the top of that, immobilization of organometallics on inorganic surfaces via surface was demonstrated to boost stereoselectivity of these considered polymerization processes.[4] In this project, we propose to combine surface organometallic chemistry

and ROP of polar monomers to design specific nanoobjects by “growing from” or “growing on” approaches, where chain growth is mediated by specifically designed supported organometallic entities. The ultimate goal will be the development of biopolymer-coated nanoparticles for future implementation into drug delivery systems.

Required background of the student:
The student should ideally be familiar with molecular (organic, organometallic and/or polymer chemistry) and materials synthesis and characterization techniques.

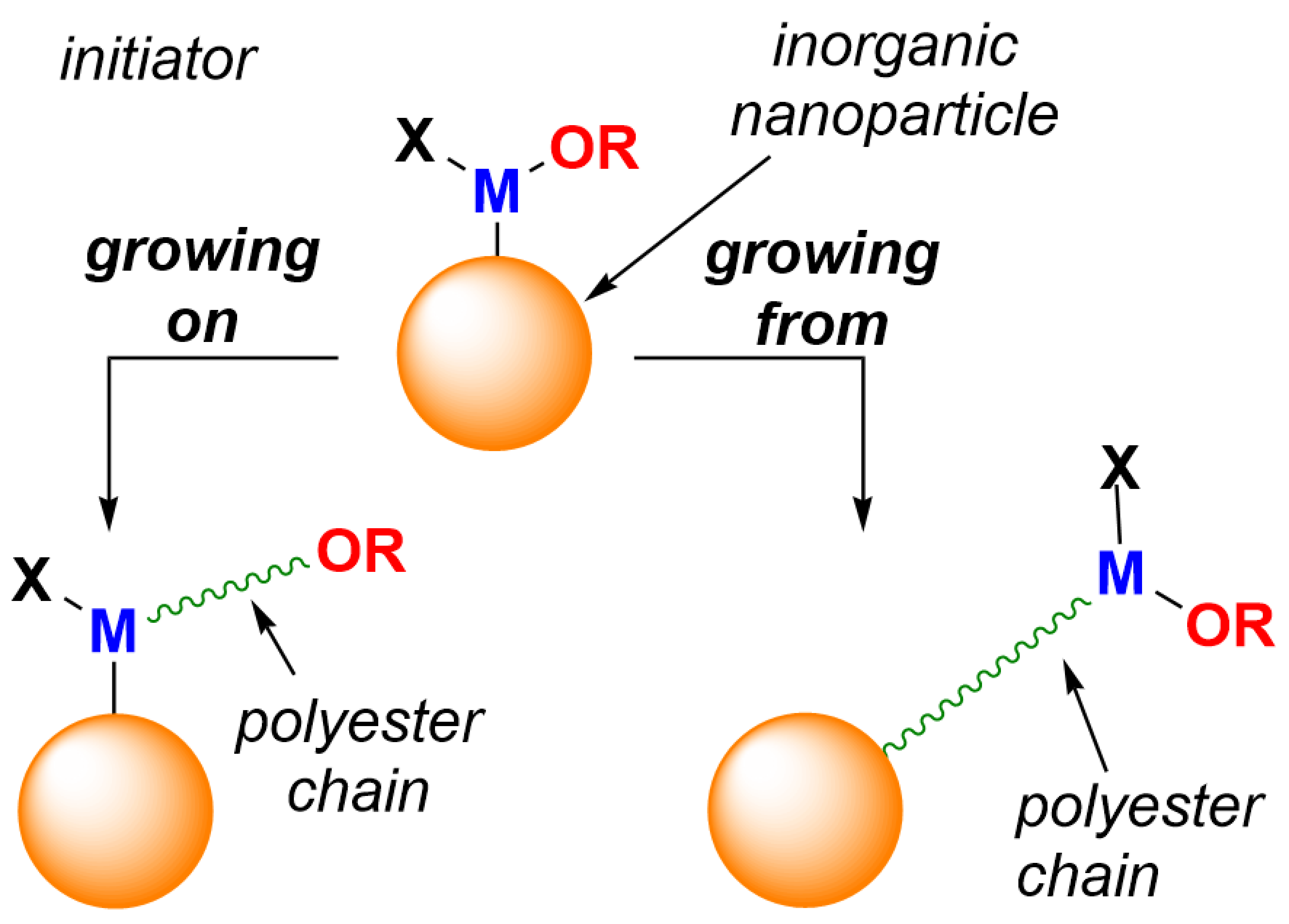
A list of (5 max.) representative publications of the group: (Related to the research topic)

1. N. Soliman, L. K. McKenzie, J. Karges, E. Bertrand,M. Tharaud, M. Jakubaszek, V. Guérineau,B. Goud, M. Hollenstein, G. Gasser, C. M. Thomas, Chem. Sci., 2020, 11, 2657-2663.

2. P. Marin, M. J.-L. Tschan, F. Isnard, C. Robert, P. Haquette, X. Trivelli, L.-M. Chamoreau, V. Guérineau, I. del Rosal, L. Maron, V. Venditto, C. M. Thomas, Angew. Chem. Int. Ed. 2019, 58, 12585-12589.

3. M. J.-L. Tschan, R. M. Gauvin, C. M. Thomas, Chem. Soc. Rev., 2021, 50, 13587-13608.

4. N. Ajellal, G. Durieux, L. Delevoye, G. Tricot, C. Dujardin, C. M. Thomas, R. M. Gauvin, Chem. Commun. 2010, 46, 1032-1034.


initiator
inorganic nanoparticle
X
M
OR
growing on
growing from
X
M
OR
polyester chain
X
M
OR
polyester chain

TITLE: HARNESSING TANDEM CATALYSIS FOR THE SYNTHESIS OF BIOBASED POLYMERS FROM RENEWABLE RESOURCES

Topic number : ***2024_029***

Field : Chemistry, Physical chemistry and Chemical Engineering - Material science, Mechanics and Fluids

Subfield:

ParisTech School: Chimie ParisTech - PSL
Research team : COCP
Research team website: https://www.ircp.cnrs.fr/equipes-recherche-ircp/equipe-cocp/
Research lab: IRCP - Institut de Recherche de Chimie de Paris
Lab location: Paris
Lab website: https://www.ircp.cnrs.fr/

Contact point for this topic:
christophe.thomas@chimieparistech.psl.eu

Advisor 1: Christophe Thomas - christophe.thomas@chimieparistech.psl.eu
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Tandem catalysis is one of the strategies used by Nature for building macromolecules.[1] However, these biological processes rely on highly complex biocatalysts thus limiting their industrial applications. In the same biomimetic spirit, we want to initiate a research effort to synthesize biodegradable polymers[2] via tandem catalytic transformations, where “activated” monomers are synthesized from raw materials (in one or more steps) and subsequently (co)polymerized. The objectives for this are clear: not only can a reduction in workload, waste, and energy consumption be achieved, but also the synthesis of complex products that are otherwise difficult to obtain (e.g., because of thermodynamic hurdles) comes within reach. In other words, the combination of chemistries may

allow the direct synthesis of macromolecules with high structural complexity. Therefore, we want to direct investigative efforts toward the synthesis of new renewable monomers and the subsequent catalytic conversion of these monomers into their corresponding polymers.[3-5] The general idea is to use a tandem procedure of combining the synthesis of new biomass-derived monomers with subsequent polymerization by well-defined metal-based catalysts, aiming at novel polymeric materials.

Required background of the student:
The student should ideally be familiar with molecular (organic and/or polymer chemistry) synthesis and characterization techniques.

A list of (5 max.) representative publications of the group: (Related to the research topic)

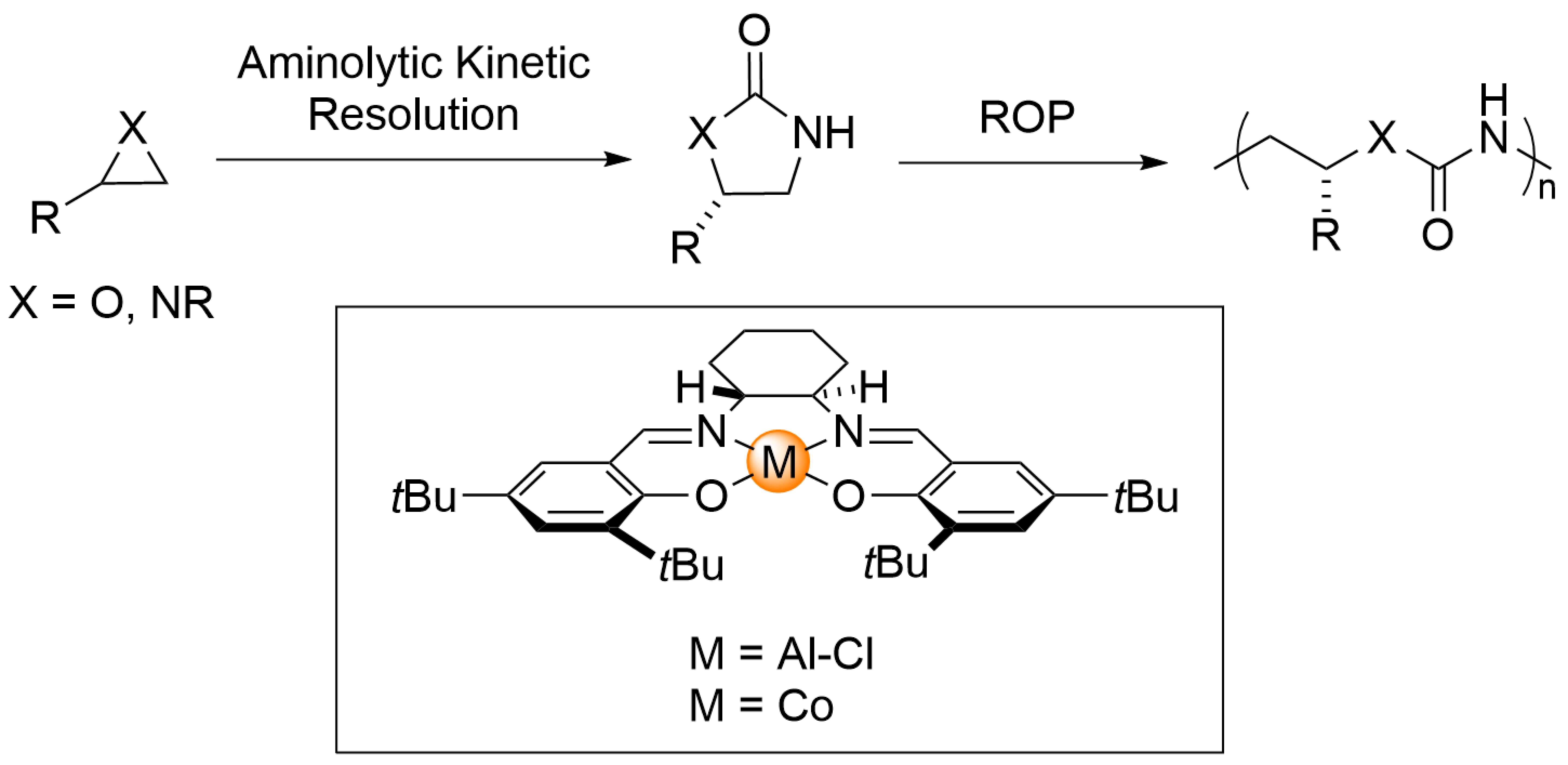
1. C. Robert, F. de Montigny, C. M. Thomas, Nature Comm., 2011, 2, 586

2. C. Robert, T. E. Schmid, V. Richard, P. Haquette, S. K. Raman, M.-N. Rager, R. M. Gauvin, Y. Morin, X. Trivelli, V. Guérineau, I. del Rosal, L. Maron, C. M. Thomas, J. Am. Chem. Soc. 2017, 139, 6217-6225

3. P. Marin, M. J.-L. Tschan, F. Isnard, C. Robert, P. Haquette, X. Trivelli, L.-M. Chamoreau, V. Guérineau, I. del Rosal, L. Maron, V. Venditto, C. M. Thomas, Angew. Chem. Int. Ed. 2019, 58, 12585-12589

4. D. Fiorito, M. Simon, C. M. Thomas, C. Mazet, J. Am. Chem. Soc. 2021, 143, 13401-13407

5. H. Fouilloux, W. Qiang, C. Robert, V. Placet, C. M. Thomas, Angew. Chem. Int. Ed. 2021, 60,19374-19382



Aminolytic Kinetic Resolution
ROP
X = O, NR
M = Al-Cl
M = Co

ParisTech

TITLE: REINFORCEMENT LEARNING-BASED TOPOLOGY-PRESERVING NON-RIGID DEFORMATION OF CAD MODELS FROM POINT CLOUDS FOR FIRST-TIME-RIGHT PRODUCTION IN SMART MANUFACTURING

Topic number* : *2024_030

Field : Design, Industrialization - Information and Communication Science and Technology - Mathematics and their applications

Subfield: Computer science, geometric modeling, computer-aided design

ParisTech School: Arts et Métiers
Research team : System engineering and digital representations
Research team website: https://lispen.artsetmetiers.fr/node/17
Research lab: LISPEN - Laboratoire d'ingénierie des systèmes physiques et numériques
Lab location: Aix-en-Provence
Lab website: https://lispen.artsetmetiers.fr

Contact point for this topic: PERNOT Jean-Philippe / jean-philippe.pernot@ensam.eu

Advisor 1: Jean-Philippe PERNOT - jean-philippe.pernot@ensam.eu
Advisor 2: Arnaud POLETTE - arnaud.polette@ensam.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
This PhD program addresses the way CAD models can be adapted and deformed to capture the manufacturing defaults and thus maintain the coherence between the digital model and its physical and manufactured counterpart. This is particularly useful to optimize tool paths and manufacturing parameters. New deformation operators will be developed to simulate and reproduce various state-of-the-art manufacturing behaviors and deviations, including free-form and non-rigid deformations. Those operators will be applied until the deviation between the CAD model and the acquired point cloud of the manufactured counterpart is minimized. During the deformation process, the topology of the CAD models will be preserved, to be able to maintain the whole coherency and

possibly available semantic information. Based on these newly defined capabilities, it will also be possible to deform CAD models a priori, i.e. without any point cloud to serve as a reference and prior to the start of the manufacturing process or before a new manufacturing step, in order to compensate for future deviations and allow for first-time-right production. This will be made possible thanks to the use of a reinforcement learning strategy, wherein an autonomous agent will learn how to define the deformation sequence to be applied to compensate the coming shape deviations between the theoretical model and its manufactured counterpart. Following this strategy, it will therefore be possible to mix both known rules coming from existing machine fault modeling theories, as well as unknown rules to be learned from experience. The proposed framework will be implemented and validated on academic as well as industrial examples.

Required background of the student:
Computer science, geometric modeling, computer-aided design.

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Peuzin-Jubert M., Polette A., Nozais D., Mari J-L., Pernot J-P., Survey on the View Planning Problem for reverse engineering and automated control applications, Computer-Aided Design, vol. 141, 103094, 2021.

2. Shah G. A., Polette A., Pernot J-P., Giannini F., Monti M., Simulated annealing-based fitting of CAD models to point clouds of mechanical parts’ assemblies, Engineering with Computers, vol. 37(4), pp. 2891-2909, 2021.

3. Hu S., Polette A., Pernot J-P., SMA-Net: Deep learning-based identification and fitting of CAD models from point clouds, Engineering with Computers, vol. 38, pp. 5467-5488, 2022.

4. Zhang C., Pinquié R., Polette A., Carasi G., De Charnace H., Pernot J-P., Automatic 3D CAD models reconstruction from 2D orthographic drawings, Computers & Graphics, vol. 114, pp. 179-189, 2023.

5. Zhang C., Pinquié R., Polette A., Carasi G., De Charnace H., Pernot J-P., eCAD-Net: editable parametric CAD models reconstruction from dumb B-Rep models using deep neural networks », Computer-Aided Design, vol. 178, 2025.

TITLE: REINFORCEMENT LEARNING-BASED 3D RECONSTRUCTION OF CAD MODELS FROM POINT CLOUDS FOR SMART MANUFACTURING APPLICATIONS

Topic number : ***2024_031***

Field : Design, Industrialization - Information and Communication Science and Technology - Mathematics and their applications

Subfield: Computer science, geometric modeling, computer-aided design

ParisTech School: Arts et Métiers
Research team : System engineering and digital representations
Research team website: https://lispen.artsetmetiers.fr/node/17
Research lab: LISPEN - Laboratoire d'ingénierie des systèmes physiques et numériques
Lab location: Aix-en-Provence
Lab website: https://lispen.artsetmetiers.fr

Contact point for this topic: PERNOT Jean-Philippe / jean-philippe.pernot@ensam.eu

Advisor 1: Jean-Philippe PERNOT - jean-philippe.pernot@ensam.eu
Advisor 2: Arnaud POLETTE - arnaud.polette@ensam.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
This PhD program addresses the way CAD models can be reverse engineered from point clouds to discover the possible building trees from which they may originate, and more precisely the ones adapted for smart manufacturing applications. Such an approach is particularly interesting to define the bill of operations adapted to a given manufacturing process, but also to automatically generate the set of CAD models associated to the manufacturing steps. Indeed, being able to compare the CAD model at a given step to its manufactured and digitized counterpart is of major interest for control purposes and process optimization in the context of the Industry 4.0. The main idea relies in the use of reinforcement learning able to learn how to perform those complex tasks in a very efficient way, and without requiring large databases. Starting from state-of-the-art and

known geometric and manufacturing rules to be established with the environment, an autonomous agent will learn the different actions to be applied at the feature level to move towards the next steps, with a known final objective that is the point cloud used as input of the algorithm. This singularity will be exploited to define the reward function to be optimized step after step. The proposed framework will be implemented and validated on academic as well as industrial examples.

Required background of the student:
Computer science, geometric modeling, computer-aided design

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Peuzin-Jubert M., Polette A., Nozais D., Mari J-L., Pernot J-P., Survey on the View Planning Problem for reverse engineering and automated control applications, Computer-Aided Design, vol. 141, 103094, 2021.
2. Shah G. A., Polette A., Pernot J-P., Giannini F., Monti M., Simulated annealing-based fitting of CAD models to point clouds of mechanical parts' assemblies, Engineering with Computers, vol. 37(4), pp. 2891-2909, 2021.
3. Hu S., Polette A., Pernot J-P., SMA-Net: Deep learning-based identification and fitting of CAD models from point clouds, Engineering with Computers, vol. 38, pp. 5467-5488, 2022.
4. Zhang C., Pinquié R., Polette A., Carasi G., De Charnace H., Pernot J-P., Automatic 3D CAD models reconstruction from 2D orthographic drawings, Computers & Graphics, vol. 114, pp. 179-189, 2023.
5. Zhang C., Pinquié R., Polette A., Carasi G., De Charnace H., Pernot J-P., eCAD-Net: editable parametric CAD models reconstruction from dumb B-Rep models using deep neural networks », Computer-Aided Design, vol. 178, 2025.

TITLE: MECHANOCHEMICAL SYNTHESIS OF SINGLE ATOM CATALYSTS AND APPLICATION IN SUSTAINABLE SYNTHESIS OF FINE CHEMICALS - BATCH VS CONTINUOUS FLOW

Topic number : ***2024_032***

Field : Chemistry, Physical chemistry and Chemical Engineering - Material science, Mechanics and Fluids

Subfield:

ParisTech School: Chimie ParisTech - PSL
Research team : SCiFLOW
Research team website: https://www.lenresearch.com
Research lab: I-CLEHS - Institute of chemistry for life and health
Lab location: Paris
Lab website: https://www.chimieparistech.psl.eu/recherche/les-laboratoires/i-clehs/

Contact point for this topic: LEN - Christophe - christophe.len@chimieparistech.psl.eu

Advisor 1: Christophe LEN - christophe.len@chimieparistech.psl.eu
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Recent advances in green chemistry and sustainable development have included heterogeneous catalysis,1,2 and alternative technologies such as continuous flow and ball milling.3 In heterogeneous catalysis, the size of the metal particles has a significant impact on catalytic performance. Smaller particles, with more weakly coordinated atoms, improve activity, but are confronted with size inhomogeneity and aggregation problems. To overcome these drawbacks, mechanochemical synthesis of single atom catalysts (SACs) has become a hot area of research in sub-nanoscale fabrication and heterogeneous catalysis.4,5 However, it should be noted that SACs have never been synthesised in a continuous mechanochemical flow. In this project, we envisage to produce novel non-noble metal SACS

(such as Fe, Ni, Co, Mn, Cu, Sn, and Zn) based on biomass support (such as humin, sporopollenin, biochar) in mechanochemistry using either ball mill (batch reactor) or Impact Continuous Heated Mechanochemical equipment – ICHEM (flow reactor). The SACs obtained will be tested in heterogeneous catalysis on model reactions mastered in the laboratory for the synthesis of molecules with a high industrial impact.

Required background of the student:

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. R. Radjagobalou, V. Rouffeteau, A. Deleu, P. Nabokoff, J. Cossy, C. Len. Continuous flow reductive alkylation of methanol by aldehydes. Synthesis of O-methyl ethers and 1,1-dimethoxyacetals. Mol. Catal. 2022, 524, 112321.

2. M.E. Medina Ruiz, R. Maderuelo-Solera, C.P. Jimenez-Gomez, R. Moreno-Tost, I. Malpartida, C. Garcia-Sancho, J.A. Cecilia, C. Len, J.M. Merida-Robles, P. Maireles-Torres. Supported palladium catalysts for the selective hydrogenation of furfural with polymethylhydrosiloxane. ACS Sustainable Chem. Eng. 2024. DOI: 10.1021/acssuschemeng.4c06333

3. C. Len, V. Duhan, W. Ouyang, R. Nguyen, B. Lochab. Mechanochemistry and oleochemistry: a green combination for the production of high-value small chemicals. Front. Chem. 2023, 11, 1306182.

4. S.K. Kaiser, Z. Chen, D.F. Akl, S. Mitchell, J. Perez-Ramirez. Single-atom catalysts across the Periodic Table. Chem. Rev. 2020, 120, 11703-11809.

5. V.B. Saptal, V. Ruta, M.A. Bajada, G. Vile. Single-Atom catalysis in organic synthesis. Angew. Chem. Int. Ed. 2023, 62, e202219306.

TITLE: DEVELOPING AI-ENHANCED SERIOUS GAMES FOR TEACHING SMART AND CONNECTED PRODUCT DESIGN

Topic number : ***2024_033***

Field : Design, Industrialization - Information and Communication Science and Technology

Subfield: Innovation, Design Science, AI, Serious Game, Smart and Connected Product

ParisTech School: Arts et Métiers
Research team :
Research team website:
Research lab: LCPI - Laboratoire conception de produits et innovation
Lab location: Chalon-sur-Saône
Lab website: https://lcpi.ensam.eu

Contact point for this topic: camille.jean@ensam.eu

Advisor 1: Camille JEAN - camille.jean@ensam.eu
Advisor 2: Ruding LOU - ruding.lou@ensam.eu
Advisor 3: Frédéric SEGONDS - frederic.segonds@ensam.eu
Advisor 4:

Short description of possible research topics for a PhD:
Design and innovation are necessary for companies to succeed in a globalized and competitive world. With the rapid development of digital technologies, forecasts on product development predict that smart and connected products will keep on growing fast. One of the key issues for companies lies in employing engineers and designers that understand the full technique of design and innovation of those product as well as continuously train those already hired. Serious games are one solution to develop skills and teach product design in a ludic way. Their usage is frequent as they can improve enjoyment, passionate involvement, structure, and social interaction while the learning takes place. AI can be used within serious games to adapt learning pathways based on individual player performance, making the experience more personalized and effective. AI can also analyze player behaviors, suggest

improvements, and offer real-time feedback, fostering an optimized learning environment. However, very few serious games tackle the subject of smart and connected product design. This thesis aims at proposing a method to develop AI-enhanced serious games for teaching smart and connected product design. Application of this method will lead to the creation of one or more physical or digital serious games for teaching smart and connected product design. The last technologies of Virtual and Augmented Reality could be used. The learning competences of the serious games created have to integrate the themes of smart and connected product design, AI, sensors integration and user experience. A robust evaluation of the serious games created will have to be carried out to validate the principles, heuristics and recommendations formulated.

Required background of the student:
Engineering student interested in optimizing the product design process

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. BRIARD, T., JEAN, C., AOUSSAT, A. & VERON, P. 2024. Sensors capabilities as a creativity tool for engineering product design. Journal of Engineering Design 145 https://doi.org/10.1080/09544828.2024.2333195
2. LI, B., SEGONDS, F., MATEEV, C., LOU, R., MERIENNE, F. (2018). Design in context of use: An experiment with a multi-view and multi-representation system for collaborative design, Computers in Industry, 103: 28 - 37, 2018. https://doi.org/10.1016/j.compind.2018.09.006
3. MA, Y., VALLET, F., CLUZEL, F., & YANNOU, B. (2019). Analyzing the Relevance of Serious Game Elements for Effectively Teaching Innovation Processes. Proceedings of the Design Society: International Conference on Engineering Design, 1(1), 439-448. https://doi:10.1017/dsi.2019.47
4. PHAM VAN, L., JEAN, C., MEYRUEIS, V., GAZO, C., MANTELET, F., GUEGUAN, J., BUISINE, S. & SEGONDS, F. 2022 IdeAM Running Quiz: A Digital Learning Game to Enhance Additive Manufacturing Opportunities Discovery. International Journal of Emerging Technologies in Learning (iJET), 17(10), pp. 32–50. https://doi.org/10.3991/ijet.v17i10.25695
5. ISAKSSON, O., ECKERT, C., (2020). Product Development 2040. The Design Society.
https://doi.org/10.35199/report.pd2040

CSC PhD Scholarships

Developing AI-Enhanced Serious Games for Teaching Smart and Connected Product Design

Keywords: Innovation, Design Science, AI, Serious Game, Smart and Connected Product

Design and innovation are necessary for companies to succeed in a globalized and competitive world. With the rapid development of digital technologies, forecasts on product development predict that **smart and connected products** will keep on growing fast (ISAKSSON et al., 2020; BRIARD et al., 2021). One of the key issues for companies lies in employing engineers and designers that understand the full technique of design and innovation of those product as well as continuously train those already hired.

Serious games are one solution to develop skills and teach product design in a ludic way (MA et al., 2019). Their usage is frequent as they can improve enjoyment, passionate involvement, structure, and social interaction while the learning takes place. AI can be used within serious games to adapt learning pathways based on individual player performance, making the experience more personalized and effective. AI can also analyze player behaviors, suggest improvements, and offer real-time feedback, fostering an optimized learning environment.

However, very few serious games tackle the subject of smart and connected product design. This thesis aims at **proposing a method to develop AI-enhanced serious games for teaching smart and connected product design.**

Application of this method will lead to the creation of one or more physical or digital serious games for teaching smart and connected product design. The last technologies of Virtual and Augmented Reality could be used (LI et al., 2018; PHAM VAN et al., 2022). The learning competences of the serious games created have to integrate the themes of smart and connected product design, AI, sensors integration and user experience. A robust evaluation of the serious games created will have to be carried out to validate the principles, heuristics and recommendations formulated.

The research will be divided into three main phases:

- **State of the art**: The first year will be devoted to the development of a state of the art on the existing methodologies for the design of smart and connected product, AI, and serious games. Following this work, specifications will be formulated, and hypotheses of resolutions proposed. At the end of this first year, a detailed schedule of experiments will be defined.
- **Proposal of a tooled methodology and experiments:** The second and third year will be devoted to experiments. The objective is to test, but above all to strengthen and validate the proposals. The methodology, tools and recommendations will be perfected by iteration, as experiments and conclusions can be drawn.
- **Formalization of research advances**: The last year will aim to synthesize all the work carried out to get an optimal proposition adapted to the context of the thesis.

References:

- BRIARD, T., JEAN, C., AOUSSAT, A. & VERON, P. 2024. Sensors capabilities as a creativity tool for engineering product design. Journal of Engineering Design 145 https://doi.org/10.1080/09544828.2024.2333195
- LI, B., SEGONDS, F., MATEEV, C., LOU, R., MERIENNE, F. (2018). Design in context of use: An experiment with a multi-view and multi-representation system for collaborative design, Computers in Industry, 103: 28 - 37, 2018. https://doi.org/10.1016/j.compind.2018.09.006
- MA, Y., VALLET, F., CLUZEL, F., & YANNOU, B. (2019). Analyzing the Relevance of Serious Game Elements for Effectively Teaching Innovation Processes. *Proceedings of the Design Society: International Conference on Engineering Design, 1*(1), 439-448. https://doi:10.1017/dsi.2019.47
- PHAM VAN, L., JEAN, C., MEYRUEIS, V., GAZO, C., MANTELET, F., GUEGUAN, J., BUISINE, S. & SEGONDS, F. 2022 IdeAM Running Quiz: A Digital Learning Game to Enhance Additive Manufacturing Opportunities Discovery. *International Journal of Emerging Technologies in Learning (iJET),* 17(10), pp. 32–50. https://doi.org/10.3991/ijet.v17i10.25695
- ISAKSSON, O., ECKERT, C., (2020). Product Development 2040. The Design Society. https://doi.org/10.35199/report.pd2040

ParisTech

TITLE: OPTIMIZATION OF FILLING STAGE DURING CASTING PROCESS USING ARTIFICIAL INTELLIGENCE

Topic number* : *2024_034

Field : Material science, Mechanics and Fluids

Subfield: Numerical methods, FE simulation

ParisTech School: Arts et Métiers
Research team :
Research team website:
Research lab: LAMPA - Laboratoire angevin de mécanique, procédés et innovation
Lab location: Angers
Lab website: https://lampa.ensam.eu/

Contact point for this topic: BEN SAADA Mariem
mariembensaada@ensam.eu

Advisor 1: Amine AMMAR - amine.ammar@ensam.eu
Advisor 2: Mariem BEN SAADA - mariem.bensaada@ensam.eu
Advisor 3: MARIE BEDEL - marie.bedel@ensam.eu
Advisor 4:

Short description of possible research topics for a PhD:
Filling is a critical stage of casting as it directly impacts the final mechanical quality of the cast part. Indeed, if a mold cavity is filled too slowly, the metal solidifies before filling completion, inducing misrun defects. On the other hand, when filling too fast, the turbulent flow leads to oxide entrapment and mold erosion (1). In order to avoid those critical defects, an appropriate filling system has to be designed. Such design rules currently exist only for gravity casting, and are based on a very simplified approach, where a filling system is made of a sprue, runners and ingates whose dimensions are given by empirical expressions (2). If those standard design rules permit to avoid misrun defect, fluid flow is always turbulent in the filling system (3), thus systematically inducing oxides in the cast parts. Some recent studies proposed filling system optimization by using Machine Learning (ML) methods (4). However, only

the dimensions of a fixed filling system were optimized (5,6). Reconsideration of filling system design in itself is still hardly considered (7). To our best knowledge, such a design reconsideration has never been performed by using ML based algorithms without geometrical constrains. However, the revolution of sand printing technology makes the geometrical constrains associated with mold making totally outdated. When considering this new technology, innovative and much more optimized filling system design rules can be developed, by considering only thermal and fluid flow constrains. Today, foundry engineers can predict the cast products characteristics without having to perform numerous time-consuming trial-and-error experiments. It is hence possible nowadays in metal casting processes to apply powerful tools and models developed with reasonable number of simulations that allows predicting parts defects and controlling complex processes (8). On the other hand, approaches combining physics based reduced order models were recently developed, enabling parametric studies, and data-driven model enrichment in the so-called hybrid modelling framework. A high accuracy is obtained with respect to the experimental measurements, while proceeding under the stringent real-time constraint (9). Therefore, in this PhD study, these approaches could be extended and enriched with Generative Design approach to optimize the filling stage of casting. To do so, an adapted casting software will be used, which combines fluid flow dynamic and heat transfer, to study the impact of different parameters on head loss during filling; mold design, mold surface condition, metal viscosity or casting speed will be considered. Then the generated numerical data will be used to develop a predictive model of head loss by using hybrid physical-data driven techniques via Machine-Learning (ML) technologies and their integration into the detailed analytical and numerical modellings. Such a model will then be used to optimize filling system design, therefore optimizing filling speed and flow rate while mastering casting yield and associated heat loss. The newly proposed design rules for filling systems will be eventually validated by experimental comparison, performed on the foundry facility of LAMPA laboratory, on both standard and optimized designs.

Required background of the student:
Continum Mechanics, Numerical methods, FE simulation

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. 1. Bedel M, Sanitas A, El Mansori M. Geometrical effects on filling dynamics in low pressure casting of light alloys. Journal of Manufacturing Processes. 1 sept 2019;45:194-207.

2. 2. Campbell J. Complete Casting Handbook: Metal Casting Processes, Metallurgy, Techniques and Design. Butterworth-Heinemann; 2015. 1055 p.

3. 3. Cross M, McBride D, Croft TN, Williams AJ, Pericleous K, Lawrence JA. Computational modeling of mold filling and related free-surface flows in shape casting: An overview of the challenges involved. Metall Mater Trans B. 1 déc 2006;37(6):879-85.
4. 4. Ambekar SA, S.B.Jaju. A review on optimization of gating system for reducing defect. International Journal of Engineering Research and General Science. 2014;2(1):93-8.
5. 9. Ammar, A., Ben Saada, M., Cueto, E. et al. Casting hybrid twin: physics-based reduced order models enriched with data-driven models enabling the highest accuracy in real-time. Int J Mater Form 17, 16 (2024).

Research topic for the Paristech/CSC PhD program

Field: Materials Science, mechanical engineering, forming process, AI

Subfield: Numerical methods, FE simulation

Title: Optimization of filling stage during casting process using Artificial Intelligence

Key words*:* Casting process, Artificial Intelligence, Machine-Learning, Data-driving

ParisTech School: Arts et Métiers Sciences et Technologies

Advisor(s) Name: Amine AMMAR, Mariem BEN SAADA and Marie BEDEL

Advisor(s) Email: amine.ammar@ensam.eu , mariem.bensaada@ensam.eu , marie.bedel@ensam.eu

Research group/Lab: LAMPA laboratory/ EA 1427

Lab location: Angers, France

(Lab/Advisor website): https://lampa.ensam.eu/

Short description of possible research topics for a PhD: (10-15 lines in English + optional figure)

Filling is a critical stage of casting as it directly impacts the final mechanical quality of the cast part. Indeed, if a mold cavity is filled too slowly, the metal solidifies before filling completion, inducing misrun defects. On the other hand, when filling too fast, the turbulent flow leads to oxide entrapment and mold erosion (1). In order to avoid those critical defects, an appropriate filling system has to be designed. Such design rules currently exist only for gravity casting, and are based on a very simplified approach, where a filling system is made of a sprue, runners and ingates whose dimensions are given by empirical expressions (2). If those standard design rules permit to avoid misrun defect, fluid flow is always turbulent in the filling system (3), thus systematically inducing oxides in the cast parts. Some recent studies proposed filling system optimization by using Machine Learning (ML) methods (4). However, only the dimensions of a fixed filling system were optimized (5,6). Reconsideration of filling system design in itself is still hardly considered (7). To our best knowledge, such a design reconsideration has never been performed by using ML based algorithms without geometrical constrains. However, the revolution of sand printing technology makes the geometrical constrains associated with mold making totally outdated. When considering this new technology, innovative and much more optimized filling system design rules can be developed, by considering only thermal and fluid flow constrains. Today, foundry engineers can predict the cast products characteristics without having to perform numerous time-consuming trial-and-error experiments. It is hence possible nowadays in metal casting processes to apply powerful tools and models developed with reasonable number of simulations that allows predicting parts defects and controlling complex processes (8). On the other hand, approaches combining physics based reduced order models were recently developed, enabling parametric studies, and data-driven model enrichment in the so-called hybrid modelling framework. A high accuracy is obtained with respect to the experimental measurements, while proceeding under the stringent real-time constraint (9).

Therefore, in this PhD study, these approaches could be extended and enriched with Generative Design approach to optimize the filling stage of casting. To do so, an adapted casting software will be used, which combines fluid flow dynamic and heat transfer, to study the impact of different parameters on head loss during filling; mold design, mold surface condition, metal viscosity or casting speed will be considered. Then the generated numerical data will be used to develop a predictive model of head loss by using hybrid physical-data driven techniques via Machine-Learning (ML) technologies and their integration into the detailed analytical and numerical modellings. Such a model will then be used to optimize filling system design, therefore optimizing filling speed and flow rate while mastering casting yield and associated heat loss. The newly proposed design rules for filling systems will be eventually validated by experimental comparison, performed on the foundry facility of LAMPA laboratory, on both standard and optimized designs.

Required background of the student: (What should be the main field of study of the applicant before applying?)

Continum Mechanics, Numerical methods, FE simulation

A list of 5 (max.) representative publications of the group: (Related to the research topic)

1. Bedel M, Sanitas A, El Mansori M. Geometrical effects on filling dynamics in low pressure casting of light alloys. Journal of Manufacturing Processes. 1 sept 2019;45:194-207.

2. Campbell J. Complete Casting Handbook: Metal Casting Processes, Metallurgy, Techniques and Design. Butterworth-Heinemann; 2015. 1055 p.

3. Cross M, McBride D, Croft TN, Williams AJ, Pericleous K, Lawrence JA. Computational modeling of mold filling and related free-surface flows in shape casting: An overview of the challenges involved. Metall Mater Trans B. 1 déc 2006;37(6):879-85.

4. Ambekar SA, S.B.Jaju. A review on optimization of gating system for reducing defect. International Journal of Engineering Research and General Science. 2014;2(1):93-8.

5. He B, Lei Y, Jiang M, Wang F. Optimal Design of the Gating and Riser System for Complex Casting Using an Evolutionary Algorithm. Materials. janv 2022;15(21):7490.

6. Ktari A, El Mansori M. On the improvement of castings quality in hybrid low-pressure sand-casting (LPSC) process in a fully integrated CAE environment. Int J Adv Manuf Technol. juill 2023;127(5-6):2309-26.

7. Sama SR, Badamo T, Lynch P, Manogharan G. Novel sprue designs in metal casting via 3D sand-printing. Additive Manufacturing. 2019;25:563-78.

8. Nouri M, Artozoul J, Caillaud A, Ammar A, Chinesta F, Köser O (2022) Shrinkage porosity prediction empowered by physics-based and data-driven hybrid models. Int J Mater Form 15(3).

9. Ammar, A., Ben Saada, M., Cueto, E. et al. Casting hybrid twin: physics-based reduced order models enriched with data-driven models enabling the highest accuracy in real-time. Int J Mater Form 17, 16 (2024).

Title: PHOTONIC CRYSTALS WITH STIMULI-RESPONSIVE HYDROGELS

Topic number : ***2024_035***

Field : Chemistry, Physical chemistry and Chemical Engineering - Physics, Optics - Material science, Mechanics and Fluids

Subfield:

ParisTech School: ESPCI Paris - PSL
Research team : Soft Polymer Networks
Research team website:
Research lab: SIMM - Sciences et ingénierie de la matière molle
Lab location: Paris
Lab website: https://www.simm.espci.fr

Contact point for this topic: yvette.tran@espci.fr

Advisor 1: Yvette TRAN - yvette.tran@espci.fr
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Recent advances in micro- and nano-technologies present opportunities to control optical properties in a way that is not possible with the materials provided by nature. Additional performances in terms of modulability and switchability using soft technology by means of synthetic stimuli-responsive polymer hydrogels could offer unprecedented enhanced devices. The general idea of the thesis is to develop photonic crystals with switchable properties based on a fine control of the architecture of stimuli-responsive hydrogels. Photonic crystals with high spectral shift will be designed thanks to the platform of nano- to micro-structures of temperature-responsive hydrogels developed in our group. Colloidal crystals will be obtained through the organized close-packing of polymer colloids which characteristics (size, distance…) can be finely adjusted. Two different strategies will be used to add thermo-responsive properties. (i) The direct approach consists of coating PNIPAM

responsive hydrogel nanoparticles. (ii) The indirect approach consists of first coating polystyrene PS nanoparticles molds and then infiltrating the empty space with PNIPAM hydrogel matrix. The polymer nanoparticles can also be enriched with metallic gold to increase the optical contrast. The swelling-collapse of responsive hydrogel allows the reversible change of photonic crystals periodicity. The thesis includes the synthesis of (PS and PNIPAM) polymer colloids, the synthesis of functionalized PNIPAM precursors for hydrogel matrix elaboration and the fabrication of responsive photonic crystals by coating and infiltration techniques. The structure of photonic crystals will be finely characterized by various techniques available in ESPCI (DLS, ESEM, ETEM, ellipsometry, AFM). They will also be characterized by large instruments techniques such as X-ray reflectivity and GISAXS at SOLEIL synchrotron. The devices will be investigated for applications in optics.

Required background of the student:
Primary background in materials science and chemical engineering

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Martwong, E.; Tran, Y. Lower Critical Solution Temperature phase transition of poly(PEGMA) hydrogel films. Langmuir 2021, 37, 8585-8593

2. Dompé, M.; Cedano Serrano, F. J.; Heckert O.; Tran, Y.; Hourdet, D.; Van den Heuvel, N.; Van der Gucht, J.; Creton, C.; Kamperman, M. Thermoresponsive Complex Coacervate-Based Underwater Adhesive. Adv. Mater. 2019, 31, 1808179

3. D’Eramo, L.; Chollet, B.; Leman, M.; Martwong, E.; Li, M.; Geisler, H.; Dupire, J.; Kerdraon, M.; Vergne, C.; Monti, F.; Tran, Y.; Tabeling, P. Microfluidic actuators based on thermo-responsive hydrogels. Nature Microsyst. Nanoeng. 2018, 4, 17069

4. Chollet, B.; Li, M.; Martwong, E.; Bresson, B.; Fretigny, C.; Tabeling, P.; Tran, Y. Multiscale surface-attached hydrogel thin films with tailored architecture. ACS Appl. Mat. Interfaces 2016, 8, 11729-11738

5. Li, M.; Bresson, B.; Fretigny, C.; Cousin, F.; Tran, Y. Submicrometric films of surface-attached polymer networks: temperature-responsive properties. Langmuir 2015, 31, 11516-11524

TITLE: PHOTONIC CRYSTALS WITH STIMULI-RESPONSIVE HYDROGELS

Field: Material science, Polymer science, Physical chemistry, Chemical engineering

ParisTech School: ESPCI Paris – PSL

Research team: Soft Polymer Networks

Research lab: Soft Matter Sciences and Engineering
Sciences et Ingénierie de la Matière Molle

Lab location: 10, rue Vauquelin. 75005 Paris. FRANCE

Lab website: https://www.simm.espci.fr

Contact point for this topic: ESPCI Paris – PSL

Advisor 1: Yvette Tran - yvette.tran@espci.psl.eu - https://blog.espci.fr/yvettetran/

Short description of possible research topics for a PhD:

Recent advances in micro- and nano-technologies present opportunities to control optical properties in a way that is not possible with the materials provided by nature. Additional performances in terms of modulability and switchability using soft technology by means of synthetic stimuli-responsive polymer hydrogels could offer unprecedented enhanced devices.

The general idea of the thesis is to develop photonic crystals with switchable properties based on a fine control of the architecture of stimuli-responsive hydrogels. Photonic crystals with high spectral shift will be designed thanks to a platform of nano- to micro-structures of temperature-responsive hydrogels developed in our group. Colloidal crystals will be obtained through the organized close-packing of polymer colloids which characteristics (size, distance…) can be finely adjusted. Two different strategies will be used to add thermo-responsive properties. (i) The direct approach consists of coating PNIPAM responsive hydrogel nanoparticles. (ii) The indirect approach consists of first coating polystyrene PS nanoparticles molds and then infiltrating the empty space with PNIPAM hydrogel matrix. The polymer nanoparticles can also be enriched with metallic gold to increase the optical contrast. The swelling-collapse of PNIPAM responsive hydrogel allows the reversible change of photonic crystals periodicity.

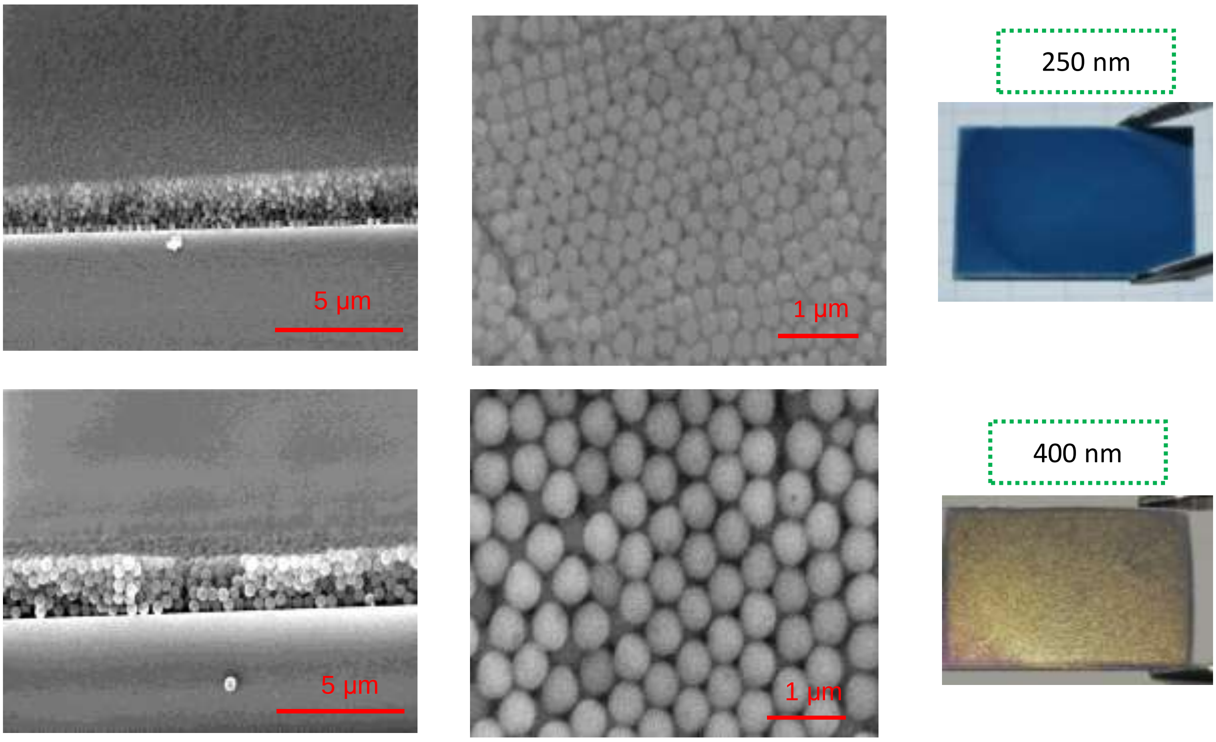
The thesis includes the synthesis of (PS and PNIPAM) polymer colloids, the synthesis of functionalized PNIPAM precursors for hydrogel matrix elaboration and the fabrication of responsive photonic crystals by coating and infiltration techniques. The structure of photonic crystals will be finely characterized by various techniques available in ESPCI (DLS, ESEM, ETEM, ellipsometry, AFM). They will also be characterized by large instruments techniques such as X-ray reflectivity and GISAXS at SOLEIL synchrotron. The devices will be investigated for applications in optics.

Required background of the student: Primary background in materials science and chemical engineering.

A list of 5 (max.) representative publications of the group: (Related to the research topic)

1. Li, M.; Bresson, B.; Fretigny, C.; Cousin, F.; Tran, Y. Submicrometric films of surface-attached polymer networks: temperature-responsive properties. Langmuir 2015, 31, 11516-11524.
2. Chollet, B.; Li, M.; Martwong, E.; Bresson, B.; Fretigny, C.; Tabeling, P.; Tran, Y. Multiscale surface-attached hydrogel thin films with tailored architecture. ACS Appl. Mat. Interfaces 2016, 8, 11729-11738 (front cover).
3. D'Eramo, L.; Chollet, B.; Leman, M.; Martwong, E.; Li, M.; Geisler, H.; Dupire, J.; Kerdraon, M.; Vergne, C.; Monti, F.; Tran, Y.; Tabeling, P. Microfluidic actuators based on thermo-responsive hydrogels. Nature Microsyst. Nanoeng. 2018, 4, 17069.
4. Dompé, M.; Cedano Serrano, F. J.; Heckert O.; Tran, Y.; Hourdet, D.; Van den Heuvel, N.; Van der Gucht, J.; Creton, C.; Kamperman, M. Thermoresponsive Complex Coacervate-Based Underwater Adhesive. Adv. Mater. 2019, 31, 1808179.
5. Martwong, E.; Tran, Y. Lower Critical Solution Temperature phase transition of poly(PEGMA) hydrogel films. Langmuir 2021, 37, 8585-8593.

Illustrations



Figures: SEM images of close-packed polystyrene colloids coatings (left: side view, middle: top view). The optical properties can be finely adjusted with the size of PS colloids (top line: 250 nm, bottom line: 400 nm) as shown by the pictures shown on right.

ParisTech

TITLE: PHYSICAL MODELING OF LOW-PRESSURE CASTING OF LIGHT ALLOYS IN 3D PRINTED MOLDS AND INDUSTRIAL SCALE EXPERIMENTAL VALIDATION

Topic number : ***2024_037***

Field : Energy, Processes - Material science, Mechanics and Fluids

Subfield:

ParisTech School: Arts et Métiers
Research team :
Research team website:
Research lab: MSMP - Laboratoire Mécanique, Surface, Matériaux et Procédés
Lab location: Aix-en-Provence
Lab website: msmp.eu

Contact point for this topic: nan KANG, nan.kang@ensam.eu

Advisor 1: Mohamed El Mansori - mohamed.elmansori@ensam.eu
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Low Pressure Casting (LPC) is widely used due to its high automation and precise control of casting parameters, producing high-quality parts. While typically used with metallic molds, LPC’s application with sand molds enhances the quality of engine blocks. To ensure defect-free castings, controlling the dynamics of filling and solidification is crucial. Poor filling can cause oxide formation or misrun, and incorrect solidification can lead to shrinkage porosity. In LPC, the flow is managed through pressure control, and factors such as casting temperature, alloy properties, part geometry, and pressure settings directly influence flow quality. During solidification, applying overpressure allows liquid metal to feed the part, preventing porosity. 3D printing of molds enables optimized designs for filling systems and risers, although careful consideration is needed due to material anisotropy. Combining simulations with industrial-scale experiments can improve process optimization, ensuring better casting

quality. The MSMP lab is seeking a PhD candidate to model and experimentally validate LPC's filling and solidification dynamics, aiming to develop optimized design rules for filling systems and risers. The work will involve new case studies, real-time and post-mortem characterization, and numerical modeling using commercial software.

Required background of the student:

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Bonollo F, Urban J, Bonatto B, Botter M. Gravity and low pressure die casting of aluminium alloys: a technical and economical benchmark. La Metallurgia Italiana [Internet]. 3 juin 2005 [cité 16 mai 2024]; Disponible sur: https://www.fracturae.com/index.php/aim/article/view/610

2. dler FJ, Lagrené G, Siepe R. Thin-walled Mg Structural Parts by a Low-pressure Sand Casting Process. In: Magnesium Alloys and their Applications [Internet]. John Wiley & Sons, Ltd; 2000 [cité 16 mai 2024]. p. 553-7. Disponible sur: https://onlinelibrary.wiley.com/doi/abs/10.1002/3527607552.ch87

3. Bedel M, Sanitas A, El Mansori M. Geometrical effects on filling dynamics in low pressure casting of light alloys. Journal of Manufacturing Processes. 1 sept 2019;45:194-207.

4. Sanitas A, Coniglio N, bedel M, El Mansori M. Investigating surface roughness of ZE41 magnesium alloy cast by low-pressure sand casting process. International Journal of Advanced Manufacturing Technology. 2017;92(5-8):1883-91.

5. Bedel M, Fabre A, Coniglio N. Defining the printing direction impact of additively manufactured sand molds on casting roughness. Journal of Manufacturing Processes. 30 avr 2024;116:329-40.

Title: Generative AI for Complex Mechanical Systems Design – Technical and Educational Perspectives

Topic number : ***2024_038***

Field : Design, Industrialization - Mathematics and their applications - Information and Communication Science and Technology

Subfield:

ParisTech School: Arts et Métiers
Research team :
Research team website:
Research lab: LCFC - Laboratoire de conception, fabrication, commande
Lab location: Metz
Lab website: http://lcfc.ensam.eu/

Contact point for this topic: HOMRI - Lazhar - lazhar.homri@ensam.eu

Advisor 1: Lazhar HOMRI - lazhar.homri@ensam.eu
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
The effectiveness of artificial intelligence (AI) technology heavily depends on the availability of high-quality and extensive training data effective design of complex systems. To Overcome this issue, generative AI has greatly enhanced the production of digital content and has recently had a significant impact on the design activities. For designers, this means access to a tool that can produce innovative and optimized designs with speed and complexity that is unachievable by human efforts or experiences. Various tools and researches started working on the benefits of generative AI, mainly models based on generative adversarial networks (GANs) and various deep learning networks for achieving automated generative design and considering engineering performances. Input prompts can help to generate design concepts automatically and to meet with design constraints, without spending considerable time and effort. Generative AI is considered to be more user-friendly for designers

without programming training. The objective of this thesis project is to develop a practical methodology for integrating the generative AI into the design process of complex systems, with a focus on predicting their behavior considering engineering and education perspectives. By taking advantage of AI-derived knowledge, this methodology aims to streamline decision-making processes, optimize system performance and promote the creation of more innovative, efficient and sustainable design solutions in complex engineering environments.

Required background of the student:
Mechanical/ industrial Engineering (product design) Mathematics, Computer science, interest for eductional framwork

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Li, Y., Li, Y., Yan, W., Yang, F., and Ding, X. (2024) Advancing Design With Generative AI: A Case of Automotive Design Process Transformation, in Gray, C., Ciliotta Chehade, E., Hekkert, P., Forlano, L., Ciuccarelli, P., Lloyd, P. (eds.), DRS2024: Boston, 23–28 June, Boston, USA. https://doi.org/10.21606/drs.2024.1260.
2. Lu, P., Hsiao, S. W., Tang, J., & Wu, F. (2024). A generative-AI-based design methodology for car frontal forms design. Advanced Engineering Informatics, 62, 102835.
3. Zouhri, W., Homri, L., & Dantan, J. Y. (2022). Identification of the key manufacturing parameters impacting the prediction accuracy of support vector machine (SVM) model for quality assessment. International Journal on Interactive Design and Manufacturing (IJIDeM), 16(1), 177-196.
4. Bartlett, K. A., & Camba, J. D. (2024). Generative Artificial Intelligence in Product Design Education: Navigating Concerns of Originality and Ethics.
5. Gupta, P., Ding, B., Guan, C., & Ding, D. (2024). Generative AI: A systematic review using topic modelling techniques. Data and Information Management, 100066.

RESEARCH TOPIC FOR THE PARISTECH/CSC PHD PROGRAM

Field: Design, Industrialization

Subfield: Mechanical Eng., Industrial Eng., Process Eng.

Title: Generative AI for Complex Mechanical Systems Design – Technical and Educational Perspectives

ParisTech School: Arts et Métiers Sciences et Technologies

Advisor(s) Name: Lazhar HOMRI
Advisor(s) Email: *lazhar.homri@ensam.eu*
Research group/Lab: *LCFC*
Lab location: *Arts et Métiers Institute of Technology, Campus of Metz*
(Lab/Advisor website): *http://lcfc.ensam.eu/*

Short description of possible research topics for a PhD:

The effectiveness of artificial intelligence (AI) technology heavily depends on the availability of high-quality and extensive training data effective design of complex systems. To Overcome this issue, generative AI has greatly enhanced the production of digital content and has recently had a significant impact on the design activities. For designers, this means access to a tool that can produce innovative and optimized designs with speed and complexity that is unachievable by human efforts or experiences. Various tools and researches started working on the benefits of generative AI, mainly models based on generative adversarial networks (GANs) and various deep learning networks for achieving automated generative design and considering engineering performances. Input prompts can help to generate design concepts automatically and to meet with design constraints, without spending considerable time and effort. Generative AI is considered to be more user-friendly for designers without programming training.

The objective of this thesis project is to develop a practical methodology for integrating the generative AI into the design process of complex systems, with a focus on predicting their behavior considering engineering and education perspectives. By taking advantage of AI-derived knowledge, this methodology aims to streamline decision-making processes, optimize system performance and promote the creation of more innovative, efficient and sustainable design solutions in complex engineering environments.

Required background of the student: Mechanical/ industrial Engineering (product design) Mathematics, Computer science,

Key words: Generative AI, Design, Engineering, Education

A list of 5 (max.) representative publications of the group:

1. Li, Y., Li, Y., Yan, W., Yang, F., and Ding, X. (2024) Advancing Design With Generative AI: A Case of Automotive Design Process Transformation, in Gray, C., Ciliotta Chehade, E., Hekkert, P., Forlano, L., Ciuccarelli, P., Lloyd, P. (eds.), DRS2024: Boston, 23–28 June, Boston, USA. https://doi.org/10.21606/drs.2024.1260.
2. Lu, P., Hsiao, S. W., Tang, J., & Wu, F. (2024). A generative-AI-based design methodology for car frontal forms design. Advanced Engineering Informatics, 62, 102835.
3. Zouhri, W., Homri, L., & Dantan, J. Y. (2022). Identification of the key manufacturing parameters impacting the prediction accuracy of support vector machine (SVM) model for quality assessment. International Journal on Interactive Design and Manufacturing (IJIDeM), 16(1), 177-196.
4. Bartlett, K. A., & Camba, J. D. (2024). Generative Artificial Intelligence in Product Design Education: Navigating Concerns of Originality and Ethics.
5. Gupta, P., Ding, B., Guan, C., & Ding, D. (2024). Generative AI: A systematic review using topic modelling techniques. Data and Information Management, 100066.

TITLE: NATURAL FIBERS FOR SUSTAINABLE DEVELOPMENT: EXPERIMENTAL STUDY OF THE SURFACE ENERGY AND THE ADHESION PROPERTIES

Topic number* : *2024_039

Field : Energy, Processes

Subfield:

ParisTech School: Arts et Métiers
Research team : Porous Media
Research team website:
https://www.i2m.u-bordeaux.fr/Recherche/TREFLE-Transferts-Fluides-Energetique/Groupe-Milieux-Poreux
Research lab: I2M - Institut de Mécanique et d'ingénierie
Lab location: Bordeaux
Lab website: https://www.i2m.u-bordeaux.fr/

Contact point for this topic: BEN ABDELWAHED Amine amine.ben-abdelwahed@ensam.eu

Advisor 1: Azita AHMADI-SENICHAULT - azita.ahmadi@ensam.eu
Advisor 2: Amine BEN ABDELWAHED - amine.ben-abdelwahed@ensam.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
The use of natural fibers (wood fibers, Flax, Cotton, etc.) as bio-materials provides several advantages for eco-materials including eco-friendliness, flexibility, cost reduction, biogenic carbon storage and biodegradation. However, natural fibers are hydrophilic materials which are highly sensitive to humidity therefore highly prone to agglomeration. Consequently, a chemical treatment that improves dispersion, adhesion, and compatibility with the matrix fluid (polymeric in general) is recommended. However, wet chemical treatment contains several steps (fibers impregnation in an aqueous solution, drying and curing) generating significant effluents, energy consumption and toxic gas emission. The aim of this PHD Thesis is to study the influence of the

chemical composition of natural fibers on moisture sorption, water retention and thus, fiber surface energy. Surface energy composed of dispersive and polar parts is an important parameter for fiber and fluid matrix adhesion. Various experiments (Fig 1: Thermogravimetric analysis, Differential Scanning Calometry, Gas Chromatography and Fig 2: adhesion and capillary properties) for different fiber samples with different compositions and different chemical treatments will be conducted to evaluate the capillary and the adhesion properties. The final goal is to find a good accommodation between the adhesion properties and the fiber chemical treatment in order to decrease effluents and toxic gas emission .

Required background of the student:
A solid theoretical and experimental understanding of the fundamentals of fluid mechanics and material science would be appreciated.

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Liu S., Ahmadi-Senichault A., Ben Abdelwahed A., Yao H., Lachaud J. (2024). Experimental investigation and DEM-CFD analysis of Darcy–Forchheimer flows in randomly packed bed systems of wood particles. International Journal of Heat and Mass Transfer, Vol 235: 126229

2. Ben Abdelwahed A., Wielhorski Y., Bréard J. (2014). Bubble formation and transport in T-junction for application to Liquid Composite Molding. J. of Composite Materials, Vol 48: 37-48

3. Wielhorski Y., Ben Abdelwahed A., Bréard J. (2013). Theoretical Approach of Bubble Entrapment Through Interconnected Pores: Supplying Principle. Transport in Porous Media, Vol 96: 105-116

4. Wu J. et al (2024). Recent development and application of natural fiber in asphalt pavement. Journal of Cleaner Production 449, 141832

5. Müller K. et al (2017). Review on the processing and properties of polymer nanocomposites and nanocoatings and their applications in the packaging, automotive and solar energy fields. Nanomaterials 7:74

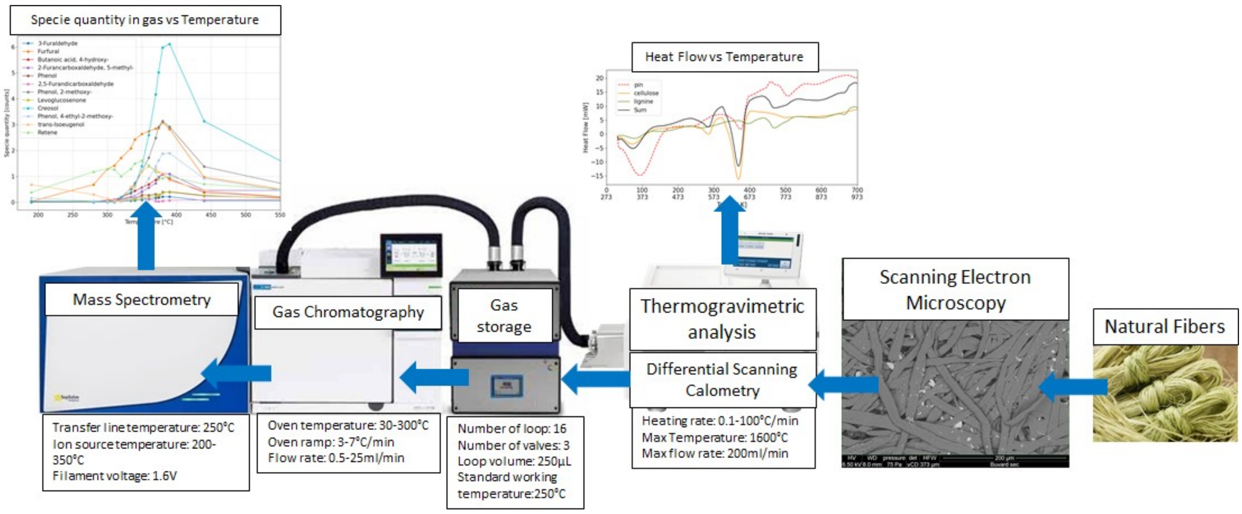


Figure 1. Experimental Setup used at I2M (Porous Media Team) to characterise the fiber chemical composition and the gas species

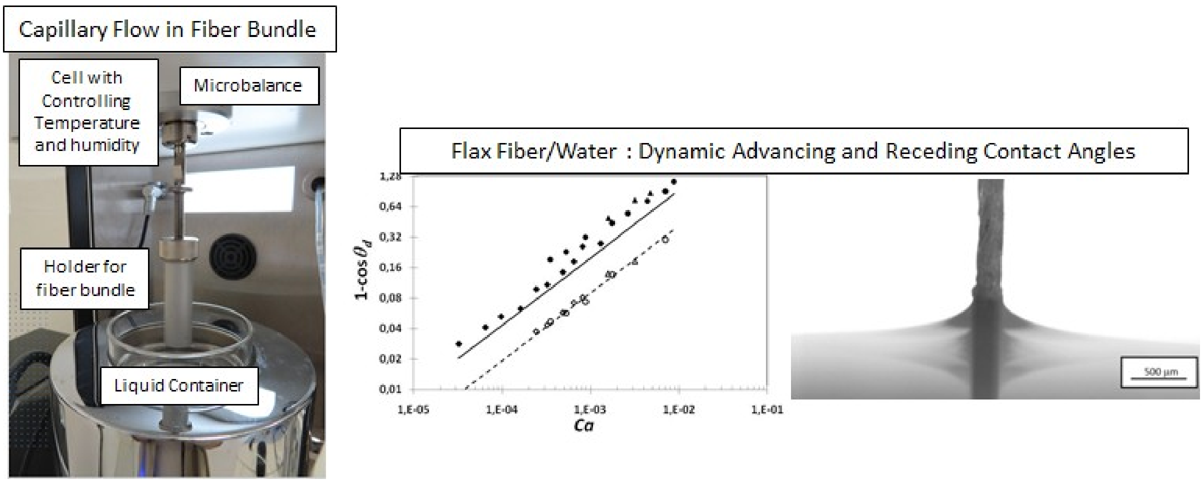


Figure 2. Experimental Setup used at I2M (Porous Media Team) to characterise: Fiber / liquid adhesion and capillary flow

TITLE: INVESTIGATIONS OF TWIP AND TRIP MECHANISMS IN ZR AND TI METASTABLE ALLOYS

Topic number : ***2024_040***

Field : Material science, Mechanics and Fluids

Subfield: TWIP TRIP alloys

ParisTech School: Chimie ParisTech - PSL
Research team : Métallurgie Structurale
Research team website:
Research lab: IRCP - Institut de Recherche de Chimie de Paris
Lab location: Paris
Lab website: https://www.ircp.cnrs.fr/en/chemistry-research-institute-of-paris/

Contact point for this topic: SUN Fan fan.sun@chimieparistech.psl.eu

Advisor 1: Fan Sun - fan.sun@chimieparistech.psl.eu
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
The phenomena of Twinning Induced Plasticity (TWIP) and Transformation Induced Plasticity (TRIP) play a crucial role in improving the mechanical properties of zirconium and titanium alloys. These alloys' metastable states enable the activation of twinning and martensitic transformations under external stress. The mechanical behavior of these alloys is influenced by factors such as the metastability of the beta phase, alloying elements, chemical composition, grain structure, secondary phase precipitation, and manufacturing and thermomechanical processes. Our recent studies have shown that the TWIP effect can be observed in various Zr and Ti alloy compositions with elements like Nb, Mo, and Sn. The interactions between dislocations and mechanical twinning significantly affect the alloys' macroscopic mechanical properties. This thesis aims to clarify the fundamental mechanisms behind these effects, which remain not fully understood.

Required background of the student:
Candidate should be last-year in master course or first-year PhD course during application
Master's degree in Material Science and Engineering or Metallic Materials
Background in electron microscopy and physical metallurgy
Proficient in English communication and writing
Competent in collaborative teamwork and project management

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Tang, J., Yang, H., Qian, B., Zheng, Y., Vermaut, P., Prima, F., & Sun, F. (2024). TWIP-assisted Zr alloys for medical applications : Design strategy , mechanical properties and first biocompatibility assessment. Journal of Materials Science & Technology, 184, 32–42. https://doi.org/10.1016/j.jmst.2023.09.051
2. Tang, Junhui; Zorgati, Ahmed; Gaillard, Jean-Baptiste; Vermaut, Philippe; Prima, Frédéric; Sun, F. (2023). Twinning-induced plasticity (TWIP) effect in multi-phase metastable beta Zr-Nb alloys. Journal of Materials Science & Technology, 139, 120–125. https://doi.org/https://doi.org/10.1016/j.jmst.2022.07.062
3. Qian, B., Mantri, S. A., Dasari, S., Zhang, J., Lilensten, L., Sun, F., Vermaut, P., Banerjee, R., & Prima, F. (2023). Mechanisms underlying enhanced strength-ductility combinations in TRIP/TWIP Ti-12Mo alloy engineered via isothermal omega precipitation. Acta Materialia, 245(September 2022). https://doi.org/10.1016/j.actamat.2022.118619
4. Qian, B., Yang, M., Lilensten, L., Vermaut, P., Sun, F., & Prima, F. (2022). In-situ observations of a hierarchical twinning–detwinning process in stress-induced α''-martensite of Ti-12Mo alloy. Materials Research Letters, 10(2), 45–51. https://doi.org/10.1080/21663831.2021.2013967
5. Tekoglu, E., Bae, J.-S., Kim, H.-A., Lim, K.-H., Liu, J., Doležal, T. D., Kim, S. Y., Alrizqi, M. A., Penn, A., Chen, W., Hart, A. J., Kang, J.-H., Oh, C.-S., Park, J., Sun, F., Kim, S., Sim, G.-D., & Li, J. (2024). Superior high-temperature mechanical properties and microstructural features of LPBF-

printed In625-based metal matrix composites. Materials Today.
https://doi.org/10.1016/j.mattod.2024.09.006

TITLE: CHEMICAL ENGINEERING FOR THE PREPARATION OF EFFICIENT AND STABLE WIDE BANDGAP HALIDE PEROVSKITE SOLAR CELLS

Topic number* : *2024_042

Field : Chemistry, Physical chemistry and Chemical Engineering - Material science, Mechanics and Fluids

Subfield:

ParisTech School: Chimie ParisTech - PSL
Research team :
Research team website:
Research lab: IRCP - Institut de Recherche de Chimie de Paris
Lab location: Paris
Lab website: https://www.ircp.cnrs.fr/equipes-recherche-ircp/equipe-mpoe/axe-4-optoelectronique-photovoltaique-et-nanostructures/

Contact point for this topic: Thierry Pauporté
thierry.pauporte@chimieparistech.psl.eu

Advisor 1: Thierry Pauporté - thierry.pauporte@chimieparistech.psl.eu
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Metal halide perovskites (MHPs) have emerged as key materials for the preparation of efficient tandem solar cells when combined with other technologies. The preparation of wide bandgap (WBG)-MPH layers for tandem top cells requires ad hoc halide mixtures and generate additional stability issues due to the halide segregation that can occur upon aging. These perovskites classically experience instability and phase segregation phenomena that must be suppressed. The preparation of stable and high-quality WBG-MHP films needs a fine control if the crystallization process. The aim of the thesis is to develop strategies to increase the stability of WBG-MHP films. The formation of the targeted phase will be reached by finely controlling the composition of the precursor solution. The use of alkylammonium additives combined with ammonium compounds at the

origin of 2D phases formation will be investigated. The student will examine in-depth the film structure and composition changes upon the various preparation steps notably to understand the ammonium group deprotonation, the halide ion exchanges and the elimination by volatilization of certain species. The remaining of the others will bring the final properties to the absorber films, especially the bandgap, the crystallinity, the microstructure and the stability properties. The global thermally induced dimensional increase of the MHP will allow to boost the properties. The efficiency and stability of the inverted solar cells prepared with these compounds will be studied.

Required background of the student:
Material science; Chemistry; Physics of semiconductors; Photovoltaics; Material characterization techniques (SEM, XRD, UV-Vis absorption).

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. M. Cresp, M. Liu, M.-N. Rager, Th. Pauporté, 2D Ruddlesden-Popper versus 2D Dion-Jacobson Perovskites: Of the Importance of Determining the "True" Average n-Value of Annealed Layers. Adv Funct Mater., (2024) 2413671. DOI: 10.1002/adfm.202413671

2. B. Zhang,1 H. Zeng, H. Yin, D. Zheng, Z. Wan, C. Jia, T. Stuyver, J. Luo, Th. Pauporté, Combining Machine Learning, Component Screening and Molecular Engineering for the Design of High-Performance and Stable Inverted Perovskite Solar Cells. Energy Environ. Sci. 17 (2024) 5532 – 5541. https://doi.org/10.1039/d4ee00635f

3. M. Liu, D. Zheng, T. Pauporté, 2D Halide Perovskite Phase Formation Dynamics and their Regulation by Co-Additives for Efficient Solar Cells. Adv. Mater. Interfaces 11 (2024) 2300773 https://doi.org/10.1002/admi.202300773

4. T. Wang, D. Zheng, K. Vegso, N. Mrkyvkova, P. Siffalovic, T. Pauporté, High-Resolution and Stable Ruddlesden-Popper Quasi-2D Perovskite Flexible Photodetectors Arrays for Potential Application as Optical Image Sensor. Adv. Funct. Mater. 33 (2023) 2304659. https://doi.org/10.1002/adfm.202304659

5. D. Zheng, F. Raffin, P. Volovitch, Th. Pauporté, Control of perovskite film crystallization and growth direction to target homogeneous

monolithic structures. Nature Commun., 13 (2022) 6655.
https://doi.org/10.1038/s41467-022-34332-3

ParisTech

TITLE: DESIGN OF GRAPHENE QUANTUM DOTS FOR THERANOSTICS APPLICATIONS

Topic number : ***2024_043***

Field : Chemistry, Physical chemistry and Chemical Engineering - Life and Health Science and Technology

Subfield:

ParisTech School: Chimie ParisTech - PSL
Research team : SEISAD
Research team website: https://iclehs.fr/research/seisad/
Research lab: I-CLEHS - Institute of chemistry for life and health
Lab location: Paris
Lab website: https://iclehs.fr

Contact point for this topic: Varenne Anne
anne.varenne@chimieparistech.psl.eu

Advisor 1: Anne Varenne - anne.varenne@chimieparistech.psl.eu
Advisor 2: Laura Trapiella-Alfonso - laura.trapiella@chimieparistech.psl.eu
Advisor 3: Bich-Thuy Doan - bich-thuy.doan@chimieparistech.psl.eu
Advisor 4:

Short description of possible research topics for a PhD:
The development of new alternative therapeutic strategies to fight cancer by limiting the undesirable side effects of conventional chemotherapy is essential. Nanomedicine is an effective approach to meet these requirements because the coupling and encapsulation of antitumor molecules with nanovectors will allow reducing their toxicity while improving their circulation and in vivo targeting. The association with imaging probes will eventually give rise to theranostic agents. The PhD proposal aims to explore the interest of carbon dots for theranostic applications. The lab has already developed some nanostructurations and aims at characterizing these nano-theranostic agents in terms of interactome (« protein corona » or « antifouling » capacity in

physiological media) and the evaluation of their biological and theranostic properties, for an efficient pre-screening for biomedical applications.

Required background of the student:
Analytical and physical chemistry, nanosciences, some theorical knowledge in biochemistry and biomedical engineering are welcome

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. L. Trapiella-Alfonso, G. Ramirez-Garcia, F. d'Orlyé, A. Varenne. Electrokinetic methodologies for the characterization of nanoparticles and the evaluation of their behaviour in biological systems. Tracs, Trends in Analytical Chemistry (2016) 84, 121-130. Invited review (DOI: 10.1016/j.trac.2016.04.022)
2. G. Ramírez-García, S. Gutiérrez-Granados, M-A Gallegos-Corona, L. Palma-Tirado, F. D'Orlyé, A. Varenne, N. Mignet, C. Richard, M. Martinez-Alfaro. Long-term toxicological effects of persistent luminescence nanoparticles after intravenous injection in mice. International Journal of Pharmaceutics (2017) 532, 686-695 (DOI: 10.1016/j.ijpharm.2017.07.015)
3. L. Trapiella Alfonso, T. Pons, N. Lequeux, L. Leleu, J. Grimaldi, M. Tasso, E. Oujagir, J. Seguin, F. D'Orlyé, C. Girard, BT Doan, A. Varenne. Clickable-zwitterionic co-polymer capped- quantum dots for in vivo fluorescence tumor imaging. ACS Appl. Mater. Interfaces (2018) 10, 17107-17116 (DOI : 10.1021/acsami.8b04708)
4. G. Ramirez Garcia, F. D'Orlyé, C. Richard, N. Mignet, A. Varenne. Electrokinetic elucidation of the interactions between persistent luminescent nanoprobes and the binary apolipoprotein-E / Albumin protein system. Analyst (2021) 146, 5245-5254. Invited Cover. (DOI: 10.1039/D1AN00781E)
5. S. Boumati, A. Sour A, V. Heitz, J. Seguin, G. Beitz, Y. Kaga, M. Jakubaszek M, J Karges, G. Gasser, N. Mignet, Doan BT. Three in One: In Vitro and In Vivo Evaluation of Anticancer Activity of a Theranostic Agent that Combines Magnetic Resonance Imaging, Optical Bioimaging, and

Photodynamic Therapy Capabilities. ACS Appl Bio Mater. 2023 ;6(11):4791-4804. (DOI: 10.1021/acsabm.3c00565)

TITLE: EFFICIENT AND ACCURATE PREDICTION OF PLASTIC INSTABILITIES IN THIN METAL SHEETS USING FAST FOURIER TRANSFORM (FFT) METHOD

Topic number : ***2024_044***

Field : Material science, Mechanics and Fluids

Subfield:

ParisTech School: Arts et Métiers
Research team : Numerical Methods, Instabilities and Vibrations
Research team website: https://lem3.univ-lorraine.fr/departement-mmsv/
Research lab: LEM3 - Laboratoire d'étude des microstructures et de mécanique des matériaux
Lab location: Metz
Lab website: https://lem3.univ-lorraine.fr/

Contact point for this topic: BEN BETTAIEB Mohamed (Mohamed.BenBettaieb@ensam.eu)

Advisor 1: Farid Abed-Meraim - Farid.ABEDMERAIM@ensam.eu
Advisor 2: Mohamed BEN BETTAIEB - Mohamed.BenBettaieb@ensam.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
The prediction of plastic instability, such as localized necking or plastic buckling, in sheet metals during forming processes represents a significant challenge. It is well known that the occurrence of such instability phenomena mainly depends on the mechanical and microstructural characteristics of the metal sheets, such as grain morphology and orientation and the crystallographic structure. To accurately account for these characteristics in instability predictions, several computational strategies based on multiscale schemes have been developed by the host research team. These strategies predict the onset of plastic instability by considering a polycrystalline aggregate as representative of the studied sheet. The mechanical constitutive equations are formulated at the single crystal (microscopic) scale, and a

multiscale transition scheme is employed to determine the overall behavior of the polycrystalline aggregate from that of the single crystal constituents. An instability criterion, such as the Rice bifurcation theory or the initial imperfection approach, is coupled with the overall polycrystalline behavior to predict the incipience of localized necking at the macroscopic level. To ensure the transition between the single crystal and polycrystalline scales, the host research team initially used the self-consistent approach. More recently, the periodic homogenization approach has been used as an alternative to the self-consistent scheme. This evolution in multiscale modeling has been motivated by the enhanced accuracy of the periodic homogenization scheme in modeling polycrystalline behavior. Despite these significant improvements, the application of the periodic homogenization scheme in predicting the onset of localized instabilities poses some technical difficulties, such as the very high CPU requirements needed for running the computation strategy, especially for polycrystalline aggregates with complex microstructures, and numerical convergence problems that may arise particularly in the large deformation range. The objective of this thesis project is to develop a new computational strategy that circumvents the technical problems related to the use of the periodic homogenization scheme. This new approach, based on the Fast Fourier Transform (FFT) method, will enable a more detailed description of thin metal sheets with complex microstructures (incorporating realistic morphology of grains, grain boundaries, size effects, ...) with a reduced CPU time. The adoption of this new computational strategy is expected to significantly enhance the capabilities of our numerical tools used to predict the onset of localized necking. The single crystal constitutive models used in previous work by the host team will be integrated into this new computational strategy. These models will be improved to better describe the microscopic behavior by considering some key challenging effects not sufficiently investigated so far, such as non-associated plasticity, thermomechanical coupling, phase transformation effects, and more. The resulting computation strategy, based on the FFT method, will be coupled with the Rice bifurcation criterion by developing the suitable software tools. The algorithmic schemes and associated computational tools developed in this project will be validated by comparing the numerical predictions to several experimental results. Once fully validated, the developed computational strategy will be used in both academic and industrial contexts to provide guidelines and assistance in the design of new generations of metallic alloys with improved ductility.

Required background of the student:
- Solid background in non-linear solid mechanics and numerical methods;
- Good analytical and programming skills (e.g., Matlab, Mathematica, C/C++, Fortran);
- Good understanding of the physics of localized necking and associated modeling.
- Previous experience with numerical schemes and their implementations in software environments would be an asset.

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Franz, G., Abed-Meraim, F., Berveiller, M., 2013. Strain localization analysis for single crystals and polycrystals: Towards microstructure-ductility linkage, International Journal of Plasticity, Vol. 48, pp 1–33.
2. Akpama, H.K., Ben Bettaieb, M., Abed-Meraim, F., 2017. Localized necking predictions based on rate–independent self–consistent polycrystal plasticity: Bifurcation analysis versus imperfection approach, International Journal of Plasticity, Vol. 91, pp 205–237.
3. Zhu, J., Ben Bettaieb, M., Abed-Meraim, F., 2020. Investigation of the competition between void coalescence and macroscopic strain localization using the periodic homogenization multiscale scheme, Journal of the Mechanics and Physics of Solids. Vol. 143, 104042.
4. Zhu, J., Ben Bettaieb, M., Zhou, S., Abed-Meraim, F., 2023. Ductility limit prediction for polycrystalline aggregates using a CPFEM-based multiscale framework, International Journal of Plasticity. Vol. 167, 103671.
5. Zhou, S., Ben Bettaieb, M., Abed-Meraim, F., 2024. A physically-based mixed hardening model for the prediction of the ductility limits of thin metal sheets using a CPFE approach, International Journal of Plasticity. Vol. 176, 103946.

RESEARCH TOPIC FOR THE CSC PHD PROGRAM

Topic title: Efficient and accurate prediction of plastic instabilities in thin metal sheets using Fast Fourier transform (FFT) method

Keywords: Sheet metal forming, Ductility limits, FTT approach, Microstructural parameters, Material design.

Topic short description: The prediction of plastic instability, such as localized necking or plastic buckling, in sheet metals during forming processes represents a significant challenge. It is well known that the occurrence of such instability phenomena mainly depends on the mechanical and microstructural characteristics of the metal sheets, such as grain morphology and orientation and the crystallographic structure. To accurately account for these characteristics in instability predictions, several computational strategies based on multiscale schemes have been developed by the host research team. These strategies predict the onset of plastic instability by considering a polycrystalline aggregate as representative of the studied sheet (see, Fig. 1). The mechanical constitutive equations are formulated at the single crystal (microscopic) scale, and a multiscale transition scheme is employed to determine the overall behavior of the polycrystalline aggregate from that of the single crystal constituents. An instability criterion, such as the Rice bifurcation theory or the initial imperfection approach, is coupled with the overall polycrystalline behavior to predict the incipience of localized necking at the macroscopic level. To ensure the transition between the single crystal and polycrystalline scales, the host research team initially used the self-consistent approach [1, 2]. More recently, the periodic homogenization approach has been used as an alternative to the self-consistent scheme. This evolution in multiscale modeling has been motivated by the enhanced accuracy of the periodic homogenization scheme in modeling polycrystalline behavior [3–5]. Despite these significant improvements, the application of the periodic homogenization scheme in predicting the onset of localized instabilities poses some technical difficulties, such as the very high CPU requirements needed for running the computation strategy, especially for polycrystalline aggregates with complex microstructures, and numerical convergence problems that may arise particularly in the large deformation range. The objective of this thesis project is to develop a new computational strategy that circumvents the technical problems related to the use of the periodic homogenization scheme. This new approach, based on the Fast Fourier Transform (FFT) method, will enable a more detailed description of thin metal sheets with complex microstructures (incorporating realistic morphology of grains, grain boundaries, size effects, ...) with a reduced CPU time [6]. The adoption of this new computational strategy is expected to significantly enhance the capabilities of our numerical tools used to predict the onset of localized necking. The single crystal constitutive models used in previous work by the host team will be integrated into this new computational strategy. These models will be improved to better describe the microscopic behavior by considering some key challenging effects not sufficiently investigated so far, such as non-associated plasticity, thermomechanical coupling, phase transformation effects, and more. The resulting computation strategy, based on the FFT method, will be coupled with the Rice bifurcation criterion by developing the suitable software tools.

The algorithmic schemes and associated computational tools developed in this project will be validated by comparing the numerical predictions to several experimental results. Once fully validated, the developed computational strategy will be used in both academic and industrial contexts to provide guidelines and assistance in the design of new generations of metallic alloys with improved ductility.

References

[1] Franz, G., Abed-Meraim, F., Berveiller, M., 2013. Strain localization analysis for single crystals and polycrystals: Towards microstructure-ductility linkage, *International Journal of Plasticity*, Vol. 48, pp 1–33.

[2] Akpama, H.K., Ben Bettaieb, M., Abed-Meraim, F., 2017. Localized necking predictions based on rate–independent self–consistent polycrystal plasticity: Bifurcation analysis versus imperfection approach, *International Journal of Plasticity*, Vol. 91, pp 205–237.

[3] Zhu, J., Ben Bettaieb, M., Abed-Meraim, F., 2020. Investigation of the competition between void coalescence and macroscopic strain localization using the periodic homogenization multiscale scheme, *Journal of the Mechanics and Physics of Solids*. Vol. 143, 104042.

[4] Zhu, J., Ben Bettaieb, M., Zhou, S., Abed-Meraim, F., 2023. Ductility limit prediction for polycrystalline aggregates using a CPFEM-based multiscale framework, *International Journal of Plasticity*. Vol. 167, 103671.

[5] Zhou, S., Ben Bettaieb, M., Abed-Meraim, F., 2024. A physically-based mixed hardening model for the prediction of the ductility limits of thin metal sheets using a CPFE approach, *International Journal of Plasticity*. Vol. 176, 103946.

[6] Gélébart, L., 2020. A modified FFT-based solver for the mechanical simulation of heterogeneous materials with Dirichlet boundary conditions, *Comptes Rendus Mécanique*. Vol. 348, N° 8–9, pp 693–704.

Required background:

- Solid background in non-linear solid mechanics and numerical methods;
- Good analytical and programming skills (e.g., Matlab, Mathematica, C/C++, Fortran);
- Good understanding of the physics of localized necking and associated modeling.
- Previous experience with numerical schemes and their implementations in software environments would be an asset.

<u>ParisTech school</u>: Arts et Métiers
<u>Research laboratory</u>: LEM3
<u>Lab location</u>: Metz
<u>Lab website</u>: https://lem3.univ-lorraine.fr/
<u>Research team</u>: Numerical Methods, Instabilities and Vibrations
<u>PhD delivered by</u>: Arts et Métiers
<u>Doctoral School</u>: Ecole doctorale SMI 432
<u>Advisors</u>: Farid Abed-Meraim, Mohamed Ben Bettaieb

<u>Contact point for this topic :</u> Mohamed Ben Bettaieb (Mohamed.BenBettaieb@ensam.eu)

<u>Research field</u>: Material science, Mechanics and Fluids

<u>Research subfield</u>: Mechanical Engineering

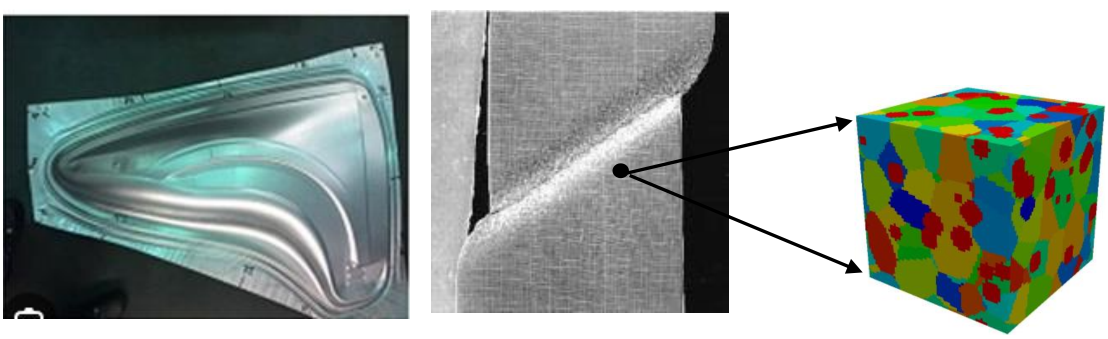


Fig. 1

ParisTech

TITLE: DEVELOPMENT OF SURROGATE MODELS FOR METAL FORMING PROCESSES

Topic number : ***2024_046***

Field : Design, Industrialization - Material science, Mechanics and Fluids

Subfield:

ParisTech School: Arts et Métiers
Research team :
Research team website:
Research lab: LCFC - Laboratoire de conception, fabrication, commande
Lab location: Metz
Lab website: lcfc.ensam.eu

Contact point for this topic: BALAN - Tudor - tudor.balan@ensam.eu

Advisor 1: Tudor Balan - tudor.balan@ensam.eu
Advisor 2: Régis Bigot - regis.bigot@ensam.eu
Advisor 3: Lazhar Homri - lazhar.homri@ensam.eu
Advisor 4:

Short description of possible research topics for a PhD:
The development of data-driven surrogate models for complex metal forming processes is crucial for speeding up the design and ramp-up phases, as well as to deal with variabilities and drifting in production phase. The convergence of advanced technologies and new data analytics provide real-time feedback for process characterization and key features identification. Associated models must deal with numerous challenging specificities: complex geometries; discrete parameters (e.g., the number of forming steps); time evolution of tensorial quantities… that could be tackled within the PhD thesis project. The scientific challenges lie in the identification and formulation of the parameters and variables to describe the complexity of these manufacturing processes, particularly their incremental / sequential nature to ensure real-time prediction and optimization.

Required background of the student:

The candidate should be initiated to data-driven approaches and in particular surrogate model development (polynomial chaos, kriging, neural networks…). Some background in metal forming processes would be helpful, and scientific / technical curiosity for this application field is needed. A certain experience in programing (Python) is necessary.

A list of (5 max.) representative publications of the group: (Related to the research topic)

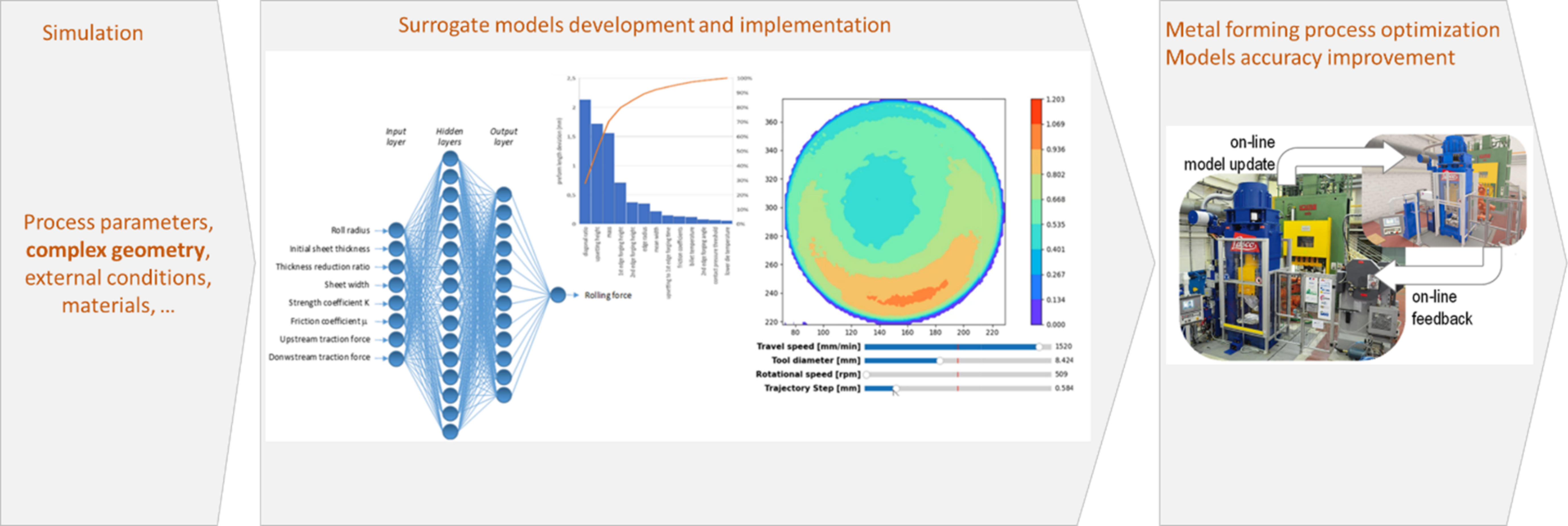
1. Zouhri, W., Homri, L. & Dantan, JY. Identification of the key manufacturing parameters impacting the prediction accuracy of support vector machine (SVM) model for quality assessment. Int J Interact Des Manuf 16, 177–196 (2022).

2. W Zouhri, JY Dantan, B Häfner, N Eschner, L Homri, G Lanza, O Theile, Characterization of laser powder bed fusion (L-PBF) process quality: A novel approach based on statistical features extraction and support vector machine, Procedia CIRP 99, 319-324

3. K Slimani, M Zaaf, T Balan, Accurate surrogate models for the flat rolling process, Int J Material Forming 16 (2023) 23, DOI: 10.1007/s12289-023-01744-5

4. Fays, S., Baudouin, C., Langlois, L., Borsenberger, M., Balan, T., Bigot, R., Compensation of billet variabilities through metamodel-based optimization in open die forging (2024) Int J Advanced Manuf Technology, 132 (3-4), pp. 1665-1678.

5. Uribe, D., Baudouin, C., Durand, C., Bigot, R., Predictive control for a single-blow cold upsetting using surrogate modeling for a digital twin, Int J Material Forming, 17 (2024), art. no. 7.


Simulation
Process parameters, complex geometry, external conditions, materials, ...
Surrogate models development and implementation
Input layer
Hidden layers
Output layer
Roll radius
Initial sheet thickness
Thickness reduction ratio
Sheet width
Strength coefficient K
Friction coefficient μ
Upstream traction force
Donwstream traction force
Rolling force
Travel speed [mm/min]
Tool diameter [mm]
Rotational speed [rpm]
Trajectory Step [mm]
1520
8.424
509
0.584
Metal forming process optimization
Models accuracy improvement
on-line model update
on-line feedback

ParisTech

TITLE: AUTOMATIC GUIDED CAD ASSEMBLY GENERATION WITH MECHANICAL CONSTRAINTS USING DEEP LEARNING

Topic number : ***2024_047***

Field : Design, Industrialization - Mathematics and their applications

Subfield: Geometric modeling

ParisTech School: Arts et Métiers
Research team :
Research team website:
Research lab: LISPEN - Laboratoire d'ingénierie des systèmes physiques et numériques
Lab location: Aix-en-Provence
Lab website: https://lispen.artsetmetiers.fr/

Contact point for this topic: Polette - Arnaud - arnaud.polette@ensam.eu

Advisor 1: Jean-Philippe Pernot - jean-philippe.pernot@ensam.eu
Advisor 2: Arnaud Polette - arnaud.polette@ensam.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
The aim of this PhD is to implement methods for generating complex mechanical assemblies using existing databases of mechanical parts. The goal is to generate assemblies by controlling the level of coherence of the assembly according to the need (functionality, imposed interfaces, types of parts, etc.), while guiding the generation using functions to maximize certain objectives (encompassing shape, aesthetics, type of assembly, etc.). The idea would be to use databases of existing assemblies whose types and interfaces between parts are known, in order to learn the assembly logic according to the type of part and the consistency of functionality between the different geometries. Several solutions can be explored, such as reinforcement learning, in order to build an agent that can iteratively build these assemblies part by part. A second solution to explore would be to use auto-encoders and/or graphs (eg. GCN, Graph

Convolutional Network). The first step will be to build a database (as the host laboratory has already carried out work on using this type of database, this part will be greatly facilitated by the existing databases), then to explore the automatic assembly methods, and to validate the operation of these methods on the databases built, by illustrating them with concrete uses in an industrial context.

Required background of the student:
Computer science, machine learning, geometric modeling, computer-aided design (assembly design)

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Lucas Vergez, Arnaud Polette, Jean-Philippe Pernot. Multi-part kinematic constraint prediction for automatic generation of CAD model assemblies using graph convolutional networks. Computer-Aided Design, Volume 178, 2025, 103805, ISSN 0010-4485, https://doi.org/10.1016/j.cad.2024.103805.

2. Lucas Vergez, Arnaud Polette, Jean-Philippe Pernot. Interface-Based Search and Automatic Reassembly of CAD Models for Database Expansion and Model Reuse, Computer Aided Design, 2023 (online publication), Volume 167, 103630, https://doi.org/10.1016/j.cad.2023.103630

3. Lucas Vergez, Arnaud Polette, Jean-Philippe Pernot. Automatic CAD Assemblies Generation by Linkage Graph Overlay for Machine Learning Applications. Computer-Aided Design and Applications, 2022, 19(4), pp. 722–732, https://doi.org/10.14733/cadaps.2022.722-732

Title: Design of theranostic peptide-based multifunctional nanovectors: from structure to biological properties

Topic number : ***2024_048***

Field : Chemistry, Physical chemistry and Chemical Engineering - Life and Health Science and Technology

Subfield:

ParisTech School: Chimie ParisTech - PSL
Research team : SEISAD
Research team website: https://iclehs.fr/research/seisad/
Research lab: I-CLEHS - Institute of chemistry for life and health
Lab location: Paris
Lab website: https://iclehs.fr

Contact point for this topic: anne.varenne@chimieparistech.psl.eu

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Advisor 3: Bich-Thuy Doan - bich-thuy.doan@chimieparistech.psl.eu
Advisor 4:

Short description of possible research topics for a PhD:
To fight cancer, the development of new alternative therapeutic strategies, that limit the undesirable side effects of conventional chemotherapy, is a prerequisite. Nanomedicine is an emerging field relying on the development of nanosystems as vectors of active moieties or activators making possible the reduction of the latter drug toxicity while improving its circulation time and targeting efficiency in vivo. Among natural building blocks to design smart nanomaterials, short self-assembling peptides have drawn significant interest due to their simple structure, relative chemical and physical stability, diversity in sequences and feasibility to synthesize in large amounts. In this context, the PhD project presents an innovative approach to design and validate novel theranostic agents based on biocompatible multifunctional peptide-containing nanoformulations including imaging probes and model drugs. In line with previous work, the project will focus on the relation between

precursor peptide structures and nanoformulation biological and imaging properties, for an efficient pre-screening of relevant nanosystems in view of biomedical applications.

Required background of the student:
Analytical and physical chemistry, nanosciences, some theorical knowledge in biochemistry and biomedical engineering are welcome.

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. L. Trapiella-Alfonso, G. Ramirez-Garcia, F. d’Orlyé, A. Varenne. Electrokinetic methodologies for the characterization of nanoparticles and the evaluation of their behaviour in biological systems. Tracs, Trends in Analytical Chemistry (2016) 84, 121-130. Invited review (DOI: 10.1016/j.trac.2016.04.022)
2. F. d’Orlyé, L. Trapiella-Alfonso, C. Lescot, M. Pinvidic, BT Doan, A. Varenne. Synthesis, Characterization and Evaluation of Peptide Nanostructures for Biomedical Applications. Molecules (2021), 26(15), 458. DOI: 10.3390/molecules26154587)
3. F. Espinola-Portilla, F. d’Orlyé, L. Trapiella-Alfons, S. Gutierrez Granados, G. Ramirez-Garcia, A. Varenne. A deep understanding of the self-assembly and colloidal stability of light and pH dual responsive spiropyran random copolymer micelle-like nanoaggregates. Materials Today Communication (2022) vol 31, 103499 (DOI 10.1016/j.mtcomm.2022.103499)
4. F. Espinola-Portilla, F. d’Orlyé, L. Trapiella-Alfonso, S. Gutierrez-Granados, G. Ramirez-Garcia, A. Varenne. Rational Understanding of Loading and Release of Doxorubicin by UV-Light- and pH-Responsive Poly(NIPAM-co-SPMA) Micelle-like Aggregates. Molecular Pharmaceutics (2023) 20, 3 1490-1499 (DOI : 10.1021/acs.molpharmaceut.2c00690)
5. A. Am, ME Faccio, M. Pinvidic, E. Reygue, BT Doan, C. Lescot, L. Trapiella Alfonso, F. d’Orlyé, A. Varenne*. A methodological approach by capillary electrophoresis coupled to mass spectrometry via electrospray interface for the characterization of short synthetic peptides towards the conception of self-assembled nanotheranostic agents. J. Chromatogr. A. 2024, 1713, 464496. (DOI : 10.1016/j.chroma.2023.464496)

Title: DEVELOPMENT OF A FRAMEWORK FOR THE ECOLOGICAL DESIGN OF CHINESE ELECTRICAL AND ELECTRONIC EQUIPMENT WITH THE REQUIREMENTS OF THE EUROPEAN UNION MARKET

Topic number : ***2024_049***

Field : Design, Industrialization - Environment Science and Technology, Sustainable Development, Geosciences

Subfield: Engineering Design, EEE, China, EU, Eco-Design, LCA

ParisTech School: Arts et Métiers
Research team : Product Design and Innovation Laboratory (LCPI)
Research team website:
Research lab: LCPI - Laboratoire conception de produits et innovation
Lab location: Paris
Lab website: https://lcpi.ensam.eu/cpi-page-accueil-112719.kjsp

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Advisor 3: Jose Hidalgo Crespo - jose-armando.hidalgo_crespo@ensam.eu
Advisor 4:

Short description of possible research topics for a PhD:
The electrical and electronic equipment (EEE) sector, recognized for its considerable resource requirements, signifies a notable prospect for waste reduction by integrating innovative eco-design and sustainability principles. These principles aid in capturing the economic and environmental worth ingrained in product design through the adoption of value retention processes, such as reuse, repair, refurbishment, remanufacturing, and recycling. The Eco-design for Sustainable Products Regulation (ESPOR) adopted in July 2024 is the cornerstone of the European Union (EU) approach to more environmentally sustainable and circular products. According to this regulation, all products placed on the

EU market should display one or more of the following characteristics: use less energy, last longer, be easily repaired, parts can be easily disassembled, contain fewer substances of concern, be easily recycled, contain more recycled content and have a lower carbon and environmental footprint over its lifecycle. This poses a big challenge on any country outside of EU wishing to export their EEE products on EU soil. This is particularly true for China, who was the largest partner for EU imports of goods (20.5%) in 2023 and represented 204.1 billion USD (20.5%) of the EU’s imports. However, difficulties in gaining access to original/spare parts and components for repairing and refurbishing devices or to support product lifetime extension, the lack of traceability regarding hazardous substances contained in EEE as well as their different materials and components which complicates the work of several companies involved in recycling and reuse practices, are some of the key barriers with these imported products. China has implemented several laws and regulations related to eco-design, particularly within the framework of green supply chain management and environmental protection policies. The Chinese government promotes eco-design practices through initiatives such as the "General Evaluation Principles of Eco-design Products" and the "Green Manufacturing Engineering Implementation Guide (2016–2020)." China has also enacted similar legislation, known as China RoHS and China WEEE to incorporate the concept of extended producer responsibility. These regulations aim to support sustainable product design by encouraging the reduction of environmental impacts throughout the product lifecycle. In addition, the first international circular economy (CE) cooperation between China and the European Union through the Memorandum of Understanding represents a milestone towards global efforts to address pressing environmental problems of extraction, resource use and waste management. Despite high expectations, the actual influence of these legislations on product design changes remains ambiguous. Several barriers impede the development of such eco-design notions that Chinese manufacturers face compared to their counterparts in developed countries. These barriers include a lack of systematic eco-design tools, limited access to advanced technologies, and a shortage of eco-design knowledge. Moreover, while regulations act as drivers, they simultaneously pose as barriers due to their complexity, making it difficult for manufacturers to comply without additional guidance and resources. Given that most of China’s circular economy related efforts are based on the recover of e-waste, the reverse logistics, and the development of recycling technologies, there is a deep gap in the inclusion of the eco-design concept in Chinese EEE manufacturers, particularly to satisfy the European market. The objective of this thesis is to develop a framework to sustain the eco-design of Chinese EEE manufacturers following the Eco-design for Sustainable Products Regulation, while keeping in mind the different economic, legal, stakeholders’ and other important constraints associated. The selected PhD candidate will critically analyze the whole value chain, starting on the product design and manufacture in China, importers, repair, remanufacture and recycling facilities and end-of-life handlers in France.

To do so, the PhD candidate, through LCPI laboratory list of contacts, will visit different actors in France to obtain information and also to apply their case study once selected. Additionally, different original equipment manufacturers in China should be contacted and one of them participate in the case study.

Required background of the student:
Engineering Background
Interest in environment preservation
Interest in electrical and electronic equipment

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Micheaux, H., & Aggeri, F. (2021). Eco-modulation as a driver for eco-design: A dynamic view of the French collective EPR scheme. Journal of Cleaner Production, 289, 125714. https://doi.org/10.1016/j.jclepro.2020.125714
2. Li, J., & Sarkis, J. (2022). Product eco-design practice in green supply chain management: A China-global examination of research. Nankai Business Review International, 13(1), 124-153. https://doi.org/10.1108/NBRI-02-2021-0006
3. Hidalgo-Crespo, J. A., Velastegui-Montoya, A., Soto, M., Amaya Rivas, J. L., Zwolinski, P., Riel, A., & Rivas-García, P. (2024). Improving urban waste management: A comprehensive study on household waste generation and spatial patterns in the Grand Guayaquil Metropolitan Area. Waste Management & Research, 42(10), 918-931. https://doi.org/10.1177/0734242X241262714
4. Luu, D.-N., Gachet, H., Maier, C.-J., Maranzana, N., & Aoussat, A. (2022). Eco-design and medicine: Opportunities to implement eco-design in the pharmaceutical R&D process. Journal of Cleaner Production, 365, 132785. https://doi.org/10.1016/j.jclepro.2022.132785
5. Bressanelli, G., Pigosso, D. C. A., Saccani, N., & Perona, M. (2021). Enablers, levers and benefits of Circular Economy in the Electrical and Electronic Equipment supply chain: A literature review. Journal of Cleaner Production, 298, 126819. https://doi.org/10.1016/j.jclepro.2021.126819

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Eco-design and medicine: Opportunities to implement eco-design in the pharmaceutical R&D process

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ABSTRACT

The pharmaceutical sector has the societal duty to make medical healthcare products both available and affordable. But like any human activity, it is not neutral in terms of environmental impact. Therefore, and like any industry, the pharmaceutical sector needs to consider the environmental aspects into its product design and activities in order to reach a sustainable production and consumption patterns, as defined by the Sustainable Development Goal (SDG) 12 of the United Nations. With a holistic perspective, the eco-design concept is an approach that aims to integrate environmental aspects into product design. To contribute to the SDGs, the pharmaceutical industry needs to consider the environmental impacts of its products. Usually, experts within Research & Development (R&D) do not have the proper level of knowledge to integrate the environmental aspects, in a Lifecycle perspective, into their decision making. Even so, those parameters are not yet part of the New Product Development (NPD) process of the medicine product. With those elements in mind, the aim of this paper is to understand which phases of the pharmaceutical R&D process represent an opportunity to eco-design such products.

We proposed two qualitative experimentations with, first interviewing ten practitioners of R&D; and second, with an assessment of the medicine NPD process and related deliverables, based on LCA results. The use of such results to investigate potential key contributors during NPD stages does not seem to be explored yet, especially for the pharmaceutical sector.

Results show that eco-design approaches can be performed all along the development of a pharmaceutical product. Main eco-design levers appear in parallel to the clinical phases 2a and 2b, in other words, when the tests on the final marketed form are initiated.

1. Introduction

As a marker of the integration of the sustainability by the international community, the United Nations has set 17 Sustainable development Goals (SDG) (2020). From a pharmaceutical sector point of view, the SDG three called "Good health and well-being" is intrinsically part of its societal duty. If we take a closer look on environment, like each industry, the pharmaceutical sector is a contributor to reach a responsible consumption and production patterns, as defined by SDG 12. And like any human activity, this sector is a contributor to the goals 13; 14; 15, respectively climate action; life below water; life on land. By integrating the environmental aspects into product design, eco-design is an approach which can support industries to contribute to these SDGs and reach the resilience of their activity.

From a scientific point of view, the planetary boundaries are setting a framework of "nine processes that regulate the stability and resilience of

Abbreviations: ACS, American Chemical Society; API, Active Pharmaceutical Ingredient; ICH, International Council for Harmonization; LCA, Life Cycle Assessment; LCM, Lifecycle Management; NDA, New Drug Application; NE, Novel Entities; NPD, New Product DevelopmenT; PEF, Product Environmental Footprint; R&D, Research & Development; SDG, Sustainable Development Goals.

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E-mail addresses: duc-nam.luu@ensam.eu (D.-N. Luu), herve.gachet@sanofi.com (H. Gachet), claus-juergen.maier@sanofi.com (C.-J. Maier), nicolas.maranzana@ensam.eu (N. Maranzana), ameziane.aoussat@ensam.eu (A. Aoussat).

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Available online 19 June 2022

the earth system" (Rockström et al., 2009). A recent update proposed a quantification of the Novel Entities (NE) boundary (Persson et al., 2022). Medicine products are made with compounds with an activity for humans or animals, called Active Pharmaceutical Ingredient (API). And, as product with a potential release & toxicity for the environment (Taylor and Senac, 2014), can be consider as NE. Some trace of consideration pollution for the environment from medicine can be found around 1970 (Hignite and Azarnoff, 1977) and are nowadays raised as a major concern (Wilkinson et al., 2022). In eco-design, those elements are only a part of the environmental impact. For instance, with the COVID-19 vaccines, Klemeš et al. are integrating in their environmental assessment not only the energy consumption of the production of the products, but also the one related to all activities (e.g.: energy of vaccination center, disinfectant used) required to administrate the doses to the patients (Klemeš et al., 2021). The point is to integrate a Lifecycle mindset into the NPD process of medicine side by side with the holistic view of the environmental impacts of the product and related activities. This mindset seems not to be widely spread in this sector and the New Product Development (NPD) of medicine products should embrace this eco-design journey.

In order to reach a systemic approach of eco-design, companies should work on three levels; the macro, by defining a clear strategy; the meso, by integrating environmental requirements into NPD; and the micro, by supporting teams with operational tools (Brones and Monteiro de Carvalho, 2015). The tools will most likely depend on the key users identified at the meso level. The macro level is a strategic decision, intrinsic of each company at a global level. As eco-design is not fully embedded within the pharmaceutical sector, the research question below, related to the meso level, appears.

RQ: In which steps of the pharmaceutical R&D process is there sufficient information available to support eco-design activities?

To answer this question, we performed two experimentations in order to feed the two hypotheses below.

H1. Eco-design activities can be focused on specific steps of the medicine NPD

H2. Quantitative environmental assessment, such as Life Cycle Assessment, can support decision making during the pharmaceutical NPD

To address this problematic, we proposed some theories around New Product Development, pharmaceutical development, and eco-design. The purpose was not to have exhaustive literature reviews, but to set the overall context of this research with these related fields. After explaining the methods of the two experimentations performed, results of the experiments are then exposed to engage discussion about main limits and interpretation are suggested. Finally, a conclusion of the work with perspectives of research is presented.

2. Theory

The purpose of this part is not to propose an exhaustive literature review on pharmaceutical R&D processes. We aimed to illustrate its main characteristics through an integrative review as defined by Snyder (2019).

We also proposed a quick overview of eco-design practices. Like previously, the point is not to have a full literature review of this research field. We aimed to set a bit of context of the two experiments, to finally highlight how they fit in a broader eco-design research framework.

2.1. Pharmaceutical R&D/NPD

The International Council for Harmonization of technical requirements for pharmaceuticals for human use (ICH) described the pharmaceutical lifecycle of a medicine through four steps (Fig. 1), the pharmaceutical development, the technology transfer, the commercial manufacturing, and the product discontinuation (ICH, 2008).

Even if Ramnarine et al. (2017) described the process as linear, usually, the technology transfer is included within the pharmaceutical development. The beginning of this phase starts when the medicine shows positive results (efficacy and safety for patients) in the early development phase. The technology transfer can start somewhere between the clinical phases 2a and 2b, as shown in Fig. 2, to optimize the time. During commercial manufacturing, the production of a medicine can be transferred from one site to another. A process of technology transfer is then initiated.

As we aimed to set a framework of eco-designers within the NPD of medicine product, we focused the rest of the paper on the sub-steps of the pharmaceutical development which can be identified within four parts: research, early development, late development, and market as shown in Fig. 2.

The purpose of target identification is to understand the origin of a disease and the potential targets for intervention. In terms of product development, it allows the project team to have a better vision of potential markets and related therapeutically products. During the lead discovery, researchers aim to screen and filter molecules with a therapeutical interest.

The Active Pharmaceutical Ingredients (API) are investigated in preclinical trials to evaluate preliminary effects. The preclinical trials are performed in the laboratory with cells (in vitro), animals (in vivo), and through informatic models (in silico). In terms of design, teams are asked here to provide products quickly. The challenge in this step is to make as much API as needed for all necessary tests.

In clinical phase 1 the first tests in humans are performed. The objective is to identify the kinetic profile of the API and to assess the metabolism. In other words, researchers are looking for the way on how the API is reacting and what are the metabolites, resulting of the reaction. The panel is constituted of healthy probands. Regarding the design of the medicine product, a first galenic form of the drug product is set but will usually not be the same as the final approved product.

If results are relevant, the phase 2a is initiated. The purpose is to determine the therapeutic dose which will have efficacy and minimal side effects. Generally, the galenic form of the product tested is similar to the final approved product. Indeed, the tests must reflect the effect of the final product who will be available to the patient to identify and prevent potential side effects.

The goal of phase 2b is the same as of phase 2a but with a larger panel of patients. The efficacy of the new medicine is then determined during phase 3.

When all stages are performed and have yielded good results, an application for authorization is sent to the authority related to the country targeted for the market. Each country has specific regulations, and the documentation must be adapted to fulfil country requirements.

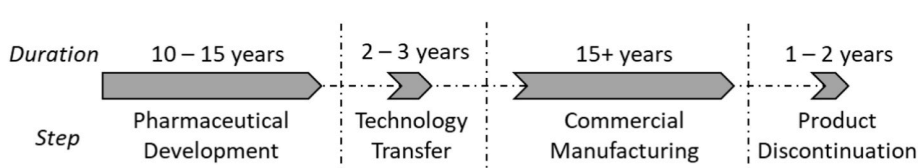

Fig. 1. Ramnarine Lifecycle steps of medicine (Ramnarine et al., 2017), based on ICH guideline.

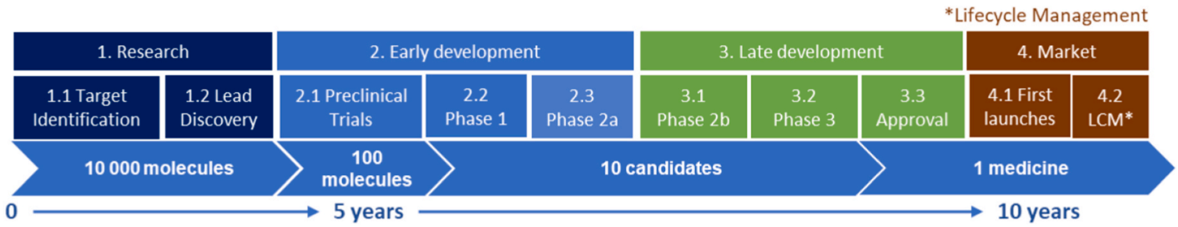

Fig. 2. Sub-steps of the Pharmaceutical Development of medicines to the LCM.

After the first launch, the life of the product continues, often referred to as phase 4. In phase 4, after market authorization, the new medicine is still tracked but in real conditions to ensure safety of patients and discovery and documentation of rare effects.

These steps explain the specific timeframe of the pharmaceutical NPD. This process is necessary to ensure patient safety from the R&D activities to the availability of the medicine product.

It is important to notice that the Lifecycle Management (LCM) within the pharmaceutical sector differs from the generic one. In this sector, LCM can be defined as *"Optimizing lifetime performance of pharmaceutical prescription brands, every time, within the context of the company's overall business, product, and project portfolio."* (Ellery, 2012). Therefore, it starts after the first launches of products, also defined as "commercial manufacturing" by the ICH (as shown in Fig. 1). This paper does not cover this stage or the product discontinuation one. For the rest of the paper, the terms "pharmaceutical development" and "pharmaceutical NPD" are considered as synonyms. They include all the sub-steps described in Fig. 2 except the LCM.

Regarding the academia perspective of the pharmaceutical R&D process, it is possible to identify five main research topics of interest to practitioners: research productivity, technology transfer, process management, clinical development, and healthcare marketing (Romasanta et al., 2020). None of these areas include environmental aspects or similar expression in their key words, showing a lack of integration of such aspects.

We can also mention Emara, who performed a review of Life Cycle Assessment of this sector, available in the literature. Less than 30 have been published in peer-reviewed journals, mainly with a cradle-to-gate scope (Emara et al., 2018).

When we are talking about eco-design within the pharmaceutical sector, it seems unfair to not talk about the Green Chemistry. The ACS Green Chemistry Institute described the first main milestone of this philosophy in 1962, with the scientific book "Silent Spring" of Rachel Carson (American Chemical Society, 2021). The Pollution Prevention Act of 1990 in the US had a key role in the development of this concept (Anastas and Williamson, 1996). The definition of this field has evolved through the decades, but the community seems nowadays to agree on 12 principles who set the approach (Anastas and Eghbali, 2010). As part of small molecules-based medicines, the chemistry within the pharmaceutical sector does not make an exception. Literature shows that companies such as Pfizer (Tucker, 2006) (Alfonsi et al., 2008), GSK (Alder et al., 2016), Bristol-Myers Squibb, AstraZeneca, Takeda, Novartis (Borovika et al., 2019), Sanofi (Prat et al., 2014) and others have integrated these principles in their activities. For instance, as described by Ang, Circular economy seems to have a momentum in the pharmaceutical sector since the publication of a white paper in 2016 by the European Federation of Pharmaceutical Industries and Association (Ang et al., 2021). But those publications are mainly turned in alternative chemistry and few of them consider processes. Moreover, the chemistry represents only the small molecule piece of the broader picture of the pharmaceutical sector as described by the ICH (2012). The holistic approach proposed by the eco-design seems therefore relevant to implement within this industry.

2.2. Eco-design approaches

The eco-design concept is defined as a *"systematic approach that considers environmental aspects in design and development with the aim to reduce adverse environmental impacts throughout the Lifecycle of a product"* (ISO, 2020). It is possible to find designers with an environmentally responsible approach earlier in the 1960's (Dewberry, 1996). Nevertheless, the crystallization of this field of research appeared in the 1990's within the scientific community (Boks, 2006).

Schäfer provided a segmentation of this discipline into five main areas of research: terminology, evolution, barriers & success factors, methods & tools, and synergies with other research disciplines (2021). Brones et al. identified around 52 integration models of eco-design and studied them to propose a unique framework (2015) as shown in Fig. 3. The authors described this model with a vertical and a transversal integration. The first one is divided within three levels: macro for the strategic part (e.g.: strategy & corporate objectives), meso for the tactical (e.g.: integration of environmental requirement into product design) and micro for the tools (e.g.: environmental assessment tools). The transversal integration, also called "soft side", is around the culture of a company and the human factors.

Literature abounds of eco-design tools frameworks (Bovea and Pérez-Belis, 2012; Jugend et al., 2020; Rossi et al., 2016; Rousseaux et al., 2017; Vallet et al., 2013; Varžinskas et al., 2020). Non exhaustively, we can mention product related (Kozderka, 2016; McAloone and Pigosso, 2018; Rio et al., 2010), managerial (Gouvinhas et al., 2016; Paula Pinheiro et al., 2018; Pigosso et al., 2013) or communication one (Del Borghi, 2013; ISO, 2017a, 2017b, 2006). This diversity of tools offers a large range of options to designers, who should be able to integrate environmental aspects into NPD requirements.

2.3. Summary of the theoretical background

The pharmaceutical NPD is well known due to common regulations. It is mainly explained by the necessity to ensure both effectiveness of the product and safety for the patient. The field of eco-design research can be set somewhere around the 1990's. The literature proposes tools to integrate this approach within industries.

Despite that, the pharmaceutical industry does not have integrated the environmental impacts of products, into their NPD process in a holistic way. It can be noted that, within the pharmaceutical R&D, neither the field of process management (Romasanta et al., 2020) nor the environmental aspects of products are topics well addressed to the experts of this sector. Therefore, a first step to understand where eco-design approaches could fit into medicine NPD is proposed in this paper.

3. Methods

This research includes two experimentations. The first one was based on semi-structured interviews of R&D practitioners, involved during the product development. The second experimentation was built with a qualitative assessment method.

The two approaches have pros & cons (see Table 1). Main ones are summarized in the table below, based on literature for the semi-

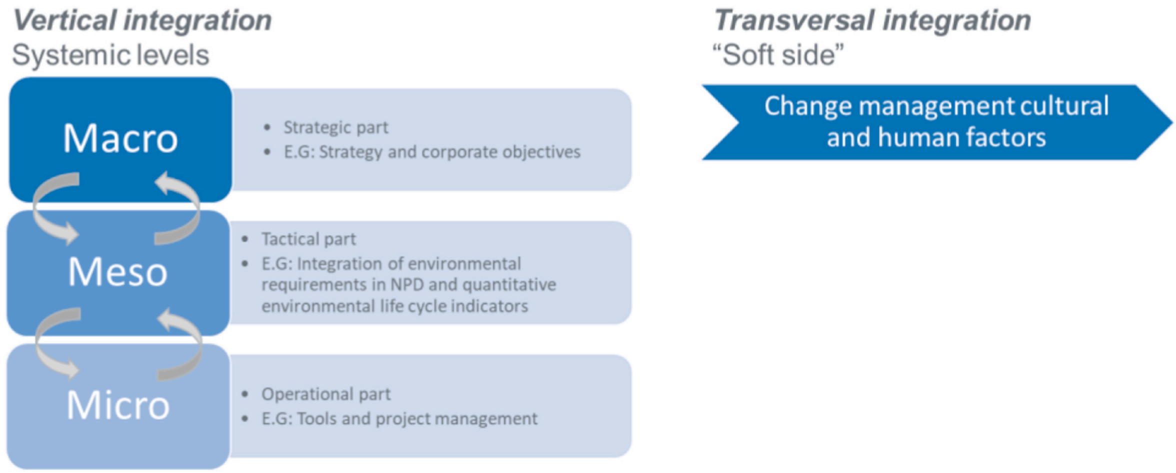

Fig. 3. Brones eco-design integration model: combining vertical and transversal integration.

Table 1
Main pros & cons of the semi-structured interview and the qualitative assessment method approaches.

Approach	Pro	Con
Semi-structured interview (Doody and Noonan, 2013; Kallio et al., 2016)	• Versatile & flexible • Reciprocity between interviewer & participant • Space for participants' individual verbal expressions • Interviewee can ask for clarification Enable complex questions	• Basic knowledge required • Time consuming *(e.g.: preparation, conduction, transcription, analysis)* • Language barriers Potential bias *(e.g.: nonverbal expression can influence interviewee)*
Qualitative assessment method	• Evaluation and results are based on objective methods • Results are rationalized Easy to use	• Values are based on knowledge and subjective perspective of expert involved Potential inflation of score with a conservative approach

Table 2
Main characteristic summary of the interviewees.

Participant	Position, Expertise	Related years of expertise	Country	Environmental knowledge	Con
P1	R&D, Environment, Health, Safety	14	United States	Regulatory based	
P2	R&D, Chemistry	24	France	Green Chemistry	
P3	R&D, Biotechnology	14	France	No	
P4	R&D, Biotechnology	12	France	No	
P5	R&D, Outsourcing	30	France	No	
P6	R&D, Medical devices	19	Germany	Contributed to a LCA study	
P7	Industrial, Packaging	25	France	Contributed to a LCA study	
P8	R&D, Vaccines	35	Canada	No	
P9	Market insights, Over the Counter	7	France	No	
P10	Procurement, Medical devices	20	France	No	

structured interview, and on our perception for the assessment method.

The semi-structured interviews rely mainly on both knowledge and understanding of the topic of interviewer and interviewees. Results should be taken carefully due to these potential biases.

These results were balanced by assessing the potential environmental impacts of the deliverables from the R&D process. This second study was launched in parallel to confront the results to the ones of the semi-structured interviews. In that sense, it represents a complementary approach to be able to confirm the convergence point.

3.1. Practitioners' interviews

The first experiment consisted of semi-structured interviews with ten practitioners of the one multinational pharmaceutical company. The purpose was to identify through them the main steps of the medicine NPD who could feed an eco-design approach. Aspect of the expertise of interviewees and environmental knowledge are summarized in Table 2. They were selected due to their pharmaceutical R&D and, or medicine product expertise and to be as much as possible complementary to cover most of process development. 60% of the participants claimed to not have specific knowledge in environment. Topics raised during the interviews are summarized in the appendix 1 and goes from the product portfolio scope, the NPD triggers, competencies for designers, indicators, or environmental data generation.

Data were processed by the eco-design expert involved as the interviewer. Then, a round of review was performed by the eco-design lead of Sanofi and a PhD student, to correct the misinterpretation of the interviewer, which was not an expert of the pharmaceutical industry.

The eco-design lead of Sanofi had a PhD in chemistry, worked for six years in R&D and 15 years at global level in the field of risk prevention. The PhD student had a background of one year in pharmaceutical R&D and four years in this industry as risk prevention engineer.

The interviews were performed between January 12, and January 21, 2021. It lasted 45 min to 1 h and a half, with an average of 1 h.

To avoid biases linked to pharmaceutical knowledge-perception, the interviews were carried out by an independent interviewer who held a PhD in eco-design. He was selected due to his six years expertise in eco-design within several industries in France and the lack of familiarity with pharmaceutical products.

3.2. Environmental aspects root cause within R&D decision making

The second experiment was based on a qualitative evaluation. We have made available to an environmental expert of Sanofi the results of a Life Cycle Assessment (LCA) of an existing medicine. The expert involved was part of Sanofi for 32 years, with responsibilities around climate risk management and previous experience regarding LCA co-ordination, environmental reporting & energy, facility management in R&D.

As it is not the purpose of this paper, we will not go into the details of the LCA results. They were used as raw data, to identify the decision steps, during the R&D process, that may have led to the environmental impacts assessed. The main characteristics of the LCA used are summarized in the Table 3.

The list of the deliverables and key design decisions during the R&D process was made available to the same expert. This list was composed of 263 deliverables. We can mention for instance the necessity to identify the main therapeutic use, the New Drug Application (NDA), the stability of the product or the industrialization choices with related technologies.

From these two elements, a first assessment was conducted through the list of all deliverables within the four stages of the pharmaceutical development process (as described in Fig. 2). The purpose of this step was to identify the deliverables with “eco-design potential”. We defined it as a deliverable who may have a direct/indirect impact on either the product specifications (e.g.: storage condition), the industrialization (e.g.: supplier selection), the supply chain (e.g.: type of transport), the use & end of life (e.g.: metabolism rate) or other data generation (e.g.: pharmacological profile) useful to assess the environmental profile of the product.

A score of the potential environmental impact of the related deliverable, based on the LCA results and on four indicators of the PEF (global warming, freshwater eutrophication, freshwater ecotoxicity, water scarcity footprint), was then set between one (low) to four (high impact). As each step of the lifecycle may contribute differently to each indicator, this approach was performed to each deliverable, per lifecycle step (the raw materials are included within API; formulation and packaging) for the four indicators. An example of the calculation is provided in appendix 2.

4. Results

Qualitative results are described for both the R&D practitioners' interviews and for the second experiment regarding R&D decision making to then engage a discussion regarding limits, highlights, and convergence points.

4.1. Practitioners' interviews

Three additional macro design steps were identified, discovery, clinical manufacturing, and industrialization. The discovery takes place during the research phase. The clinical manufacturing is between the preclinical trials and phase 3. Finally, the industrialization takes place at the end of the preclinical trials until the LCM and usually includes the technology transfer mentioned in Fig. 1.

During interviews, all participants with no environmental knowledge were at first focused on their own activities and understanding of the potential environmental impacts (e.g.: “*We use a lot of paper, we could reduce our impact with the digitalization*”). Results of the discussions are described below.

- Discovery

During discovery, APIs are synthesized by all means in order to eliminate ones without therapeutical potential. Synthesis routes are therefore at laboratory scale, with a high margin of error in terms of environmental assessment as both attrition rate and uncertainties are high.

Data regarding raw materials are linked to the APIs manufactured at the laboratory scale and does not represent at all the ones for the marketed medicine. The same goes for the energy of processes, the localization of manufacturing, wastes, emissions and transportation.

Choices made during this step will impact indirectly the lifecycle of the product. For instance, monoclonal antibodies are today expected to degrade to small peptides and individual amino acids. In other words, not harmful for the environment, which is not the case for most of small molecules based on usual chemistry. As the level of uncertainty is high at this stage, qualitative eco-design guidance could be interesting to implement.

- Clinical manufacturing

At this step, first production scale up appears to launch trials. It takes place at pilot scale, and specifications of the product are explored. The API, formulation (final form of the product taken by the patient. e.g.: tablet, ointment, liquid injectable), packaging begins to be set as the trials need to be conducted on a form representative of the marketed one.

Estimation of energy required for the processes, waste generation and other emissions can be performed. Transportation starts to be investigated, same as the usage (e.g.: administration route), manufacturing plant, and preliminary eco-toxicity profile. An eco-designer could seize the opportunity of the generation of such data to provide semi-quantitative insights, based on LCA approach, to guide decision making.

- Industrialization

When the API shows positive results, industrialization is launched to manufacture the product with the same pharmacological properties studied during trials.

Accurate data regarding raw materials, energy consumption, localization of manufacturing plant, waste generation and other emissions, transportation, usage and end of life are available or being to be. As data begin to be more accurate, the eco-designer could support the development process by giving quantitative through LCA.

4.2. Environmental aspects root cause within R&D decision making

A first assessment was conducted through the list of all deliverables within the pharmaceutical development process. The purpose of this step was to identify the deliverables with an “eco-design potential” as defined in chapter 3.2. Results are summarized in the Table 4 and showed an average of 36% of deliverables with an “eco-design potential”, up to 43% in the research phase.

After this first assessment, a score between one (low environmental impact) and four (high environmental impact) was performed for each deliverable. Data in Fig. 5 represents the breakdown by lifecycle stage of the level of influence of the deliverables and example of calculation is provided in appendix 2. In every step, the early development is the most

Table 3
Main characteristics of the LCAs used for the study.

Characteristic	Description
Year of the LCA	2020
LCA method	Product Environmental Footprint (PEF)
Function	Treat symptoms
Functional Unit	One gram dosage per drug intake for one adult *(equivalent of the dosage of Active Pharmaceutical Ingredient into one tablet)*
Reference flow	One tablet
API	Chemical based
Galenic form	Tablet
Packaging	Blister PVC/Aluminum
System boundary	Cradle-to-Grave *(Raw material; API synthesis; formulation; packaging; distribution; use & end of life)*

Table 4
Number of deliverables and potential eco-design ones per sub steps of the pharmaceutical development.

NPD step	Number of deliverables	Deliverables with eco-design potential		Con
1. Research	49	21	43%	
2. Early development	84	29	35%	
3. Late development	109	21	19%	
4. Market	72	23	32%	
Total	**263**	**94**	**36%**	

impactful (between 37% and 40%). Less significantly, the late development contributes secondly (between 22% and 28%) to the climate change impact profile. Then, depending on the lifecycle step, research and market are sharing the third and last places (between 15% and 23%).

A similar profile can be observed for the water scarcity footprint. But the ones for freshwater ecotoxicity and freshwater eutrophication differ. Even if for all the indicators, the early development seems to be the major contributor (between 31% and 40%), for both freshwater ecotoxicity and freshwater eutrophication, the research stage contributes in second position to the API, formulation, and use & end of life steps (between 27% and 29%). The late development comes then for these lifecycle steps (around 21%). Still for freshwater ecotoxicity and freshwater eutrophication, the late development seems to come in second place of contributor for packaging and distribution (between 28% and 31%) and the market at the third one (between 19% and 21%). The figures are provided in appendix 3. The Table 5 propose a global view with a breakdown of eco-design potential with an aggregation of the lifecycle steps.

5. Discussion

In this part, we aim to expose the major's highlights, convergence points and main limits.

5.1. Practitioners' interviews

This first study allowed us to see that eco-designers could be set mainly between phase 2a and 2b. Qualitative or quantitative approaches could be performed all along the NPD and should be adapted, to both available data and the environmental levers, within each step.

Despite our effort to have experts knowledgeable of the medicine NPD, two limitations linked to this panel can be mentioned. First, even if the regulation requires some harmonized steps within the pharmaceutical sector, each company may have their own way to integrate these requirements. The experts involved were only part of one multinational company.

Secondly, medicines are complex products. It is therefore always possible to find experts with a targeted activity and related expertise within a sub-step of the pharmaceutical development. Our approach was to interview people with both an overview of the process and operational knowledge. Therefore, the interviews could gain in deepness by adding other complementary expertise within the pharmaceutical NPD.

The data available for an eco-design approach was explored during the interview but due to the complexity of the product, deep levels of granularity were not defined.

5.2. Environmental aspects root cause within R&D decision making

Like the previous approach, the purpose of the experiment was not to catch all the specificities of medicines. Additionally, in terms of development, the deliverables are most likely different due to the different processes and specifications of such products. In this approach, we did not include these kinds of complexities.

In Fig. 6, the profile of the curve seems to tend to a gaussian form. "anomalies" can be noted for the phases 1 and 3. For phase 1, no significant deliverables were identified. For the second one, as the product is still in trials during phase 3, modification of medicine should be still feasible or at least have a higher potential than the approval phase where everything is frozen for the market authorization. A misunderstanding of the steps and related eco-design potential may explain the results here.

One of the limitations of the approach is linked to the expert involved. Despite the documentations made available (list of deliverables within the R&D process and LCA results), results may differ depending on the level of understanding of both the R&D processes and environmental aspects of the expert part of the experiment.

Another bias who could be mentioned is the level of uncertainty and the attrition rate linked to the advancement of the project. Indeed, both are usually high at the beginning and the more a project is going through the different stages, the more accurate the environmental aspects can be assessed but less environmental levers appear. This bias was indirectly considered in the approach with the number and the type of deliverables of each stage.

Nevertheless, our experiment led us to the potential contribution of the NPD stages of medicine, to the environmental aspects per lifecycle step profiles shown in Figs. 4 and 5; and the eco-design potential levers of product in Fig. 6.

5.3. Major highlights and convergence points

For R&D practitioners, we noticed a lack of understanding of eco-design approach. Even if all interviewees are aware of the environmental issues that we are facing and are convinced of the necessity to integrate environmental aspects into their activities, a lack of holistic perspective is perceivable.

Despite the three macro design steps described in chapter 4.1, we decided to present major highlights and convergence points through the four main stages described in Fig. 2 as it is commonly used in the pharmaceutical sector.

- Research

Result show that, at this stage, the objective is to identify a molecule with a possible therapeutic target and its role in the disease. Other product aspects (such as the galenic form or the packaging) are usually not studied. Nevertheless, some decisions may have some indirect impact on the rest of the lifecycle steps. For instance, for the same disease, either if the API is based on biologic or small molecule, the specifications will most likely not be similar and imply different possibilities, such as the administration mode (e.g.: one API is only stable in solution

Table 5
Breakdown of eco-design potential within the pharmaceutical NPD for the global warming impact with the aggregation of the lifecycle steps (API, formulation, packaging, distribution and use & end of life).

Research		Early development			Late development			Market	
Target identification	Lead discovery	Preclinical trials	Phase 1	Phase 2a	Phase 2b	Phase 3	Approval	First launches	LCM
6%	*13%*	*15%*	*/*[a]	*23%*	*21%*	*3%*	*10%*	*4%*	*5%*

[a] Anomaly due to no clear deliverable in the list provided to the expert.

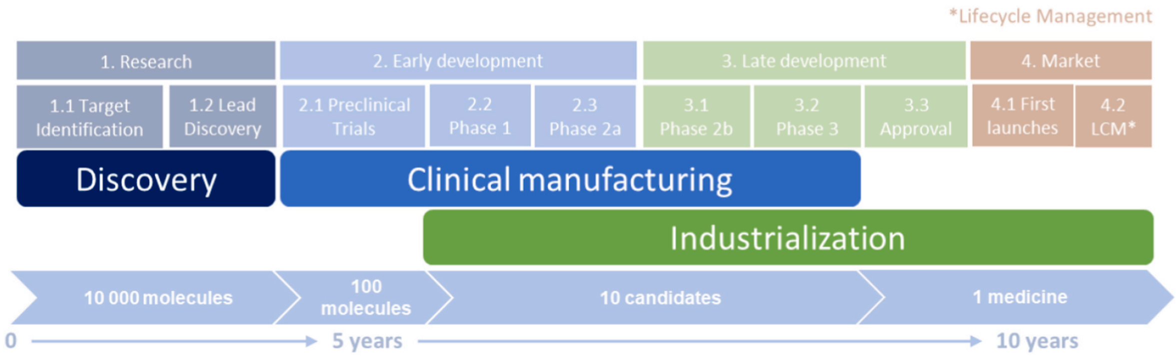

Fig. 4. The three macro design steps within the Pharmaceutical Development process.

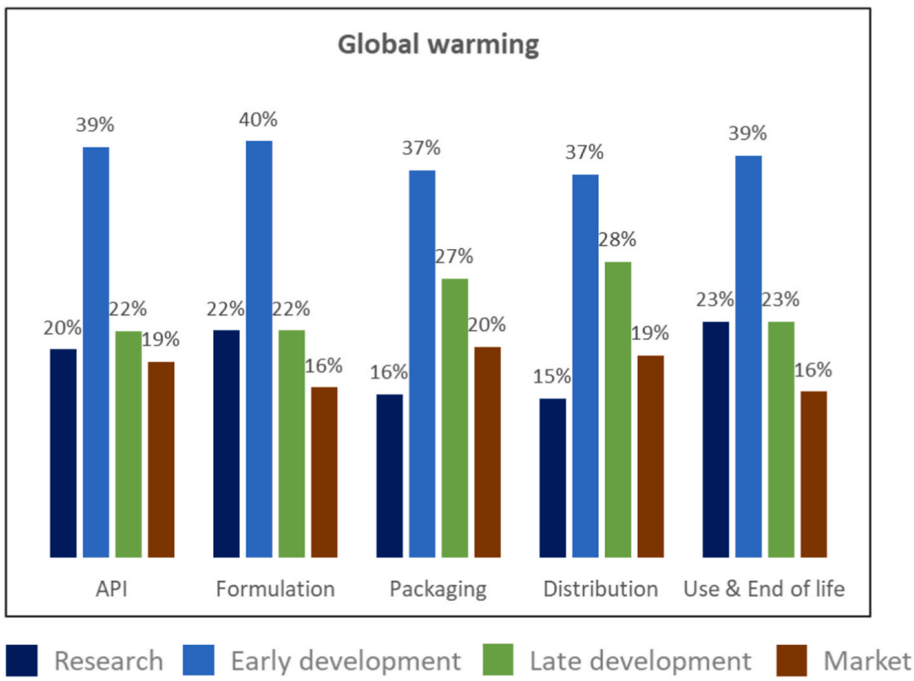

Fig. 5. Breakdown by lifecycle stage of the level of influence of the deliverables of the medicine NPD, for the global warming impact per lifecycle steps (API, formulation, packaging, distribution and use & end of life), based on 263 deliverables assessed.

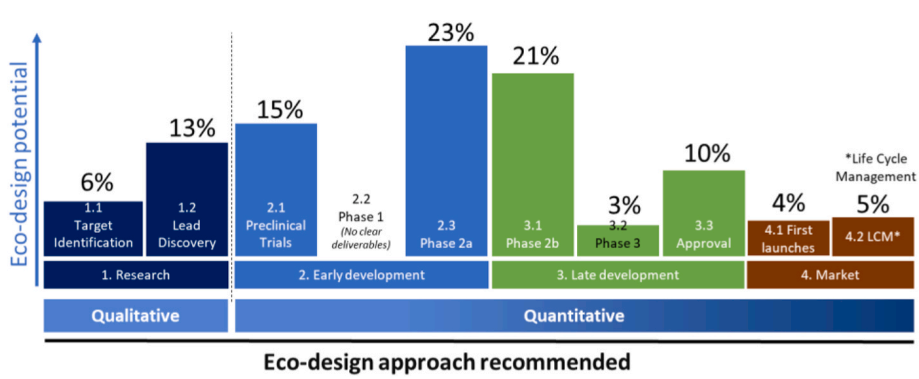

Fig. 6. Eco-design approach recommendation with the potential levers of product (average of each step of the lifecycle) per sub-step of the pharmaceutical development, for the global warming indicator.

and the other in powder, who allow to have oral forms like tablets). In this case, it will impact indirectly the galenic form of the product, related excipients and by extension, the supply chain required to manufacture the product.

We can conclude that, depending on the type of the API, the eco-toxicity profile of it may vary and lead to different environmental impacts. Nevertheless, key decisions choices for APIs begin at this stage to reduce the number of candidates. It could be an explanation of the contribution for freshwater ecotoxicity and freshwater eutrophication profiles.

The level of uncertainty remains high and does not allow for a quantitative assessment. Some examples can be mentioned who are explaining this aspect: the high number of API candidates screened, the laboratory scale of production (which is not representative of the industrialized), the final marketed form is neither studied nor even defined yet. Nevertheless, API decision remains key for the ecotoxicity impact, and this stage should not be excluded. Therefore, a qualitative approach seems appropriate.

- Early development

The results show that the "eco-design potential" levers are mainly within this stage, when trials are conducted (clinical trials, phase 1 & 2a). During the clinical trials, the galenic form used to perform studies is not representative of the marketed product. If the molecule shows preliminary efficacy, other forms are developed for phase 1 & 2a, who are closer to the marketed product. Indeed, studies to set the specifications and to ensure safety for patients must be conducted on the final form. The packaging is not defined during this stage. As one of the main roles of the primary packaging aim to ensure the safety of patients by keeping the product stable and secure, choices of API, galenic form or even administrative route will imply ranges of packaging. As an example, liquids for injectables will not have blisters as primary packaging, unlike tablets for oral use. And on the other hand, tablets for oral will most likely not be in pre-filled syringe. With the same way of thinking, those decisions will have indirect impacts on the distribution (e.g.: storage conditions of the product, who may differ in the choice of packaging). Therefore, decisions during this stage will define most of the environmental aspects of the product.

As the validation of processes takes time, when the medicine shows some positive results in trials, industrialization steps may begin (e.g.: Scale up of processes). Therefore, evaluation of industrialization pathways may begin after the preclinical trials.

In other words, we can understand that data regarding the final marketed product begin to be generated and environmental improvements remain possible since decision making is still on going. These non-exhaustive elements may explain the importance of the early development in the decision making in terms of eco-design.

- Late development

During this stage, our study shows that the purpose of phase 2b is to study the product with a form close to the marketed one, major modifications around API or the galenic forms are usually not expected. The specifications of the product are usually frozen after phase 2b.

The industrialization choices continue to be explored (e.g.: technology for production) and some options start to be assessed (e.g.: packaging, distribution mode). At the end of this stage, every aspect of the product is defined and frozen due to regulatory constraints.

It means that in terms of eco-design, all data should be available to assess the environmental profile of the product. Nevertheless, major modification of the product cannot be performed at this stage or require another round of trials or years of studies. For instance, modification of the galenic form of a tablet to a liquid, may imply changes of the excipients. Depending on the interaction between each compound and the processes to manufacture the drug product, the physical property of the product may change (e.g.: condition of stability) and need to be assessed. Therefore, both product aspects and related activities (e.g.: industrialization, distribution), should be optimized at the end of this stage.

- Market

Right before the first launches, our results show that decision making regarding secondary and tertiary packaging may occur. Main parameters are usually fixed and due to the regulatory constraints, modifications are complex as mentioned previously.

At this stage, we can understand that, even if the level of understanding of the product is high, the levers to improve the product are small. It seems possible to fine tune some aspects, but most of the effort should be deployed in other stages.

The figure below summarizes our eco-design recommended approaches to adapt with every sub-step of the pharmaceutical NPD.

6. Conclusion

One of the main societal duties of the pharmaceutical sector is to provide medicines. As defined by the SDG three, they need to make them available and affordable in order to grant good health, despite the inequities all around the world. But this responsibility does not allow the pharmaceutical industry to avoid the environmental concerns related to its activities and products. Nowadays, environmental risk assessments are performed. Nevertheless, this approach does not provide a holistic view of the environmental impact of the product and is not based on a lifecycle perspective. Eco-design is an approach which can support industries to consider them. Trace of environmental approaches integrated into design can be found around 1960, but the field of eco-design research seems to be formalized in the 1990's Despite the effort of the pharmaceutical industry to consider environment aspects), the literature suggests that this sector seems to struggle when it comes to have a holistic approach of eco-design into the medicine NPD process.

Therefore, the research question *"In which steps of the pharmaceutical R&D process is there sufficient information available to* support *eco-design activities?"* was raised in this paper. We tried to focus on the meso level of the integration of eco-design as described by Brones. To answer this question, we performed two experimentations in order to feed our two hypotheses; H1 *"Eco-design activities can be focused on specific steps of the medicine NPD"*; H2 *"Quantitative environmental assessment, such as LCA, can* support *decision making during the Pharmaceutical NPD"*. We have found that information is available at each stage of the R&D process that could support eco-design activities, but quantitative environmental assessments would only be possible in the later stages due to high uncertainty in the data available during the research and early development stages.

The first experimentation consisted of semi-directive interviews of 10 practitioners of the pharmaceutical R&D. The second one was an investigation performed with both LCA results of an existing medicine and R&D process & related deliverables. The aim was to identify eco-design potential levers & decision-making during medicine NPD process. This last one was not yet explored in the literature, and we proposed to have a first case within the pharmaceutical sector.

Results show that, even if unknowns and uncertainties regarding the specificities of the product remain in the research phase, the environmental levers are high, and an eco-design approach should not be excluded. At the early development, characteristics of the product and industrialization start to be investigated. Therefore, a focus on eco-design seems to be appropriate. At the beginning of late development, eco-design levers still are relevant but seem to decrease exponentially until the market. The key focus of eco-design within the pharmaceutical R&D seems to appear between the early development and the late one. In other words, between clinical phases 2a and 2b. Therefore, the H1 "*Eco-design activities can be focused on specific steps of the medicine NPD*" seems to be validated.

Even if eco-designers can be identified during the whole pharmaceutical development, the level of understanding of the final form marketed is not the same at each phase. It is therefore not possible and does not seem relevant to have a quantitative environmental assessment at each phase. The H2 *"Quantitative environmental assessment, such as LCA, can* support *decision making during the Pharmaceutical NPD"*, is therefore not fully validated but could be rectified by the possibility to engage eco-design qualitative or quantitative approaches, all along the NPD. Due to the lack of data during research, quantitative approach cannot be initiated. Nevertheless, linked to the environmental potential levers, qualitative approaches are strongly recommended to support the medicine NPD as the decision making will have indirect impact in the rest of the development (e.g.: administration route will impact the galenic form). The quantitative approach should start at the beginning of the early development until the market. The maximum eco-design potential seems to be between phase 2a and 2b.

7. Future work

Medicines are complex products and development specificities (e.g.: small molecules, biologics) are not explored in this paper. This study could be fostered with interviews of other experts, to better represent both R&D process and practices in other pharmaceutical industries. The second experiment could gain in deepness by integrating not only other different environmental experts but also practitioners of pharmaceutical development.

The integration of eco-design should include the macro part, the meso, the micro and the soft side. In this paper, we focused on the meso level, and we showed that it is possible to integrate eco-designers all along the medicine NPD with qualitative or quantitative approaches. To foster the meso level, it seems necessary to identify the types and the levels of environmental requirements per phase.

Another perspective should be to work on the micro level, or in other words, tools to support the eco-design approaches. Both tools to support assessment and improvement could be fostered. For instance, few Product Category Rules are available for pharmaceutical products (Emara et al., 2018; Jiménez-González and Overcash, 2014; Martin et al., 2022). It is therefore complex to adopt a harmonized approach of LCA without such documentation formalized. As the LCAs are time-consuming and complex to handle, simplified models to foster the environmental assessment could be proposed for R&D experts (Suppipat et al., 2021). The model should integrate the level of uncertainty, who most likely will depend on the phase of the pharmaceutical development. A more technological approach could also be a way to foster eco-design. For instance, the opportunities offered by the industry 4.0 could ease the data collection for LCA (Dahmani et al., 2022; Ding, 2018; Garcia-Muiña et al., 2019; Gupta et al., 2021).

For improvement tools, it could be interesting to develop guidance for R&D practitioners. As an example, for galenic formulators, if they need a film coating for a tablet, a list of excipients with this function could be proposed with their related environmental impacts. The development of model to generate optimal solutions through the LCA approach can be an opportunity to guide the development teams (Tao et al., 2018). The circular economy concept is already known is the pharmaceutical sector, especially when we talk about solvents and catalyzers. Nevertheless, this approach could be fostered in the whole Lifecycle of the product and coupled with the LCA to make sure of the environmental benefit of closing loop and therefore support the viability of medicines (Aguiar et al., 2021; Ang et al., 2021; Dumée, 2022; Hobson, 2021).

Finally, the macro level and the soft side of eco-design was not part of this paper. The macro piece is intrinsic of each company, and they should integrate eco-design in their strategy (e.g.: clear targets for every level of the organization). The soft side is focused on people and behavior. It is therefore recommended to adapt the eco-design management approach to the company's culture and by considering the changes resistance (Boks, 2006).

CRediT authorship contribution statement

Duc-Nam Luu: Conceptualization, Methodology, Writing – original draft, Visualization, Investigation. **Hervé Gachet:** Formal analysis. **Claus-Jürgen Maier:** Project administration, Validation, Writing – review & editing. **Nicolas Maranzana:** Supervision, Writing – review & editing. **Améziane Aoussat:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.132785.

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Product eco-design practice in green supply chain management: a China-global examination of research

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Abstract

Purpose – This paper comprehensively and systematically reviews and critiques the product eco-design practice in green supply chain management studies. It seeks to explore drivers, barriers and initiatives of eco-design practice with a specific emphasis on China in comparison to non-China countries.

Design/methodology/approach – This paper adopts a systematic literature review approach. It also uses a conceptual thematic landscape of the global eco-design practice along supply chains to critically evaluate published studies. The Web of Science™ Core Collection database is used as the source.

Findings – Results show that although common factors exist, China exhibits a higher number of barriers, leading to an overall lag in eco-design adoption. China's advantage lies in pressing market demand, actively engaged human resources and a cooperative culture. Alternatively, non-China countries demonstrate their relative superiority in eco-design tools, knowledge and innovation. Findings also indicate stakeholders simultaneously act as the three roles of eco-design practice in all countries, so do environmental regulations in China.

Originality/value – A thematic framework is introduced that can be used to further investigate and identify research opportunities. This study aids practitioners take stock of current eco-design management issues. It also includes pertinent recommendations on international eco-design performance improvement. It especially provides significant insights into successful eco-design implementation to green supply chains in China.

Keywords China, Literature review, Implementation, Green supply chain management, Eco-design practice

Paper type Literature review

1. Introduction

Economic development typically arises with rapid industrial modernization and commensurate natural environmental problems. Growing environmental concerns make practices such as green supply chain management (GSCM) critical for modern businesses. A prominent aspect of managing GSCM activities is product design. In this situation, eco-design practices receive greater significance. Eco-design aims to reduce the negative impacts of a product on the environment and society in the product design process without compromising other criteria and specifications such as product performance, mode of use or appearance. Eco-design practices have an effect on supply chain environmental, economic, operational and intangible performance. Even with eco-design significance, there are

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organizational challenges such as allocating the time and resources for this practice in a very competitive market environment.

As an emerging GSCM dimension, eco-design's benefits are abundant. It improves firm environmental and social reputation and image by complying with environmental protection regulation. It offers resource management and efficiency such as minimizing hazardous substances (Lennox *et al.*, 2000; Linton *et al.*, 2007; Dyllick and Rost, 2017), especially given that 80–90% of the total cost of a product life cycle is determined at the design stage (Gattenby and Foo, 1990). It also influences supply chain partners as new environmental designs will likely require changes in supplier development of eco-efficient materials or components (Hemel and Cramer, 2002; Zhu *et al.*, 2012a). Despite its potential environmental and commercial gains, eco-design can be complex, vague and expensive (Knight and Jenkins, 2009; Short *et al.*, 2012; Deutz *et al.*, 2013).

China is now the world's second largest economy and foreign investment source. Studies confirm that eco-design is the most widely adopted GSCM initiative globally (Zhu and Sarkis, 2006; Eltayeb and Zailani, 2009; Eltayeb *et al.*, 2011). This observation is especially true in China owing to resource scarcity and environmental degradation. To motivate eco-design practice adoption, China's government rewards some producers that meet the eco-design requirements (Gu *et al.*, 2017). On a more proactive side, globally, green products by Chinese manufacturers can help build corporate market share and provide greater revenue margins (Zhu and Sarkis, 2006). With China's attention shifting to circular economy principles (Veenstra *et al.*, 2010), eco-design becomes broadly integral. Therefore, it is important to help evaluate China's eco-design practice, summarize the key factors of motivations, obstacles and measures and compare them with the corresponding dimensions of other countries. In view of this, our research questions are as follows:

RQ1. What are the similarities and dissimilarities of eco-design practice in GSCM between non-China countries and China?

RQ2. What implications for eco-design could we learn from this comparison and examination?

The purpose of this study is to delve into these issues. The most distinct and important characteristics of practice – drivers, barriers and initiatives – in non-China countries and China, are respectively, evaluated and analyzed. This evaluation is based on existing applications and studies. We outline the most salient eco-design characteristics of current practice. In doing so, this study provides a reference for GSCM eco-design improvement in China and other countries.

The contributions of this study are threefold. Scholarly contribution includes conceptualizing the field to make some progress towards theory building. Identifying key variables that influence the eco-design adoption assist to this development. For practitioners understanding eco-design application in China and other countries provides insights and lessons that can be garnered by their organizations. The range covers benchmarking eco-design practices; an assessment of strengths and weaknesses; and a shared vision for eco-design implementation. For policymakers and other community stakeholders it is devoted to providing study resources and practices aggregation for governmental and community policies that can use eco-design principles for the broader social good.

To help meet our objectives and contribution in this study, a comprehensive literature review is completed. Section 2 introduces eco-design in GSCM background. The methodological details for this study appear in Section 3. Section 4 describes three evolving perspectives of product eco-design practice of non-China countries. A similar classification and description in China emerge in Section 5. Section 6 provides a comparison of all identified factors from a synthesis of published works. Section 7 discusses these comparison results with highlighting promising research directions and implications. In the end, Section 8 gives a conclusion.

2. Background

Literature and research reviews in the field of eco-design are rapidly developing. Most current studies focus on successful factors (Johansson, 2002), main barriers and principal methods and tools (Rossi *et al.*, 2016). Our review differs from these studies by introducing a regional perspective of eco-design practice, which has not seen investigation. China has seen substantial progress in this area over the past couple decades. There are multiple factors that can provide insights for summary and research. The objective is to understand the fundamental changes in the eco-design practice of GSCM and how the practice compares between China and other nations.

Eco-design conceptualization and its relationship to GSCM performance set the foundation for this research review. These issues are briefly overviewed.

2.1 Product eco-design

Product eco-design is a dynamic process consisting of ecological attributes and various stakeholder demands over the full product life cycle. Eco-design requires innovative practices, uses ecological principles and encompasses social and ethical aspects. Renewable energy, sustainable material selection, durability, modularity, maintainability, disassembly, eco-friendly transportation and green packaging characterize the eco-design practices. Some general and popular eco-design strategies include design for reduction/elimination, design for reuse, design for recyclability (recovery), design for remanufacturing and design for resource efficiency (Singhal, 2013). It has been integrated into ISO standards (ISO 14040, 2006; ISO 14006, 2011; ISO 14001, 2015), which is central to greening of organizations.

Eco-design practice addresses product functionality while simultaneously minimizing life cycle environmental impacts. Take the information and communications technology sector as a case. Lenovo's 2018/19 Sustainability Report shows that as a global sustainability leader, its Environmentally Conscious Products program is continually raising the bar on eco-design. Lenovo conserves natural resources and environment by minimizing materials usage; installing local renewable energy generation sources where feasible; increasing product's durability to prolong the time in use; promoting the use of recycled or environmentally preferable materials and maximizing reuse and recycling opportunities at the end of the product's life.

These various functionalities show that eco-design has critical GSCM linkages (Zhu and Sarkis, 2006; Zhu *et al.*, 2008a; Kuei *et al.*, 2015). The product life cycle consideration enables the engineering team to support upstream supplier selection; downstream customer green requirements; and end-of-life management with designing for disassembly and recycling.

2.2 Eco-design relationships to green supply chain management performance

Eco-design can help improve resource efficiency in supply chain partnerships, thus resulting in green supply chain performance benefits (Zhu *et al.*, 2005; Zhu and Sarkis, 2004; Shang *et al.*, 2010). Investment in product eco-design is critical to environmental leadership (Li *et al.*, 2016), not only for product performance but also for performance of organizations and their partners.

Eco-design effects on economic performance can be highly significant. Studies find cost-effective production, domestic and overseas market expansion and product quality improvement are each possible (Sroufe, 2003; Plouffe *et al.*, 2011; Bag *et al.*, 2018). The financial performance of Lenovo – hundreds of millions of customers and four devices sold per second – indicates its industry leadership. Public reports explicitly state that this is partially as a result of an eco-design and sustainability strategy.

Green product design may not have a direct impact on financial performance. It has been demonstrated to mediate environmental orientation which could eventually lead to superior performance (Li *et al.*, 2016; Chan *et al.*, 2012). Although studies showed minimal significance in other relationships, majority of them can be contingent on circumstances (Zhu and Sarkis, 2004).

The relationship between eco-design and economic performance is related to external GSCM practices such as green purchasing, customer cooperation on environmental concerns and investment recovery. Short-term benefits from eco-design include: revenues and volume of sales are predominantly higher for the green products; variable costs are lower and the B2B sector is more sensitive to eco-designed products performance results (Plouffe *et al.*, 2011).

Internal GSCM practices may facilitate information sharing across functional areas to improve green operations and process designs (Yu *et al.*, 2014). Eco-design has the potential to improve operational performance when green purchasing is in place. Upstream environmental supplier collaborations seem to greatly influence the way eco-design contributes to operational performance, which has been found to comprise lowered inventory levels, greater product flexibility (increased produce lines) and improved quality (Zhu *et al.*, 2012a). Indirect and mediating effects of environmental performance from eco-design in GSCM were also found (Fernando and Uu, 2017).

3. Methodology

A systematic literature review helps to reach conclusions on what is and is not known in a research field. It involves selecting and evaluating contributions, analyzing and synthesizing data and reporting the evidence (Denyer and Tranfield, 2009). This method serves two purposes: consolidating research findings in a specific area and identifying research gaps that can guide future research (Tranfield *et al.*, 2003). For our literature review we apply a structured content analysis process as suggested by (Seuring and Gold, 2012). The four major steps include: material collection, descriptive analysis, category identification and material evaluation. Content analysis allows for understanding the focus of written text in a rule-governed way, thus enhancing replicability (Seuring and Gold, 2012). A good systematic review is based on a well-formulated, answerable question (Xavier *et al.*, 2017). In accordance with the research questions in the Introduction, we aim to critically examine product eco-design practice from the perspective of GSCM.

3.1 Material collection

To ensure acceptable studies appear in our review, we limit our search to English-language peer-reviewed academic journals. The material search was performed using the main scientific databases: Scopus, ScienceDirect, JSTOR, Springer, Wiley, Web of Science and Emerald databases.

Eco-design practice articles published from 2000 to August 2019 were collected. We defined the keywords and search strings. Five different perspectives within the literature are used to describe product eco-design: "design for environment" or "environmentally responsible design" or "green design" or "life cycle design" or "sustainable design." Though "eco-design" is the most frequently used term, some studies apply these terms interchangeably which provide similar definitions as eco-design. Therefore, this paper will consider the five terms as replaceable search strings.

The following search keyword strings are used within the title, abstract and keywords fields:

- ("green supply chain management*" OR "sustainable supply chain management*") AND ("sustainable*" OR "green*")
- ("sustainable supply chain management*" OR "green supply chain management*" AND ("eco-design*" OR "design for environment*" OR "environmentally responsible design*" OR "green design*" OR "sustainable design*" OR "life cycle design*")
- ("China*" OR "Chinese*" AND ("eco-design*" OR "design for environment*" OR "environmentally responsible design*" OR "green design*" OR "sustainable design*" OR "life cycle design*")

The basis on which information sources have been included and excluded should be recorded precisely (Denyer and Tranfield, 2009). Following this logic, the features of each study are evaluated on the following criteria:

Inclusion criteria:

- a description of the eco-design concept;
- an illustration of the eco-design drivers, barriers or initiatives; and
- an interpretation of how above factors happened.

– *Exclusion criteria:* Studies that did not concern eco-design practice in the context of GSCM, such as methods and tools for evaluation, were discarded.

Study evaluations are a key part of the systematic literature review (Briner and Denyer, 2012). Figure 1 summarizes the process of literature evaluation and inclusion. An Excel spreadsheet was used to aggregate the needed information. A total of 1,071 articles resulted from the keywords, titles or abstracts. After removing duplicates and filtering for peer-reviewed impact factor publications, 168 articles remained for evaluation. We then

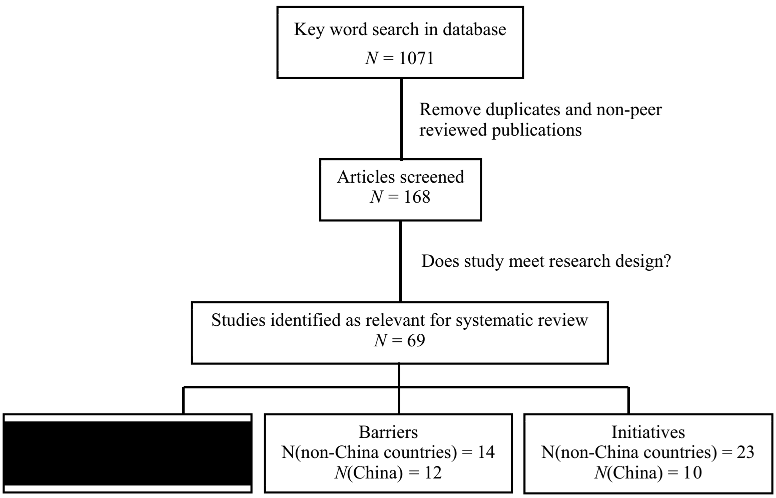

Figure 1.
Overview of literature evaluation and inclusion

proceeded to review the full contents of these 168 articles to assess if they fit our research questions. Only papers that map the main domains of our research and identify critical factors of practice were deemed relevant for further analysis. Each study was critically appraised through a second filter, considering the inclusion and exclusion criteria.

After this filtering analysis, 69 peer-reviewed articles fitting the eco-design practice theme in non-China countries and China remained. However, as more than one dimension of eco-design practice were considered in a single study, the resulting number of studies overlapped classifications. For example, Hemel and Cramer (2002) studied both drivers and barriers of eco-design in non-China countries. Liu *et al.* (2012) simultaneously investigated drivers, barriers and initiatives of Chinese eco-design practice.

3.2 Descriptive analysis

The descriptive analysis requires a detailed article evaluation based on the study typology and classifications. The research team read through the selected papers and arrived at an overall impression. Content of the studies were classified into constituent parts, including publication year, reference, application sector, research method, geographic coverage, journal's name and predominant insights. This classification made it possible to synthesize, integrate and accumulate information on the research topic, in accordance with the objectives and initial questions posed (Xavier *et al.*, 2017).

The selected publications appear in 33 different journal outlets. A wide variety of journals publish in this topic, furthering supporting the multi-disciplinary nature of this topic. Table 1 summarizes the number of studies found in the leading journals. The remaining journals concentrate on environment, management and operations: each with one publication.

3.3 Category identification

A primary objective of our study is eco-design practice evaluation in China and non-China contexts. In particular, careful attention was given to the Chinese practice description. If the article does not specifically identify a country, we classified it as non-China. Drivers, barriers and initiatives classifications are also part of our study. Drivers and barriers are initial practice adoption attributes. These elements are used to determine whether a company implements an innovation. Initiatives that influence practice adoption include organizational processes or activities and stakeholder programs such as governmental policies. These three dimensions highlight country-specific organization perceptions towards eco-design. The definition of categories relied on research team interpretation. Research strings that combine keywords with their synonyms assisted in classification, as shown in Table 2.

Leading journals	Publication quantity
Journal of Cleaner Production	17
International Journal of Production Economics	7
International Journal of Operations and Production Management	4
Journal of Business Ethics	3
Business Strategy and the Environment	3
Omega	2
Supply Chain Management: An International Journal	2
Journal of Operations Management	2

Table 1. Publication quantity in the leading journals

3.4 Material evaluation

In this step, all publications were evaluated on the categories identified in the previous step. Eco-design practice dimensions were coded to reflect the focus of each article on either drivers, barriers or initiatives. The total number of each dimension in China or non-China countries is shown in Figure 1. An aggregative approach helps extract the data and categorize the findings presented in the studies (Medeiros *et al.*, 2014). To enhance the comprehensiveness of our review, we sought associations among the dimensions identified in individual studies and described how these dimensions relate to each other. There exist similarities and dissimilarities of eco-design practice factors between non-China countries and China. Some factors also play multiple roles in different countries. In this view, each factor is given an explicit description to make it clear. We synthesized and compared the main results of the three dimensions – drivers, barriers and initiatives, to provide a mapping of the state of the art and to identify gaps for future research in this field of knowledge.

4. Product eco-design practice in non-China countries

Globally, outside China, manufacturers have broadly recognized that eco-design is a vital part of GSCM. Considering the non-China focus, eco-design drivers, barriers and initiatives identified in published studies are described and critiqued.

4.1 Drivers

The driver categorization appears in Figure 2. Three interrelated groups are presented: external drivers, supportive drivers and internal organizational drivers.

Product eco-design can be influenced by stakeholder requirements, greater market share or strict environmental policies and regulations. These approaches relate to risk-avoidance and opportunity seeking behaviors (Silvestre *et al.*, 2018). By contrast, internal drivers may include morality considerations, decision-maker values or organizational culture (Muller and Kolk, 2010). These driver elements cover corporate reputation, image, innovation or strategic direction.

Product eco-design based on internal motivations is more likely or easier to institutionalize. In fact, studies show that “getting your house in order” is the first step in successful sustainable innovation (Zhu *et al.*, 2013). While external and internal incentives are broad, two supportive incentives or drivers play particular roles. Supplier and customer cooperation, on either side of supply chain, are of great importance given that eco-design is justified only if the products are finally accepted by the organizational partners. This situation differs from stakeholder pressures, which do not necessarily focus on cooperative efforts. Both partnerships provide two-way drivers with joint business issues as a goal.

More detail on these drivers is shown in Table 3. Regulatory and policy measures for products to have beneficial environmental attributes exerts strong influence on design

Theme	Rationale	Synonyms
Drivers	Drivers that enable successful implementation of product eco-design practices in green supply chains	enablers/drivers/triggers/promoter/ facilitator/catalyst/incitant/stimuli
Barriers	Barriers that inhibit product eco-design implementation in green supply chains	obstacles/challenges/difficulties/ obstructive/barriers
Initiatives	Initiatives for product eco-design implementation	practices/actions/initiatives/activities/ measures

Table 2. Themes applied to eco-design practice and selection of criteria

changes (Zhu *et al.*, 2013; Escobar and Vredenburg, 2011; Dubey *et al.*, 2015; Iranmanesh *et al.*, 2019; Dalhammar, 2016; Ardente *et al.*, 2014). For example, export-oriented automotive firms need to consider product environmental design characteristics in their manufacturing processes (Yu *et al.*, 2014; Quella and Schmidt, 2003). The pressures are varied, including tax-subsidy systems and stringent but flexible norms, which typically lead to radical innovations in product design (Roy, 2018).

Considering external stakeholder factor inputs can improve eco-design and are integral to GSCM practice (González-Benito and González-Benito, 2005; Bundgaard *et al.*, 2017;

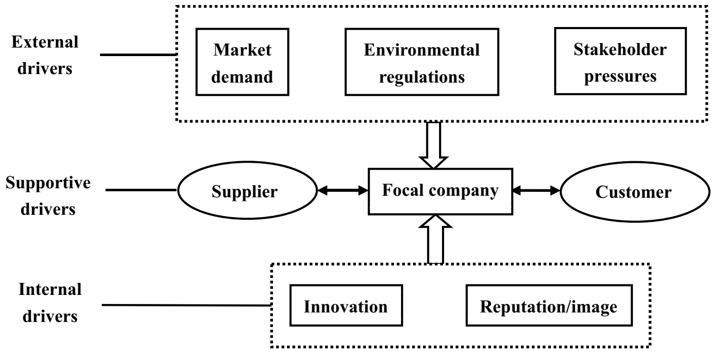

Figure 2. Drivers for product eco-design in non-China countries

Drivers	Description	Studies
External drivers		
Environmental regulations	These acts can force manufacturers to implement eco-design practice, such as EU's 2009 Eco-design for Energy-related Products Directive	Zhu *et al.* (2013), Escobar and Vredenburg (2011); Ardente *et al.* (2014), Dalhammar (2016); Hemel and Cramer (2002), Iranmanesh *et al.* (2019); Roy (2018)
Stakeholder pressures	Primary stakeholders are suppliers, consumers, recyclers and governmental authorities, secondary ones are media, NGOs, financial institutions	Bundgaard *et al.* (2017); González-Benito and González-Benito (2005); Sarkis *et al.* (2010)
Market demand	Pressure from customers willing to buy green or environmental-friendly goods or services	Dubey *et al.* (2015), Shen *et al.* (2014); Eltayeb and Zailani (2009), Hemel and Cramer (2002)
Supportive drivers		
Suppliers	Close supplier relationships are established	Johansson (2002); Zhu *et al.* (2012a)
Customers	A strong customer focus is adopted. Companies train their customers in environmental issues	Johansson (2002); Zhu *et al.* (2012a); Bundgaard *et al.* (2017)
Internal drivers		
Innovation	Use technology to lessen environmental impact	Santolaria *et al.* (2011); Köhler (2013)
Reputation or image	It is a direct catalyst for building customer loyalty, attraction and new product development	Hart and Dowell (2011), Kara *et al.* (2014)

Table 3. Drivers for product eco-design in non-China countries

Sarkis *et al.*, 2010). Systemic eco-design is more likely to arise from market demand (Shen *et al.*, 2014). Engagement with suppliers and customers beyond capacity building is also valuable. Supportive relationships with them drive eco-design implementation and improve economic performance (Zhu *et al.*, 2012a; Bundgaard *et al.*, 2017; Johansson, 2002).

Studies reveal decision-maker intrinsic motivations in innovation support successful product eco-design (Santolaria *et al.*, 2011). The environmental performance of a technology is primarily determined by innovation from early design stages (Köhler, 2013). Maintaining and improving reputation or image is an important reason for organizations to engage in eco-design (Hart and Dowell, 2011; Kara *et al.*, 2014). Firms risk a reputational loss if environmental or social problems occur at earlier supply chain stages. Effective and open eco-design practices can mitigate this concern.

4.2 Barriers

Difficulties and challenges in eco-design implementation still exist despite its benefits and drivers (Boks and Stevels, 2007; Poulikidou *et al.*, 2014). Figure 3 summarizes the factors hindering eco-design in GSCM. These barriers are characterized by the literature as internal and external groups.

Several factors within an organization lead to limited eco-design commitment. Integration management, missing strategy and culture are major obstacles. Lack of market demand and key partner exit are two important external barriers across the world. In many cases, eco-design is partially adopted without a structured and systemic approach. This situation exerts an irresponsible environmental and social impact, makes it unlikely for effective green product and green market development (Sellittoa and Hermann, 2016), eventually damaging green corporate image and competitive advantage.

Table 4 specifies a number of barriers. Integration eco-design management into the product development process is the most often-mentioned challenge. It exists across all organizational departments and levels. The lack of time, money and manpower; techniques integration; tool requirements; internal communication; information exchange; knowledge dissemination; competences and expertise needed for eco-design are identified as critical managerial concerns (Dekoninck *et al.*, 2016; Sinding, 2000).

Organizations find it difficult to develop and update a strategy, especially when making radical strategic changes required for eco-design practices (Porter and Kramer, 2006; Sharma, 2000; Sarkis *et al.*, 2010). Sustainability initiatives can have high costs and may be limited by organizational economic goals (Sinding, 2000). Furthermore, business culture and

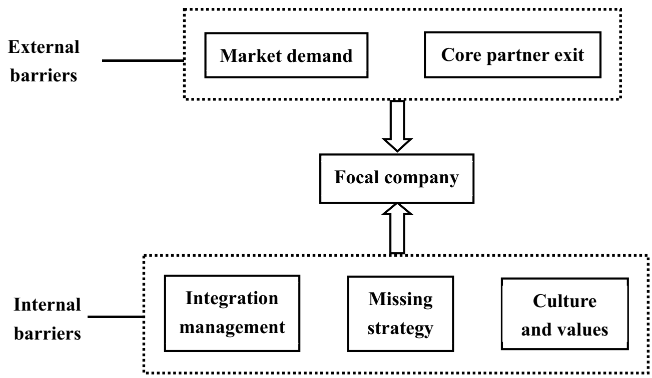

Figure 3.
Barriers to product eco-design in non-China countries

executive values can be corporate environmental sustainability barriers (Daily and Huang, 2001; Sarkis *et al.*, 2010), such as the reactive mentality of waiting for external factions to force an issue (Sroufe *et al.*, 2000). The role of organizational culture is fundamental in the formation of internal environmental awareness (Perron *et al.*, 2006).

External barriers to eco-design practice also exist. Eco-design activities need to consider the entire supply chain entailing stakeholder collaboration (Vachon and Klassen, 2006). The unforeseeable exit of a core partner – a major supplier – may disrupt product eco-design efforts (Sarkis *et al.*, 2011; Knight and Jenkins, 2009), so does lack of market demand for green products (Hemel and Cramer, 2002; Short *et al.*, 2012; Rossi *et al.*, 2016). This concern partly deals with perceptions. For instance, products with "eco-properties" are often perceived as more expensive to purchase, and most people are skeptical in paying extra for a green product image.

4.3 Initiatives

Initiatives, namely, actions or activities, enable product eco-design practices within organizations (Figure 4). Eco-design directives and standards, such as Integrating environmental aspects into product design and development – ISO/TR 14062 (Quella and Schmidt, 2003), Guidelines for incorporating eco-design (ISO 14006, 2011) and Directive

Table 4
Barriers to product eco-design in non-China countries

Barriers	Description	Studies
Internal barriers		
Integration management	The lack of integration of eco-design activities into existing new product development process	Dekoninck *et al.* (2016), Sinding (2000)
Missing strategy	Companies do not incorporate eco-design into product developing strategy in the long run	Porter and Kramer (2006), Sharma (2000); Sarkis *et al.* (2010), Sinding (2000)
Culture and values	Shortcomings in organizational culture and decision makers' value	Perron *et al.* (2006), Daily and Huang (2001); Sarkis *et al.* (2010), Sroufe *et al.* (2000)
External barriers		
Core partner exit	The unforeseeable exit of a core partner is also an obstacle to eco-design	Sarkis *et al.* (2011), Knight and Jenkins (2009); Vachon and Klassen (2006)
Market demand	Most customers are skeptical to higher prices of green products	Short *et al.* (2012), Rossi *et al.* (2016); Hemel and Cramer (2002)

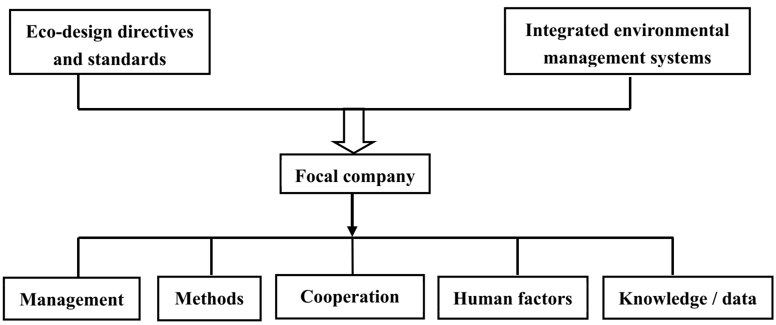

Figure 4.
Product eco-design initiatives in non-China countries

2005/32/EC of eco-design requirements for energy-using products (EuP) (Dalhammar, 2016), all require compulsory certification and measurable objectives. Integrated environmental management systems launched by governments also propose systemic approaches to ensure and evaluate a complete integration of eco-design (IEMS, 2000). These acts and programs represent external governance mechanisms to encourage eco-design adoption.

Dozens of success factors for eco-design implementation are recognized to address these external requirements and pressures (Johansson, 2002). Five key measures are summarized in Figure 4 and Table 5. They are management, methods, cooperation, human factors and knowledge-data, respectively.

Efficient internal management is a widely accepted organizational initiative (Yang *et al.*, 2010; Zhu *et al.*, 2012a; Graves *et al.*, 2013; Kurk and Eagan, 2008). Management indicators for eco-design practice include personal and departmental environmental performance metrics, green corporate culture and integrated, formal processes (Sroufe *et al.*, 2000). Eco-design maturity models are management frameworks that can support strategic and tactical deployment for eco-design (Pascual *et al.*, 2003; Pigosso *et al.*, 2013; Sihvonen and Partanen, 2017).

Methods require compatibility with company culture and legacy systems (Eltayeb and Zailani, 2009; Kurk and Eagan, 2008; Rossi *et al.*, 2016). For instance, the value of life cycle assessment (LCA) in eco-design entails integration with current institutions (Sroufe *et al.*, 2000; Peuportier *et al.*, 2013; Matos and Hall, 2007; Mirabella *et al.*, 2014). Other emergent tools and methods for environmental impact analysis also effectively embody everyday eco-design practice.

Intra-organizational cooperation and expanding to outside parties is a vital initiative to eco-design (Johansson, 2002; Zhu and Sarkis, 2008; Rossi *et al.*, 2016). With the deepening of eco-design understanding, stakeholder demands and involvement must be taken into consideration (Walton *et al.*, 1998). Technological integration with suppliers and customers is positively linked to environmental monitoring and collaboration (Vachon and Klassen, 2006).

Initiatives	Description	Studies
Management	Top management support, eco-design maturity models	Pigosso *et al.* (2013), Sihvonen and Partanen (2017); Zhu *et al.* (2012a); Johansson (2002), Yang *et al.* (2010); Graves *et al.* (2013), Kurk and Eagan (2008); Pascual *et al.* (2003), Sroufe *et al.* (2000)
Methods and tools	Tools and methods to develop the product	Eltayeb and Zailani (2009), Kurk and Eagan (2008); Sroufe *et al.* (2000), Rossi *et al.* (2016); Peuportier *et al.* (2013), Matos and Hall (2007); Mirabella *et al.* (2014)
Cooperation	Both with the inner units and outside parties	Zhu and Sarkis (2008b); Johansson (2002), Vachon and Klassen (2006); Rossi *et al.* (2016)
Human factors	Attitudes and cognitive concepts, emotions, personal traits, motivations	Boks (2006); Hart and Dowell (2011), Escobar and Vredenburg (2011); MacDonald and She (2015), Johansson (2002); Pascual *et al.* (2003), Rossi *et al.* (2016)
Knowledge and data	Knowledge sharing and a circulation of data needed	Short *et al.* (2012), Johansson (2002); Rio *et al.* (2013), Pascual *et al.* (2003); Sroufe *et al.* (2000), Rossi *et al.* (2016)

Table 5
Initiatives to implement product eco-design in non-China countries

Human factors and talent initiatives continue to be paramount for eco-design effectiveness (Johansson, 2002; Pascual *et al.*, 2003; Rossi *et al.*, 2016), though they are relatively less studied for eco-design integration (Escobar and Vredenburg, 2011; Boks, 2006). Human issues to eco-design include: an ecological worldview is important for building eco-design attitudes and beliefs within employees (Hart and Dowell, 2011); motivation to broaden problem solving and creativity skills constitutes the "soft side of eco-design" (Boks, 2006); cognitive concepts leading to the purchase and use of eco-products (MacDonald and She, 2015).

Finally, comprehensive knowledge and data, related to all the other initiatives, are necessary for information sharing and eco-innovation (Short *et al.*, 2012; Johansson, 2002; Rio *et al.*, 2013; Pascual *et al.*, 2003; Rossi *et al.*, 2016). In general, education, training or environmental specialist supports are needed for product development personnel. Specifically, integrated environmental management information systems will impact the breadth of environmental options and firm performance (Sroufe *et al.*, 2000).

Each of these initiatives requires adequate resources and capability building. Large corporations are positively related to eco-design by having more resources and capabilities to attempt costly or risky environmental investments (Singhal, 2013; Wu, 2013).

5. Product eco-design practice in China

The merit of using green supply chain practices for economic and environmental performance in the Chinese manufacturing industry is extensively studied (Zhu and Sarkis, 2004). We intend to explore this complex phenomenon – with an eco-design focus – from similar perspectives as international practice: drivers, barriers and initiatives.

5.1 Drivers

Figure 5 outlines drivers for product eco-design adoption in China, which were investigated in the context of various industrial applications. The major elements begin with external incentives – market demand; environmental regulations and stakeholder pressures. Then comes supportive drivers – Guanxi, which refers to the cultural characteristics of individual and firm level relationship ties that exist within a society (Geng *et al.*, 2017a). Eventually there are internal drivers that contain cross-functional cooperation and competitive advantage. A summary of studies on eco-design implementation drivers in China appears in Table 6.

External environmental drivers are very important in adopting green practices (Wu *et al.*, 2012). Commercial competitive pressures drive organizations to pursue internal eco-design initiatives (Dubey *et al.*, 2015; Chung and Wee, 2008). Chinese consumers are increasingly

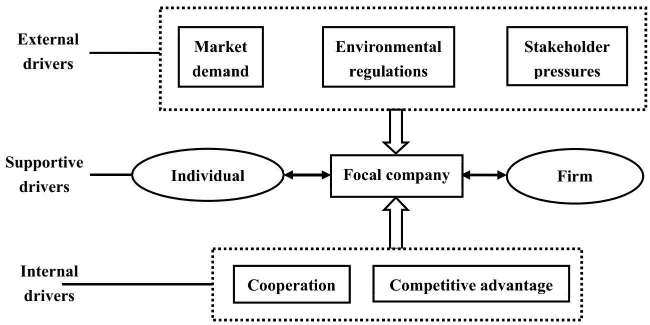

Figure 5.
Drivers for product eco-design in China

Drivers	Description	Studies
External drivers		
Market demand	Chinese consumers increasingly heightened their interest in "green" products.	Wu *et al.* (2012), Chung and Wee (2008); Dubey (2015), Liu *et al.* (2012)
Environmental regulations	These acts can force manufacturers to implement GSCM practices, such as certain eco-design principles	Wu *et al.* (2012), Yuan *et al.* (2006); Zhu and Sarkis (2008), Zhu *et al.* (2013); Kuei *et al.* (2015), Liu *et al.* (2012)
Stakeholder pressures	Suppliers, customers, communities, competitors, etc.	Christmann and Taylor (2001), Zhu and Sarkis (2008); Zhu *et al.* (2007), Liu *et al.* (2012)
Supportive drivers		
Guanxi	The relationship both at individual level and firm level	Geng *et al.* (2017a)
Internal drivers		
Cooperation	Cooperation in industrial symbiosis: Chinese companies have a responsibility to comply with foreign legislation	Zhu and Sarkis (2008b); Kuei *et al.* (2015)
Competitive advantage	The organizational resources and capabilities	Wu *et al.* (2012)

Table 6
Drivers for product eco-design in China

environmentally aware and prefer *green* products (Liu *et al.*, 2012). Moreover, an important driver is the strong influence of China-unique government policies (Wu *et al.*, 2012; Liu *et al.*, 2012; Yuan *et al.*, 2006; Zhu and Sarkis, 2008; Zhu *et al.*, 2013; Kuei *et al.*, 2015). For instance, "Implementation plan of EPR (Extended Producer Responsibility)," "Made in China 2025" and "Green Manufacturing Engineering Implementation Guide (2016–2020)" are examples of manufacturer-focused policies. Stakeholder pressures from external factors – suppliers, customers, communities and competitors – are especially acute in China and drive Chinese enterprises to implement eco-design (Christmann and Taylor, 2001; Zhu *et al.*, 2007; Zhu and Sarkis, 2008; Liu *et al.*, 2012).

Guanxi, informal but strong relationships, plays a decisive role in Chinese corporate sustainability development. Two types of Guanxi in GSCM adoption are identified: Guanxi at individual level and aggregated Guanxi at firm level (Geng *et al.*, 2017a). These two levels help companies manage their relationships with other green supply chain partners, thus positively influencing eco-design practice.

There also exists two internal drivers. Cross-functional cooperation is a factor (Zhu and Sarkis, 2008). For example, electrical products sold to the European market are manufactured in China, requiring Chinese product developers to play a crucial role in global green supply chain (Kuei *et al.*, 2015). In this view, internal product eco-design collaboration is an indispensable catalyst.

Enterprise competitive advantage – resources and capabilities – are also closely related to eco-design adoption in China (Wu *et al.*, 2012). Superior resources include organizational support, social capital and government involvement. Product stewardship and the strategic capability of pollution prevention are also asserted to achieve sustainable development.

5.2 Barriers

Eco-design lags across Chinese GSCM practices. Several barriers have been identified in Figure 6. Internal barriers include a lack of knowledge, no applicable eco-design tools, insufficient innovation capabilities and perceived adoption costs. External barriers derive from complexity of regulations and higher-tier suppliers. Table 7 details these challenges. If limited resources are not used in an eco-effective manner, the consequences are the increasing release of pollutants and their accumulating impact on ecological life-support systems in China (Wang and Côté, 2011).

Lacking GSCM knowledge is a key barrier to implementing green practices in Chinese firms (Kuei *et al.*, 2015). Most manufacturers only operate domestically or in Asia, limiting access to globally advanced technologies and expertise. Product eco-design is difficult for organizations that lack innovative capabilities (Alblas *et al.*, 2014).

Product eco-design often entails high initial costs, which are not as great as perceived benefits according to Chinese manager opinions (Chung and Wee, 2008; Geng *et al.*, 2017a). This perception becomes another key barrier (Abdulrahman *et al.*, 2014). Finally, eco-design

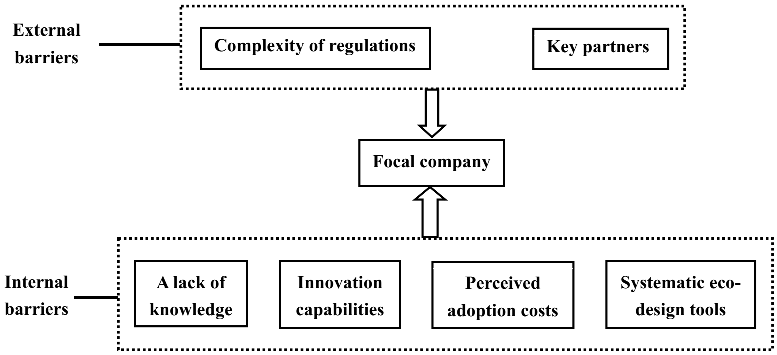

Figure 6. Barriers to product eco-design in China

Barriers	Description	Studies
Internal barriers		
A lack of knowledge	A lack of eco-design knowledge and its access	Kuei *et al.* (2015)
Innovative capabilities	Exploration, experimentation, double-loop learning, creativity and entrepreneurship that can be used to solve organizational coordination problems and to manage these process capabilities	Alblas *et al.* (2014)
The perceived costs of adoption	The high costs and the lack of financial return	Abdulrahman *et al.* (2014); Geng *et al.* (2017b); Chung and Wee (2008)
Systematic eco-design tools	Methods/tools utilized to apply the product eco-design projects	Zhu and Liu (2010)
External barriers		
Complexity of regulations	Significant differences in countries' local environmental regulations	Rauer and Kaufmann (2014), Yang and Rivers (2009); Lee (2011)
Key partners	Lack of influence on second- and higher-tier suppliers' green behavior	Kuei *et al.* (2015); Lee *et al.* (2014a); Gimenez and Tachizawa (2012), Abdulrahman *et al.* (2014); Rauer and Kaufmann (2014), Liu *et al.* (2012)

Table 7. Barriers to product eco-design in China

is in its infancy for Chinese organizations, there is a lack of systematic eco-design tools to support them (Zhu and Liu, 2010).

Multiple environmental rules from different countries, together with governmental control and enforcement mechanisms, act as major barriers for eco-design adoption in China. In many cases, interventions are required for companies to manage the labyrinth of regulatory policies (Rauer and Kaufmann, 2014). Regulation complexity also serves as an obstacle for developed countries to diffuse high GSCM and eco-design standards to Chinese suppliers (Yang and Rivers, 2009; Lee, 2011).

Chinese organizational cooperation with external supply chain members is very limited (Liu *et al.*, 2012). Focal companies typically cannot exert influence on key partners (Kuei *et al.*, 2015), especially sub-suppliers (Lee *et al.*, 2014a). Studies have shown that extending GSCM practices, such as eco-design, to second- and third-tier suppliers is extremely challenging (Abdulrahman *et al.*, 2014; Gimenez and Tachizawa, 2012). Most collaboration occurs between a focal company and its first-tier suppliers (Rauer and Kaufmann, 2014).

5.3 Initiatives

Initiatives pertaining to product eco-design help Chinese firms become more environmentally responsible while meeting operational performance goals (Kuei *et al.*, 2015). These initiatives do result from eco-design standards and demonstration projects. Correspondingly, we divided these initiatives into five categories: top management commitment, Chinese culture and characteristics, collaborative relationship with stakeholders, foreign institutional pressures and environmental awareness data. Figure 7 presents a summary of those approaches.

Globalization has motivated the Chinese government to focus on GSCM. A number of regulatory policies have caused Chinese organizations to embrace eco-design across their supply chains. For example, the "Industrial Green Development Plan (2016–2020)" calls for product eco-design. The evaluation standards for 66 products have been launched on the basis of "General Evaluation Principles of Eco-design Products" and "Eco-design Products Identification." The Chinese government has also supported 61 pilot enterprises for demonstration projects since 2015. As models of implementing eco-design practice, they are provided with additional subsidies upon a satisfactory official assessment. Chinese initiatives for product eco-design are summarized in Table 8.

Eco-design has become an emerging GSCM practice in China and has significant influence on corporate environmental performance (Zhu and Geng, 2001). However, Chinese manufacturers will have difficulty in eco-design practice without top management commitment (Graves *et al.*, 2013), which includes green purchasing, internal financial incentives and investment recovery (Zhu *et al.*, 2012a).

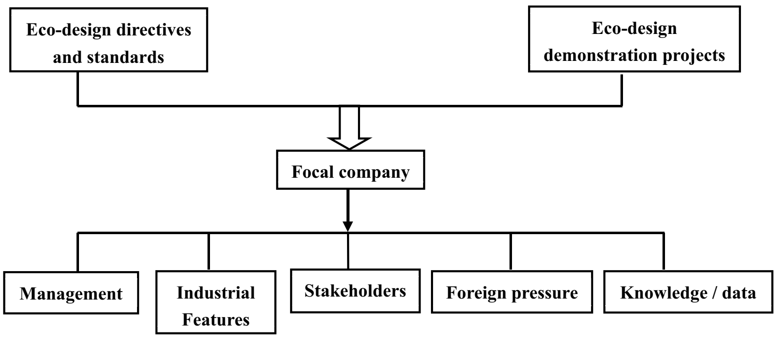

Figure 7.
Initiatives to implement product eco-design in China

Chinese industrial features are reflected in manual capabilities. Arming manual employees with knowledge on how to disassemble or recover materials quickly and accurately, should be an objective when designing products. Another salient characteristic is resource scarcity. As a result, in concert with "circular economy" policy, eco-design products with lesser consumption tend to garner more market share in China (Zhu *et al.*, 2008a).

With product eco-design pressures, it is expected that Chinese manufactures will gradually establish closer relationships with stakeholders (Johansson, 2002). Two important stakeholder initiatives are backward collaboration with suppliers and forward coordination with customers (Zhu *et al.*, 2008a; Zhu and Sarkis, 2008). Continuously educating consumers through informative green advertising could develop consumer trust and promote environmental involvement in product eco-design (Wei *et al.*, 2017).

Foreign knowledge infusion, normative institutional pressures from international partners or counterparts also support product eco-design (Zhu *et al.*, 2008a). Organizations in developed countries evaluate their direct and secondary suppliers (Christmann and Taylor, 2001). Chinese joint ventures may imitate their parent companies and then diffuse their experiences to other subsidiary enterprises (Zhu *et al.*, 2007; Zhu and Liu, 2010).

Knowledge data is a critical initiative needed to address pressures from regulations, customers and competitors. Chinese companies have sought to implement systematic eco-design by increasing environmental awareness of both employees and suppliers. Frequent environmental training and certification is a good way to enhance a company's learning capacity, which greatly determines GSCM practice level (Liu *et al.*, 2012; Zhu and Liu, 2010). Good information management systems can be further developed to provide basic data for eco-design solutions.

6. Comparing China and global product eco-design practice

The core objective of this study is a critical examination of product eco-design practice between China and non-China countries. We use drivers, barriers and initiatives to provide a path for consolidating eco-design practice knowledge within the GSCM context, allowing for some insights into the integration of eco-design and GSCM themes (Escobar and Vredenburg, 2011). Figure 8 summarizes the comparative results.

In comparison with non-China countries, China has more barriers that differ. Nevertheless, a number of Chinese industries have shown growth owing to government, professional society and international collaborative involvement and incentives (Roy, 2018). In China, the category of eco-design regulations simultaneously acts as a driver, a barrier

Initiatives	Description	Studies
Management	Top management commitment	Zhu and Geng (2001); Zhu *et al.* (2012a); Graves *et al.* (2013)
Industrial features	Incorporate Chinese industrial culture and characteristics into international eco-design partners	Zhu *et al.* (2008a)
Stakeholders	Establish collaborative relationships with stakeholders	Zhu and Sarkis (2008b); Zhu *et al.* (2008a); Johansson (2002), Wei *et al.* (2017)
Foreign pressures	Foreign knowledge infusion, normative and mimetic institutional pressures	Zhu *et al.* (2008a); Zhu and Liu (2010), Zhu *et al.* (2007)
Knowledge – data	Increasing environmental awareness and data	Zhu and Liu (2010), Liu *et al.* (2012)

Table 8. Initiatives to implement product eco-design in China

and an initiative. Studies show the direct relationship between environmental policy and eco-design practice remains an open question (Dalhammar, 2016; Pujari *et al.*, 2004). Overcoming these barriers requires the development of political-level alignment capabilities, legislation-focused sensing capabilities and technical and commercial resilience capabilities (Rauer and Kaufmann, 2014). Policymakers in China play a very proactive role in formulating "carrot plus stick" approaches to motivate eco-design practice (Zhu and Geng, 2001).

Figure 8 shows stakeholder factor is prominent within global eco-design practices. Good relationships are important antecedents to eco-design actions. Despite of stakeholder relationships and collaboration advantages, there are downsides. There is an old adage stating "while water can carry a boat, it can also overturn it." This double-edged perspective speculates that reducing cooperation levels and worsened relations that can occur with multiple conflicting stakeholders, could give rise to green practice failure (Cheng, 2011). It is necessary to have a clear understanding of this phenomenon for successful GSCM practices (Zhu *et al.*, 2005; Pascual *et al.*, 2003).

China and other countries do have additional common eco-design practice factors (Table 9). The three most influential external stimuli – market demand, environmental regulations and stakeholders – help arouse organizational interest in eco-design (Hemel and Cramer, 2002; Dubey *et al.*, 2015; Wu *et al.*, 2015). Policies and regulations could turn into incentives for improving product eco-design (Ardente *et al.*, 2014) and recyclability of valuable resources through the inclusion of "push" (mandatory) and "pull" (voluntary) measures. Also, relationships with suppliers and customers in non-China countries, or Guanxi in China, are critical firm resources and an important governance mechanism that facilitates trust and benefits exchanges among organizations (Wiegel and Bamford, 2014; Cheng *et al.*, 2012).

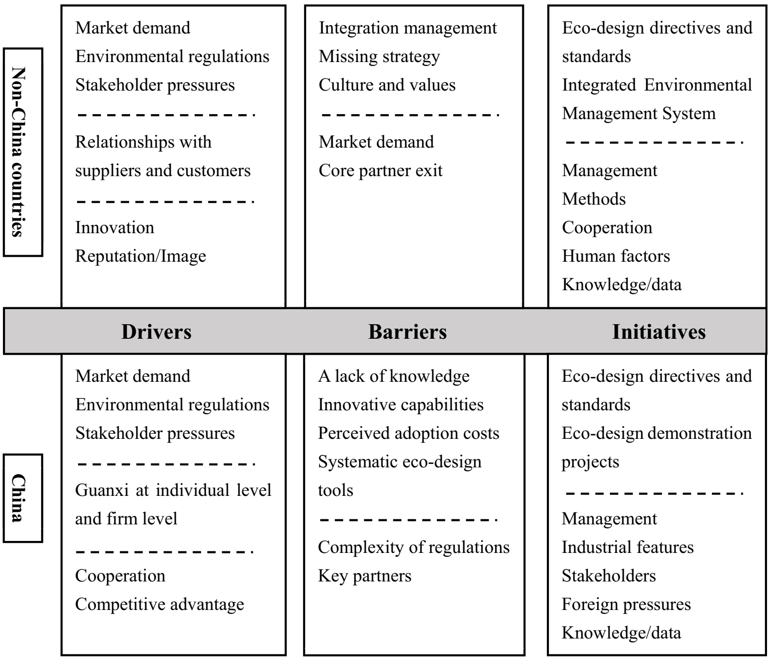

Figure 8.
Summary of three products eco-design practice aspects in non-China countries and China

Guanxi in China has a stronger effect on green practice adoption than relationships in the West (Park and Luo, 2001).

Only one common barrier exists across global countries. Studies indicate that manufacturers fail to recognize the importance of building effective collaboration with their supply chain partners (Vachon and Klassen, 2006; Vachon and Klassen, 2008; Rao and Holt, 2005). Most organizations do not know how to measure and monitor supplier green practices (Govindan *et al.*, 2014), or undertake supplier audit programs only with their first-tier suppliers, typically ignoring deeper tiers of suppliers (Gimenez and Tachizawa, 2012). Part of partnership difficulties lies in the multiple supply chain players and stages (Rauer and Kaufmann, 2014). A solution is to establish a transparent and intimate relationship with key partners.

Two initiatives – management and knowledge data – also exhibit similarities. Operating managers need to understand the positive links between eco-design and environmental, operational and economic performance (Geng *et al.*, 2017b; Azevedo *et al.*, 2011), which can enhance eco-design acceptance and contribute to successful strategies. Organizational awareness about product characteristics and potentials, aligned with specific knowledge of sustainability issues considerably improve technological innovation (Lee *et al.*, 2014b). Environmental data sharing and availability is also integral for modifying traditional design processes. Data transparency in green supply chain is critical for designers.

Likewise, eco-design practice dissimilarities between China and non-China countries are evident (Table 10). Six representative factors are identified.

Technological innovation serves as a driver in non-China countries, but is viewed as a barrier in China. New product development is directly associated with hard (e.g. cleaner production equipment) and soft (e.g. increased supplier involvement) innovations (Zhu *et al.*, 2012b; Hassini *et al.*, 2012). In non-China countries, stable and quality delivery contributes to eco-design success (Donnelly *et al.*, 2006; Johansson and Magnusson, 2006; Tingstrom *et al.*, 2006). However, China lags in this innovation capability. It may be mitigated by joining various associations or programs that help in benchmarking practices.

Eco-design practice	Similarities
Drivers	Market demand
	Environmental regulations
	Stakeholders
	Relationships/Guanxi
Barriers	Key partners
Initiatives	Management
	Knowledge-data

Table 9. Eco-design similarities between non-China countries and China

Identified factors	Non-China countries	China
Innovation	Driver	Barrier
Market demand	Barrier	Driver
Methods/tools	Initiative	Barrier
Human resources	Initiative	Driver
Knowledge	Initiative	Barrier
Cooperation	Initiative	Driver

Table 10. Eco-design dissimilarities between non-China countries and China

Market demand also plays a role in country-level differences. Market demand is a barrier in non-China countries, whereas it may be classified as a driver in China. In non-China countries, there is a minimal market response to green products usually because of their higher prices (Eltayeb and Zailani, 2009). Product design has to be consistent with market priorities (Uzzi, 1997). In contrast, China's consumers actively embrace green and sustainable products – when available – as sustainability awareness grows.

Eco-design methods and tools also differ. They are perceived more as initiatives in non-China countries, yet as barriers in China. Feasible eco-design tools in manufacturing industries have been widely adopted in most developed countries, such as LCA – used to monitor eco-design solutions throughout the whole product life cycle. Meanwhile, Chinese managers are not able to respond to green supply chain implementation partly owing to lack of eco-design tools. In China, less sophisticated tools might prevail over high-tech solutions if they can be implemented rapidly (Yu *et al.*, 2008).

Another distinction is human resources. They are recognized as a driver in China, but an initiative in non-China countries. Human factors greatly affect GSCM if supportive ecological worldviews and motivations exist. Non-China countries recommend coordination between designers, manufacturers, marketers and government policymakers to achieve positive individual behavior changes, leading to product eco-design adoption. Chinese employees who are equipped with eco-design technologies and knowledge exert a significant effect on stimulating product sustainability (Kuei *et al.*, 2015).

Knowledge is a solution to the eco-design practice, however, it is also viewed as a barrier in China. Chinese manufacturers have different implementation paths for GSCM practices. The environmental performance of products may depend on seemingly minor design aspects that are initially overlooked by Chinese industries. Eco-design knowledge and information campaigns from upstream to downstream firms in China are needed.

The final dissimilar factor is cooperation. Eco-design is a broader-based interaction practice in GSCM. China has evolved to be an indispensable and crucial role in global supply chains (Jiang, 2002). Chinese manufacturers have greater responsibility to comply with foreign regulatory policies. This effectual cooperation is a strong driver for eco-design and GSCM practice. Non-China countries seek to achieve internal and external collaboration for their fundamental roles in GSCM. In this sense, cooperation can be seen as an initiative to improve environmental performance (Guo and Miller, 2010).

7. Discussion

Eco-design has become a growing organizational environmental sustainability issue over the past two decades. Without further adoption of eco-design practices, GSCM improvement is unlikely (Zhu *et al.*, 2008a). Comparison and evaluation of GSCM practices among different countries is important for innovation diffusion and can also determine if the construct is culturally robust – whether it is congruous across country borders (Zhu *et al.*, 2008b). Our study resolves this issue by determining current eco-design practices and research needs. This literature review details the causes and effects of eco-design practice in China and non-China countries, each of which may have a varying objective and perspective on greening supply chains.

The findings imply that stakeholders simultaneously act as a driver, barrier and initiative in all countries. Stakeholders play a vital role in the successful implementation of eco-design. However, if the relationships with them are improperly handled and the interests of all parties are not balanced, key partners can become barriers to eco-design practice. A stable, appropriate and cooperative symbiotic relationship with multiple stakeholders should be established to not only share information and benefits but also achieve synergetic sustainable development.

Market demand and environmental regulations are traditionally the most influential drivers for eco-design adoption. Even with these forces, more incentives are needed to reward complete and successful GSCM (Zuidwijk and Krikke, 2008). Regulators can prescribe a variety of product eco-design standards and policies (Bundgaard *et al.*, 2017). It is possible to promote positive changes by incorporating customer interests into eco-design (Thun and Müller, 2010). Eco-sensitive customers are increasing in some markets. Manufacturers should seek to capture this growing demand. Energy-saving subsidies, green travel, and green products are dominant green consumption patterns in countries such as Germany, Singapore and Australia. The Japanese government attaches particular importance to the promotion of green consumption owing to its energy and resources limitations.

Customization is an important corporate marketing strategic decision. Consumers are likely to continue buying products with greater personal specification. Industry 4.0, including the Internet of Things, Big Data and Cloud Platforms, can provide an opportunity of customization where customers and products interact to monitor the performance of the operations (Rajput and Singh, 2019a). Promising research questions include the following:

Q1. Does the development of technologies moderate the relationships between customers and product design teams?

Q2. How can green consumption be supported through technological support?

Management and knowledge both provide efficient initiatives for eco-design adoption. It is imperative that environmental considerations be integrated into product development strategy (Brones and Carvalho, 2015). Organizations can address product value through eco-design solutions globally. Several key issues have been emphasized including the initial environmental assessment and specific strategies based on product characteristics.

Producers are willing to modify their raw materials and models to meet eco-design standards. These efforts demand time, human resource and a new holistic sense of design. To make continuous eco-design improvements, some advanced enterprises acquire knowledge and expertise and then monitor and compel sub-suppliers to follow innovations and changes.

Whereas significant differences exist in local environmental regulations, legislation plays a significant role in inducing Chinese organizations to implement eco-design. The Chinese government believes eco-design – optimizing design over a product's whole life cycle is critical for an "ecological civilization" and supply chain performance.

By October 2019, the Ministry of Industry and Information Technology had released 91 eco-design product standards, covering 89 product categories. They encouraged 61 eco-design demonstration enterprises to explore technologies and methods, exchange practical experience and share the fruits of green growth. These practices exert an immense influence and build green capabilities across various industries.

China has seen rapid green development owing to industrial transformation and upgrading, but the academic theoretical research has not kept up with the pace of practice. As more eco-design experience is gained with certain cases, an integrative study of theoretical sustainability plus practical operations could yield significant insights (Alblas *et al.*, 2014). For example, from data collection, another interesting research question arises as follows:

Q3. Do efforts to product eco-design practice vary over time for most effectiveness in different countries?

In contrast with developed countries, China's adoption and exposure to eco-design occurred relatively later owing to socio-economic development, technological innovation, eco-design tools and relative knowledge. Chinese organizations had to play catch-up with technological solutions, integrated life cycle design process and effective knowledge flows between stakeholders (Kuei *et al.*, 2015).

Given available resources, innovative approaches, such as closed-loop material and renewable energy, have been included in traditional design process. Advanced digital technologies – rapid prototyping and 3D printing – can also unlock the resources circularity within supply chains (Sousa Jabbour *et al.*, 2018), in the end facilitating sustainability in both business and environmental aspects (Gu *et al.*, 2019). Integrating these burgeoning technologies with product eco-design provides substantial research opportunities. In future study, it would be interesting to explore in-depth intelligent eco-design in GSCM. This leads to the fourth research question as follows:

Q4. How do smart and digital technologies influence product eco-design practice?

The advantages of China lie in pressing market demand and a rich culture. As the world leading production base for many global products, Chinese companies have built capabilities to actively meet the international green market requirements and steer domestic green consumerism trends (Chen *et al.*, 2005).

In China, government regulations stipulate green products should meet eco-design evaluation criteria. A total of 1,097 green products have been marketed in the fields of steel, nonferrous metals, chemical industry, automobile, electronic appliances, light industry and textiles. Chinese consumers have been increasing their attention to green products with less material and energy-intensive designs, indicating the potent effect of green advertising and publicity (Zhang and Li, 2019).

Guanxi plays a crucial supportive role in Chinese eco-design practice. There is a strong collectivism culture and more reliance on Guanxi in Chinese controlled companies – cooperation among the different functions and departments or coordination between supply chains and government policymakers (Zhao *et al.*, 2011). The success of eco-products depends on the success of this collaboration and coordination (Bag *et al.*, 2018; Koufteros *et al.*, 2007; MacDonald and She, 2015). Product design can also guide and change the behavior of users (Zhang and Li, 2019).

Non-China countries lead in eco-design strategy and innovation. Country-level sustainability priorities are catalysts for manufacturer eco-design adoption. Incorporating national and regional needs into design strategies can lead to product sustainability (Hallstedt *et al.*, 2013; Petersen *et al.*, 2005).

Technical development accompanied with eco-design initiatives include enhancing resource efficiency and optimizing production and consumption patterns. Industry 4.0 can support eco-design principles and maintain sustainable operations management (Rajput and Singh, 2019b). These technological innovations working with eco-design tools and methods are more mature in non-China countries.

Studies confirm that market demand and culture can have unfavorable effects on eco-design. Consumers are still skeptical about paying premiums for green products. This skepticism is a major barrier to corporate eco-design adoption in GSCM. These issues may be solved by government subsidies resulting in long-term learning curve improvements. Integrating dynamic and heterogenous customer needs rather than static design inputs in eco-design is needed – this customization may allow for greater acceptance of premium pricing for green products. Considering this, we present the following research question:

Q5. How and when should corporations integrate user behavior into eco-design and tailor product designs to different customer groups?

Based on the discussion of the above results, this study provides thought-provoking managerial implications for the eco-design practice in China. First, under the policy of vigorous circular economy, consumers' green consciousness is becoming more and more intense, and their consumption demands also show diversified and personalized characteristics. Governments and enterprises should strive to do market research and guide green consumption, improve product eco-design techniques in time, increase investment in green innovation, strengthen the product green image and the sustainable competitive advantage. Second, the core enterprise can increase the dependence on a small number of suppliers and consumers and invest on the relationship between specific assets, thereby increasing their knowledge sharing motivation. Through collaborative integration, enterprises can acquire and absorb external knowledge more quickly and effectively to develop sustainable products. Third, enterprises should create various sustainability learning channels, such as work experience, colleague assistance and education training, to equip employees with avenues to acquire eco-design knowledge. In addition, the expertise and technology of partners provide high-quality resources for green innovation. For example, Lenovo developed tools which can easily and quickly calculate the carbon footprint of products in collaboration with MIT, HP, Cisco and Seagate. Fourth, enterprises need to maximize openness and cooperation. The success of eco-design cannot be separated from the joint efforts of other enterprises, government, academic institutions, industry associations and other stakeholders. Enterprises can break through the barriers of green technology innovation through openness and cooperation, such as sustainable materials recycling methods and product life cycle extension. As such, the certification standards of green products in the industry will be improved, and an ecosystem of sustainability synergy will be formed to meet the needs of multiple stakeholders.

8. Conclusion

Sustainability is of growing global urgency. Organizations respond to it with product eco-design practice and other measures in GSCM. This paper reviews this topic from a global perspective. The effective drivers, barriers and initiatives are identified and compared between China and non-China countries based on published scholarly studies. Results show that although common factors exist, China exhibits a higher number of barriers. However, its advantage lies in pressing market demand, actively engaged human resources and a cooperative culture. Alternatively, non-China countries demonstrate their relative superiority in eco-design tools, knowledge and innovation. Findings also indicate stakeholders simultaneously influence various eco-design practices in all countries. By using these eco-design drivers, barriers and initiative factors, a systemic review framework is presented to help practitioners and researchers take stock of current eco-design management issues. According to the results, our study provides insights into advancing eco-design implementation and future research directions.

There are also some limitations for our study. Arguably, the review has covered key peer-reviewed leading publications within the research area, but it cannot be considered exhaustive because a time lag exists between what leading corporations are doing and what is being published. Additionally, the validation of the factors and frameworks is an ongoing process. More evidence and cases should be gleaned systematically across countries to justify the results.

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Enablers, levers and benefits of Circular Economy in the Electrical and Electronic Equipment supply chain: a literature review

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A B S T R A C T

Circular Economy in the Electrical and Electronic Equipment (EEE) supply chain has a significant (and still unexploited) potential. This paper aims to systematically review the knowledge emerging from the literature at the intersection between Circular Economy and the EEE supply chain, with a special focus on enablers, levers, and their potential environmental, economic and social benefits. An original framework is developed to categorise Circular Economy enablers, levers and potential benefits. Companies in the EEE industry aiming to implement Circular Economy can exploit several enablers (grouped into digitalization, government intervention, and users' active role) and levers (grouped into circular product design, servitised business models, and supply chain management) to generate economic, environmental and social benefits. Based on the framework, 115 articles were scrutinised. The analysis led to the definition of a research agenda, with policy and industry implications. To advance Circular Economy research in the EEE supply chain, future studies should address: (i) the enabling role of digitalization, particularly within blockchain, 3D Printing, augmented and virtual reality; (ii) design strategies focused on 'reduce'; (iii) servitised business models based on result-oriented offerings; (iv) collaboration in the EEE supply chain; (v) the assessment of social and economic benefits to users. Future research should also investigate the systemic interrelations between enablers, levers and benefits.

1. Introduction

Circular Economy (CE) contributes to sustainable production and consumption by decoupling economic growth from resource use and waste generation (Hofmann, 2019). CE is an 'umbrella concept' (Blomsma and Brennan, 2017) and has its roots in other schools of thought such as industrial ecology, industrial symbiosis, blue economy, product-service systems, cradle-to-cradle, and biomimicry (Geissdoerfer et al., 2017). Within the context of manufacturing companies and supply chains, CE can be implemented to replace the End of Life (EoL) concept with strategies such as reduce, reuse, remanufacture and recycle, by redesigning products, business models and supply chains (Bressanelli et al., 2019).

The application of CE to the Electrical and Electronic Equipment (EEE) supply chain has a significant potential. EEE includes a wide range of products (such as cooling and freezing equipment, screens and monitors, lamps, washing machines, vacuum cleaners, microwaves and information and communication technologies) whose manufacturing and usage is resource-demanding. Furthermore, Waste of Electrical and Electronic Equipment (WEEE) represents a global concern. In 2019, a total of 53.6 million metric tons of WEEE was generated worldwide, and only 17% of this was properly collected and recycled (Forti et al., 2020). With a yearly growth rate of WEEE between 3 and 5%, recycling activities are not keeping pace with the global growth of EEE (Cucchiella et al., 2015). In addition, EEE have a large economic potential: WEEE has the potential to generate 2 billion € in revenue from recycling in Europe alone, although most precious and special metals are still lost in recycling processes (D'Adamo et al., 2016).

Despite the attention devoted to the enabling role of digitalization and the fact that product eco-design and reverse logistics for sustainability have been part of research and development agendas for decades, companies in the EEE supply chain are still struggling with the implementation of CE, lacking a systemic support to understand its potential and to develop implementation roadmaps (Lieder and Rashid, 2016; Rosa et al., 2019). According to the Ellen MacArthur Foundation (2012), the CE paradigms is based on a set

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of building blocks. Manufacturing companies should leverage on circular product design to keep products, components and materials at their highest utility and value; servitised business models – based on the provision of the function instead of the product itself – to retain product ownership by the manufacturer and encourage take-back systems; supply chain management to integrate collaboration and reverse logistics into traditional, linear supply chains. Moreover, some contextual factors may favour the transition, such as digitalization, users' awareness, government intervention and financing. These building blocks have been often recalled in the scientific literature, although in a scattered way. Elia et al. (2020) evaluated the adoption of CE practices in industrial supply chains by investigating companies which have taken some actions in circular product design and production, business models, reverse logistics and collaboration. Govindan and Hasanagic (2018) analysed these building blocks in the context of supply chains through a systematic review, differentiating between drivers (such as policy, health, and environmental protection) and practices (such as product development, cooperation, logistics, etc.). Geissdoerfer et al. (2018) discussed the sustainability performance of business models and supply chain levers in the move towards a sustainable CE. Generally speaking, it is possible to identify two categories of building blocks for CE implementation: levers (i.e., tools and practices on which companies may leverage on to activate the implementation of CE, and enablers (i.e., conditions and contextual factors that facilitate the implementation of such levers). From the scientific point of view, literature reviews on the implementation of CE lack a systemic and holistic perspective in the joint application of such levers and enablers (Merli et al., 2018). This holds true also for literature reviews focused on EEE: for instance, Berssaneti et al. (2019) reviewed the literature to identify the variables related to value creation in the case of remanufactured electronic products, focusing only on the reverse logistics lever; Rosa et al. (2019) reviewed 283 articles to investigate the benefits of servitised business models for EEE, thus addressing only the servitisation lever; Islam and Huda (2018) reviewed 157 papers to define differences of reverse logistics processes for WEEE, thus addressing only supply chain management levers. To the best of the authors' knowledge, no systematic literature review jointly addressed, in a systemic perspective, how CE enablers and levers can be applied to the EEE supply chain, with a clear understanding of the potential benefits.

Thus, this paper aims to systematically review the knowledge emerging from the literature at the intersection between CE and the EEE supply chain, with a particular focus on enablers, levers, and their potential environmental, economic and social benefits. The focus of the analysis has been put on levers, enablers and benefits because they are the most recurrent themes in the EEE literature, thus calling for a systematization. Moreover, they have direct practical implications for EEE companies moving towards CE. In fact, they answer to (i.) what should be done (i.e., redesign of products, business models, and supply chains); (ii.) how to enable the transition (i.e., by exploiting digitalization, government intervention, and users' active role); and (iii.) why (i.e., for gathering economic, environmental and/or social benefits). Other aspects, such as potential side effects and rebounds, are intentionally left out of the scope of this paper.

To better frame the research objective, the following research questions have been formulated:

RQ1. What CE enablers and levers have been pointed out by the literature in the EEE supply chain, and how do they operate?
RQ2. What kind of potential economic, environmental and social benefits have been associated to the adoption of such enablers and levers?

The paper is organised as follows. Section 2 provides the research methodology and the research framework employed for classifying and analysing the articles. The results of the systematic literature review are presented in Section 3. Section 4 provides a critical discussion of the relations between levers, enablers and benefits. It includes a research agenda, key recommendations for managers and policy-makers, and a critical appraisal of the research limitations. Lastly, Section 5 draws concluding remarks.

2. Research methodology

2.1. Literature review process

The scientific literature has been scrutinised in a systematic way to answer the research questions, following the guidelines developed by Seuring and Gold (2012). An initial search was conducted on Scopus, combining two sets of keywords: (i) the research streams underlying the CE umbrella concept; (ii) the key terms focusing on the EEE supply chain (Table 1). Since the combined search of the two main representative terms ('circular economy' and 'Electrical and Electronic Equipment') led to the extraction of only 21 contributions on Scopus, the set of keywords was expanded. Keywords referring to Product-Service Systems, Closed-loop Supply Chain and other streams close to CE has been included in the first set while, for the second set, research terms were expanded to include washing machines, given their relevance for both CE and EEE streams (Bressanelli et al., 2017).

All the combinations between the two sets of keywords have been scanned in Scopus, for a total of 3951 entries (Fig. 1). Only papers written in English have been selected. To further refine the set of documents, and to ensure quality and relevance of the contributions, only articles that appeared in Journals with Impact Factor – according to Clarivate Analytics – have been selected. Thus, 1374 articles were scrutinised by reading the title and the abstract. To be selected, an article must meet three criteria. Only studies addressing (i.) environmental concerns falling into the CE umbrella concept, in the (ii.) EEE industry that (iii.) provides implications for supply chains were included. Based on the application of these three criteria, 106 papers have been selected. The set of articles has been complemented with another 9 articles obtained through cross-referencing. In total, 115 papers (see Supplementary Material) have been selected and further analysed in detail.

2.2. Descriptive analysis

Fig. 2 shows the distribution over time of the 115 articles that lie at the intersection between CE and the EEE supply chain. The first contribution, published in 2000, discussed the idea of moving towards a service economy coupled with the improvements in energy efficiency as a way to stimulate the social changes needed for a sustainable development (Foxon, 2000). The number of publications started to grow after 2005, with most studies (70 out of 115, i.e., more than 60%) published in 2014 or later. This trend confirms the general claim that the number of published articles about CE has grown considerably in the last few years, which can also be observed within the field of the EEE supply chain. The 115 articles are distributed across 43 scientific journals (Fig. 3). Most articles (51%) have been published on 6 journals, i.e., *Journal of Cleaner Production (19%), Resource, Conservation and Recycling (10%), International Journal of Consumer Studies (7%), Energy Efficiency (6%), Sustainability (5%)* and *Journal of Industrial Ecology (4%)*. This shows that research lying at the intersection between CE and EEE is strongly connected to sustainability aspects. Overall, the application of CE to the EEE supply chain is an emergent and rapidly growing topic, tightly connected with sustainability research.

Table 1
Sets of keywords scanned.

Keywords Set 1 – Circular Economy	Keywords Set 2 – EEE
Circular economy; Durability; Eco-eff*; Sustainab*; Closed-loop; Reverse supply chain; Reverse logistics; Reus* OR re-us*; Remanuf* OR re-manuf; Refurbish*; Disassembly; Repair; Eco-design; Shar*; Product-service system	EEE; WEEE; Appliance; Washing Machine

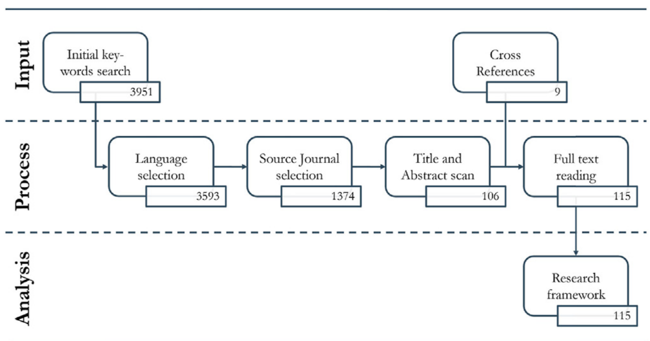

Fig. 1. Systematic Literature Review process.

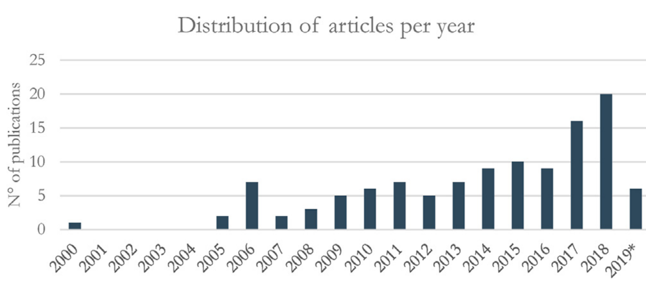

Fig. 2. Evolution of publications per year (last update: May 2019).

2.3. Research framework: enablers, levers, and potential benefits

An original research framework has been developed to answer the research questions and guide the literature analysis. The framework is used as a reference guide to examine the selected articles in a systematic way. First, we identified the three layers of levers, enablers and benefits through a conceptual elaboration on relevant (general and EEE-specific) literature, as described in the Introduction. The coding process that brought to the development of the framework, then, involved two steps: (i.) analysis of the first 65% of the 115 selected articles (i.e., 75 articles) to define options for CE enablers, levers and benefits; (ii.) iterative refinement and validation of each option used for the classification, through the analysis of the remaining set of 40 articles. Consequently, the framework (Fig. 4) has been built on three layers of analysis:

(i) CE enablers, defined as conditions and contextual factors that facilitate the implementation of CE levers; they are characterized by their *exogenous* nature and by their *enabling* role on the CE levers.
(ii) CE levers, defined as tools and practices to support the implementation of CE in companies; they are characterized by their *endogenous* nature, since companies directly invest and primarily act on them in order to implement CE.
(iii) Potential benefits, defined as potential advantages that may be obtained from the adoption of CE enablers and levers,

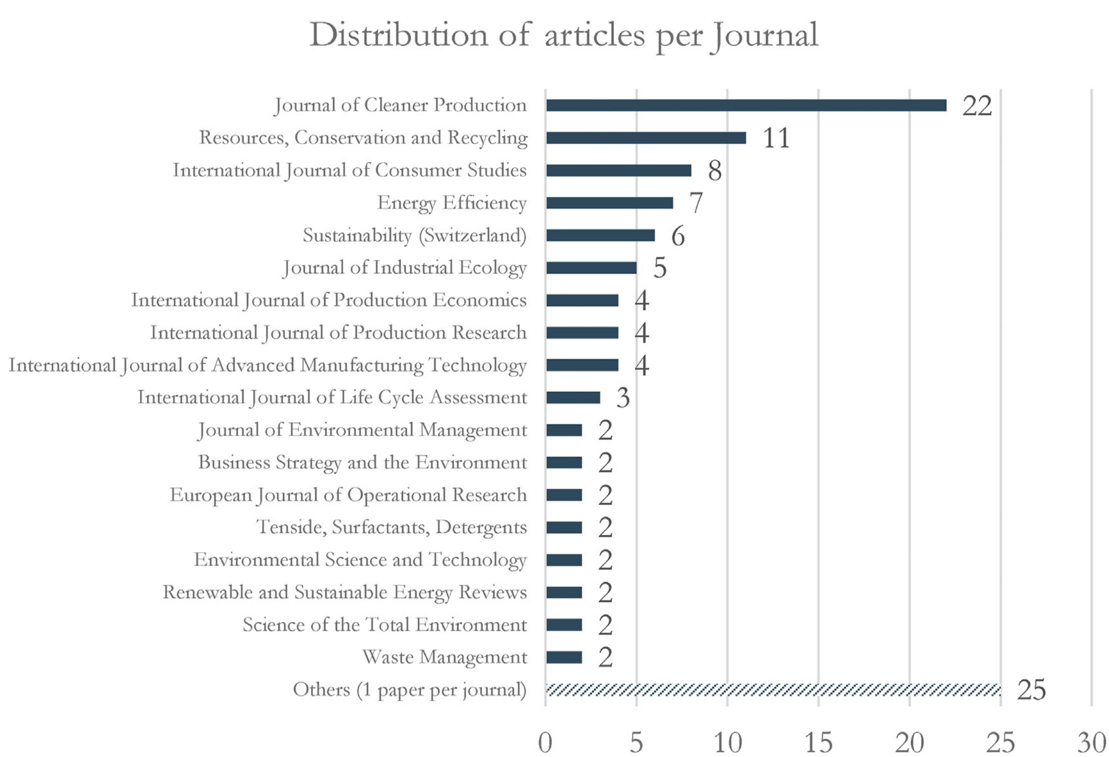

Fig. 3. Distribution of articles per Journal.

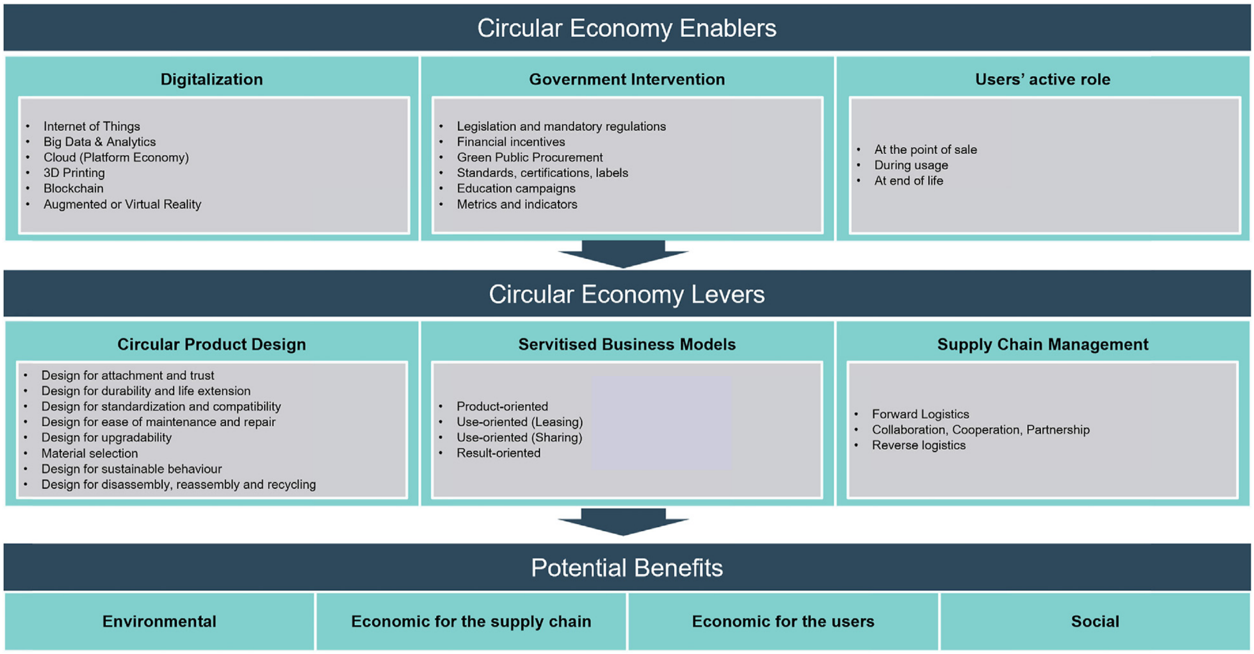

Fig. 4. Research framework.

under the triple bottom line perspective of sustainability (i.e., environmental, economic and social benefits).

The three layers have been divided into categories based on the literature. In turn, we found different options in each category, as shown in Fig. 4. A full definition of each option, including the selection criteria, is available in the Supplementary Material of this paper. The categories are instead introduced hereafter.

First, the three enablers for CE implementation addressed in this paper are: digitalization, government intervention and users' active engagement:

- Digitalization can enable the transition to CE through the introduction of digital technologies connected to Industry 4.0, such as Internet of Things (IoT), Big Data and Analytics, 3D Printing, Cloud, Blockchain, Virtual and Augment Reality (Alcayaga et al., 2019; Saberi et al., 2018). As a CE enabler, digitalization facilitates access to data that supports product management throughout its entire life cycle, lifetime extension and optimization, provision of spare parts, enhanced understanding of user behaviour, technology for service-based business models, decision support for the selection of the most suitable circular strategies at the end of use phases, and so forth. It is important to highlight that digital technologies, by itself, are not the end but rather the means through which enabling a redesign of products, business models and supply chains;
- Government intervention can enable CE by enacting legislation and mandatory regulations; providing financial incentives; promoting green public procurement; promoting the introduction of norms, labels and standards (such as the ISO 14001); promoting education campaigns and advertisement; promoting the adoption of environmental-focused indicators and metrics (Morseletto, 2020; Viani et al., 2016);
- Users' active role and engagement in a CE is the last enabler that companies may exploit. This can happen, for instance, at the point of sale by choosing circular products, during usage by adopting green practices, and at the end of life by properly discarding old items (Lieder and Rashid, 2016).

Second, based on literature, we identify three levers on which companies may act to implement CE: circular product design, servitised business models and supply chain management:

- Circular product design: several circular product design levers can be pursued to keep products, components and materials at their highest utility and value throughout their life cycle. They are: design for attachment and trust; design for durability and life extension; design for standardization and compatibility; design for ease of maintenance and repair; design for upgradability; design for material selection; design for sustainable behaviour; design for disassembly, reassembly and recycling (Bocken et al., 2016; Bovea and Pérez-Belis, 2018);
- Servitised Business Models (SBM): a shift from the sales of products to the provision of services is envisaged to leverage companies in adopting CE (Rondini et al., 2017). Tukker (2015) proposes three SBM types, namely product-oriented (e.g., after sales services, maintenance, repair), use-oriented (e.g., leasing, sharing), and result-oriented (e.g., pay-per-result);
- Supply Chain Management (SCM): to decouple economic growth from environmental losses and resource extraction, companies may leverage on SCM by optimizing forward logistics, by setting-up partnerships and close collaborations in the supply chain and by introducing reverse logistics (De Angelis et al., 2018; Farooque et al., 2019).

Finally, we point out four categories of benefits that can be achieved through the exploitation of CE enablers and the implementation of CE levers: environmental benefits, economic benefits (for the supply chain and for users), and social benefits:

- Environmental benefits arise when CE brings net gains to the environment, by successfully decoupling value creation from resource consumption, which will ultimately lead to a lower consumption of resources and to a higher value capture from waste streams (e.g., through reuse, remanufacturing and recycling);

- Economic benefits for the supply chain are achieved when CE brings net profits to the supply chain, by successfully developing more efficient and effective products/services, which leads to savings in materials purchasing costs, and higher value-added solutions which can enhance the company's competitiveness and market share;
- Economic benefits for the users are achieved when CE brings net savings to users, by successfully providing additional value and access to products that can successfully deliver the intended function, leading to overall life cycle cost savings (e.g., minimized total cost of ownership) or access to high value-added and more efficient products (e.g., sharing models);
- Social benefits arise when CE brings net social gains to the society, by successfully enabling the creation of new market segments connected to extended life and closed-loop strategies, which lead to job creation and enable access to products that can successfully enhance the quality of life.

According to the framework illustrated in Fig. 4, companies in the EEE supply chain may exploit the *enablers* to implement the *levers* for gaining the potential *benefits*.

3. Findings

3.1. Circular Economy enablers

Companies aiming to implement CE should exploit digitalization, government interventions and/or users' active role. In total, 106 articles out of 115 (92%) addressed at least one of those CE enablers. Fig. 5 shows their distribution: 92 articles out of 115 (80%) pointed out the government role in favouring the implementation of CE, 64 articles (56%) addressed the users' active role in enhancing this transition, while only 19 (17%) investigated the role of digitalization in enabling such transformation. Although this enabling character is suggested by the general literature on CE, the role of digitalization in the EEE industry seems to be significantly under-investigated. A relevant set of articles jointly addresses government intervention and users' active role in enabling CE through green purchasing decisions and usage habits (51 papers). Interestingly, only 3 articles address simultaneously the three enablers, indicating a gap in the adoption of a systemic perspective over the CE enablers.

Fig. 6 further details the enabling role of **digitalization**, i.e., what and how many digital technologies have been addressed by the literature. It is remarkable that only three technologies (IoT, Cloud computing and Big Data) have been addressed to date. IoT was the most investigated technology (17 articles). Thanks to both advances in ICT infrastructures and reduction in costs, manufacturers started to provide integrated communication modules for home automation in EEE and appliances such as washing machines and fridges (Nistor et al., 2015). This automation enabled smart appliances, thus creating a two-way link between the virtual and physical worlds (Khan et al., 2015). Few studies addressed cloud computing applications to EEE (8 articles). A cloud platform is an integrated cyber-physical system that provides on-demand digital and physical services by offering a shared pool of resources like software, facilities and capabilities (Wang and Wang, 2017). For EEE, cloud technology could support reuse, remanufacture and recycle of WEEE by setting up a platform where all the data of individual EEE at all life cycle stages can be maintained in an integrated and shared way (Vincent Wang et al., 2015). Only 6 articles addressed Big Data in the EEE industry. While the concept of IoT focuses more on the interconnection of cooperative objects, the concept of Big Data also considers the computational decision-making processes to provide intelligence, responsiveness and adaptation (Leitão et al., 2015). Data mining usually allows extracting valid, previously unknown and comprehensible information from large Big Data databases (Marconi et al., 2019). Overall, digital technologies are rarely investigated together: as depicted in Fig. 6, only two articles out of 115 investigate IoT coupled with Big Data and Cloud technologies. Lastly, none of the articles addressed the CE enabling role of blockchain, 3D Printing, augmented or virtual reality. This is a clear research gap that should be addressed in future research.

Fig. 7 details the enabling role of **government intervention**, i.e., what and how many government interventions have been addressed by literature. Interestingly, the majority of articles (71 out of 115, i.e. 62%) recognizes the enabling role of governments to force the implementation of CE into companies by the means of mandatory regulations (Favot et al., 2018). Other types of government interventions are investigated, but less frequently. Education campaigns and public advertising to better inform users, companies and citizens have been addressed by 25 articles. For instance, the consumers' usage habits can be improved through environmental education to save resources during usage or to avoid behaviours that may compromise the functioning of the product (Alborzi et al., 2017). The promotion of standards, certifications and eco-labels have been suggested by 24 articles, especially through ISO 14001 or energy efficiency labels (Morgan et al., 2018; Scur and Barbosa, 2017). The introduction of financial incentives to directly

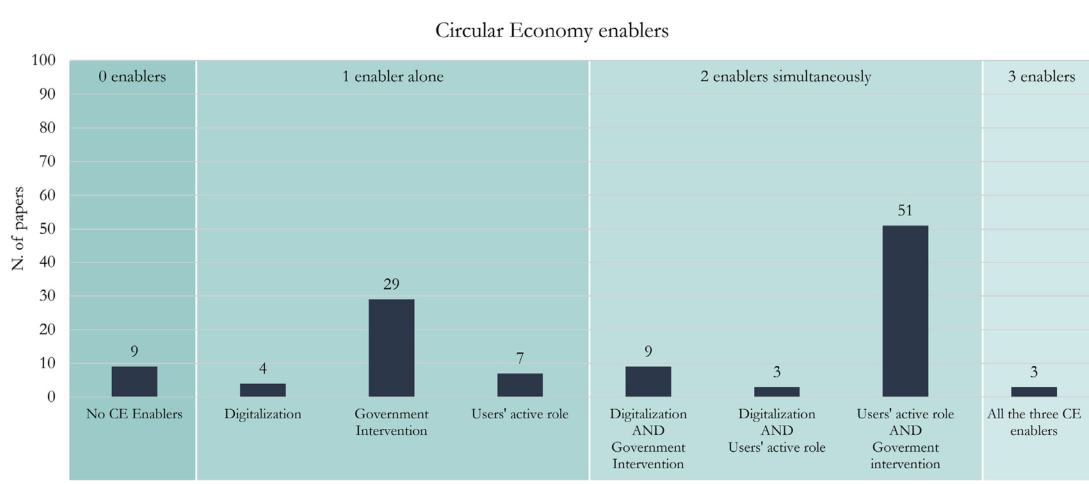

Fig. 5. Number of articles addressing each CE enabler and their combinations.

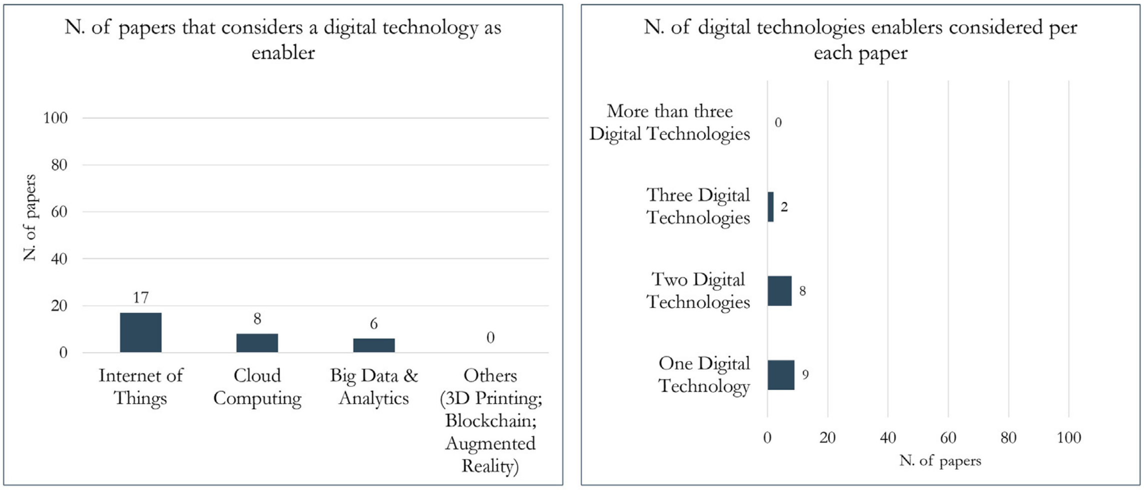

Fig. 6. Digitalization enabling role.

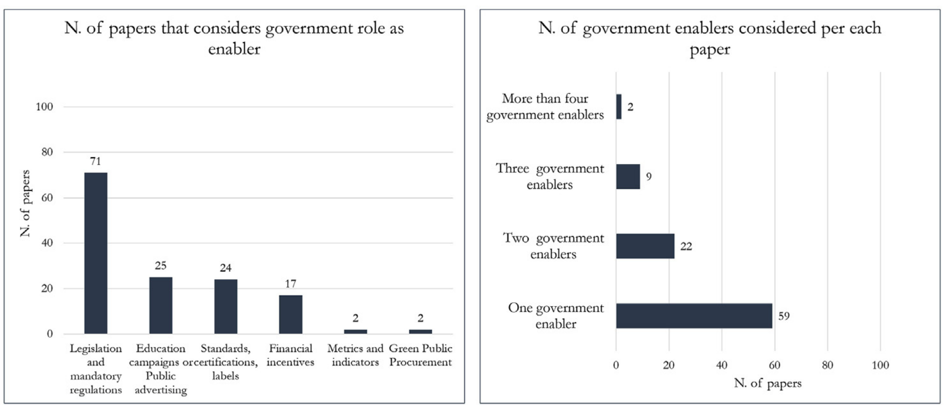

Fig. 7. Government enabling role.

support CE initiatives has been addressed in 17 contributions (e.g. Gnoni et al., 2017; Vendrusculo et al., 2009). Lastly, the introduction of appropriate measures and indicators as well as green public procurement (Singh et al., 2018) have been poorly investigated in the EEE industry, being both addressed by only two publications. Overall, the combination of government measures is very seldom addressed: as depicted by Fig. 7, only two articles investigate more than four government enablers simultaneously.

Fig. 8 details the **users' active role** in enabling CE. Users may have an active role in pushing the transition towards CE during the purchase (22 papers out of 115), the usage (39 papers out of 115) and the EoL of EEE (25 papers out of 115). During purchasing, they can choose greener, more efficient, refurbished or remanufactured models (Abeliotis et al., 2011). During the usage phase, users may be involved by lowering the resource consumption through better usage habits (Conrady et al., 2014) or by properly choosing the best time to replace appliances, counterbalancing the impact of continuing to use old products *versus* the impact of buying new ones, which consume less resources during usage (Ardente and Mathieux, 2014). During EoL, users play a crucial role in how products are discarded, thus improving the supply for recovery processes like reuse, remanufacture or recycling (Parajuly and Wenzel, 2017). Overall, the combination of users' role in different lifecycle phases has been rarely investigated: only two articles investigate simultaneously the users' active role during purchasing, usage and at the EoL.

3.2. Circular Economy levers

82 articles out of 115 (71%) addressed at least one CE lever (Fig. 9). Most articles focused on circular product design or SCM levers alone (respectively 23 and 21 articles). Interestingly, only 9 articles out of 115 addressed simultaneously all the three CE levers.

Fig. 10 illustrates what and how many **circular product design** options have been addressed by literature. Design is the phase where 70% of the cost of a product is set and where commitments to reducing environmental impact are made (Kumar and Putnam, 2008). "Design for disassembly, reassembly and recycling" was the most investigated design option (27 papers). It aims to support designing EEE that can both be easily disassembled into components so to guarantee an efficient recovery of parts and materials within CE models (Mandolini et al., 2018). It mainly depends on factors such as repair rates, product lifetimes, labour costs, collection rates and knowledge about products that reach EoL (Peeters et al., 2017). Modular design, i.e. developing products architectures as a joint union of physically detachable modules, can make disassembly, reassembly and recycling easier, since each module can be assembled and disassembled as a group, and components that can be recycled through the same shredding or separation process (Yang et al., 2011). "Material selection" was addressed by 19 articles, as a design option to promote the use of secondary raw materials such as recycled ones (Gu et al., 2016; Kim et al., 2009), materials with high recyclability rates (Favi et al., 2019) or non-

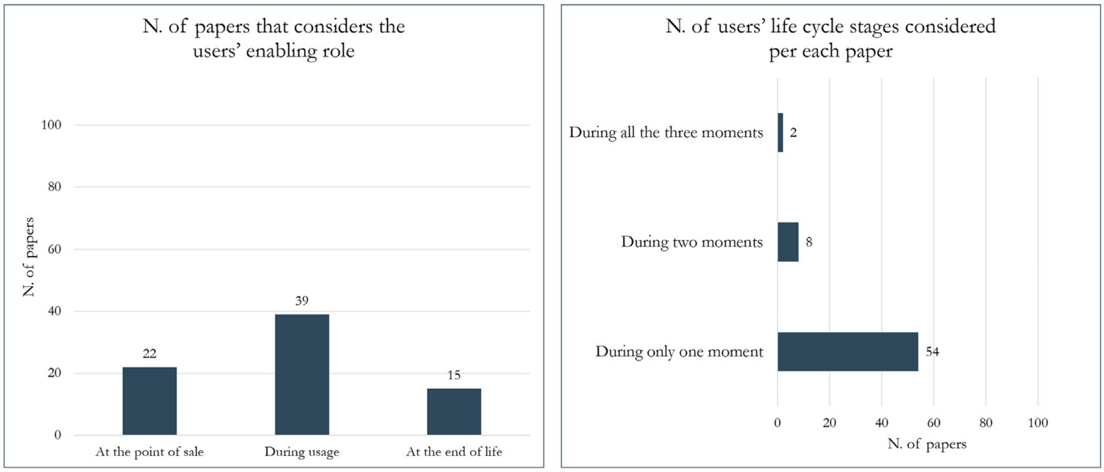

Fig. 8. Users' enabling role.

Fig. 9. Number of articles addressing each Circular Economy lever and their combinations.

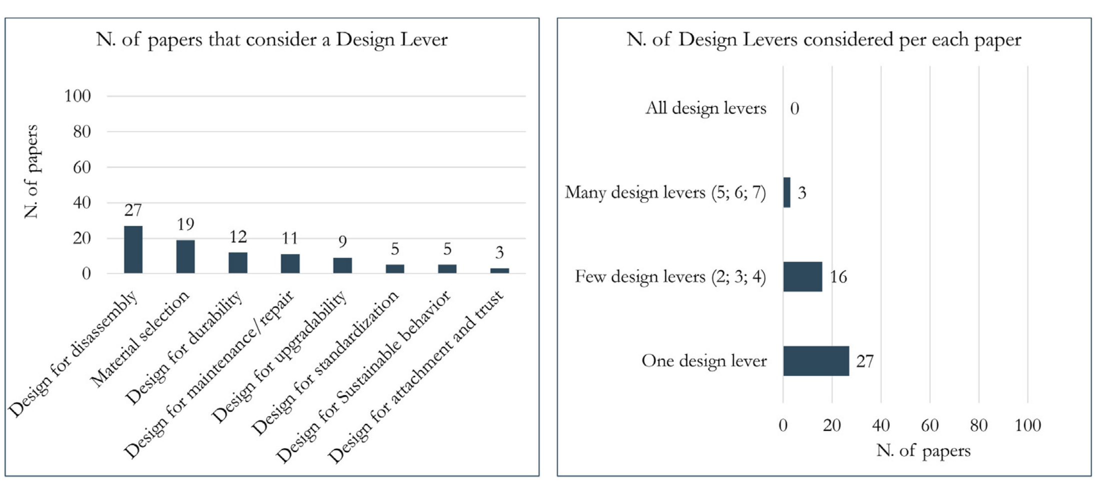

Fig. 10. Circular design levers addressed.

toxic, non-polluting or eco-friendly materials (Gu et al., 2017; Sousa-Zomer et al., 2018). "Design for durability" (Ardente and Mathieux, 2014; Stamminger et al., 2018), "ease of maintenance and repair" (Cooper, 2005; Tecchio et al., 2019) or "upgradability" (Kumar and Putnam, 2008; Sundin and Bras, 2005) have been targeted by only 12, 11 and 9 articles, respectively. Lastly, very few articles addressed the reduction of different non-standard components for eliminating the risk of selecting the wrong part during reassembly (Sundin et al., 2009), design for sustainable behaviour (Amasawa et al., 2018) and design for attachment and trust (Bakker et al., 2014). Overall, circular design strategies are seldom investigated together: only 19 articles investigate more than one design strategy, while none of the analysed articles addressed all the eight circular product design strategies.

Fig. 11 details what and how many **SBM options** have been addressed by literature, following Tukker's typology (Tukker, 2015). Not surprisingly, most articles focused on product-oriented SBM, e.g., after-sales services (24 articles). Maintenance and repair are useful strategies to increase the lifespan of products (Intlekofer et al., 2010). Maintenance is usually grouped into three categories, i.e., reactive, preventive or predictive maintenance (Vincent Wang et al., 2015). In all the three options, the provision of spare parts is crucial (Altekin et al., 2017). Use-oriented SBM have almost the same popularity, with 23 articles (20%). Product leasing helps moving from the current 'replacement system' to the 'optimal usage' of products coupled with an extension of their life spans, since leasing internalizes the life cycle costs to the OEM (Tasaki et al., 2006). Moreover, in use-oriented SBM, product return rates are generally high since OEM retain the ownership of EEE (Krikke, 2011), thus having financial incentives for implementing remanufacturing and design for remanufacturing (Sundin and Bras, 2005). On the other side, sharing models in EEE have been overlooked by literature, addressed by 5 articles only. Lastly, only 10 articles addressed result-oriented SBM, where customers pay for achieving a pre-defined and agreed result, such as a pay-per-wash SBM in the case of washing machines (Bocken et al., 2018). Overall, servitised strategies are seldom investigated together: only two articles out of 115 investigate all the three (product-oriented, use-oriented, and result-oriented) options.

Fig. 12 details what and how many **SCM levers** have been addressed by literature. Several papers (40) focused on reverse logistics to close supply chains (Kara et al., 2007). Reverse logistics includes the processes of planning, implementing and controlling flows of materials, goods and related information from the point of consumption to the original point in an efficient and cost-effective way and for the purpose of recapturing value (Achillas et al., 2012). Usually, used EEE can be supplied from individual users, from collection sites or from retailers (Kissling et al., 2012). How to configure a reverse logistics network is a complex problem, which comprises determining the optimal sites and capacities of collection and inspection centres, remanufacturing facilities and recycling plants (Alumur et al., 2012). Nine articles focused on the optimization of forward logistics too, since integration of forward and reverse logistics is required to build an effective closed-loop supply chain (Islam and Huda, 2018). But more surprisingly, only 18 articles address collaboration among supply chain stages (including partnership, upstream or downstream integration, etc.) and its relevance as a SCM lever (Berssaneti et al., 2019). Overall, the integration of forward logistics, collaboration and reverse logistics has been rarely addressed, since only 5 articles focused on all the three SCM options simultaneously.

3.3. Potential benefits

Fig. 13 illustrates the distribution of the 115 articles analysed across the four types of potential benefits.

All the 115 articles address the potential to generate **environmental benefits** in the EEE industry. This result arises from the criteria adopted for the selection of articles. Many of them highlight three main environmental benefits: (i.) reducing the need of extracting virgin resources from the environment, achieved by using secondary resources taken from the recycling of WEEE, thus avoiding the impacts of new materials production, along with its related energy intensive mining, refining and disposal processes (Van Eygen et al., 2016); (ii.) reducing the amount of waste generated at the EoL, achieved especially through EEE life extension or through recovery options such as reuse and remanufacturing (Stamminger et al., 2018); (iii.) savings on consumables during the usage of EEE, achieved by replacing old appliances with high energy efficient ones, through better and greener usage behaviour or by upgrading EEE (Nakamura, 2016). These three main environmental benefits mitigate greenhouse gas emissions such as CO_2, thus contrasting climate change (Ameli et al., 2016). Other environmental benefits targeted by the articles are the (iv.) prioritization of renewable energy, e.g. through the installation of smart appliances with demand-response mechanism (Khan et al., 2015), or (v.) limiting the release of pollutants such as micro-plastics: for instance, clothes made by synthetic textiles (petroleum-based organic polymers such as polyester) usually release micro-plastics fibres during washing (EEE usage phase), and these effluents can reach the aquatic marine environment via wastewater (Henry et al., 2019; Napper and Thompson, 2016).

A large share of articles (47 out of 115) highlighted how CE can provide **economic benefits to the EEE supply chain**. Overall, the

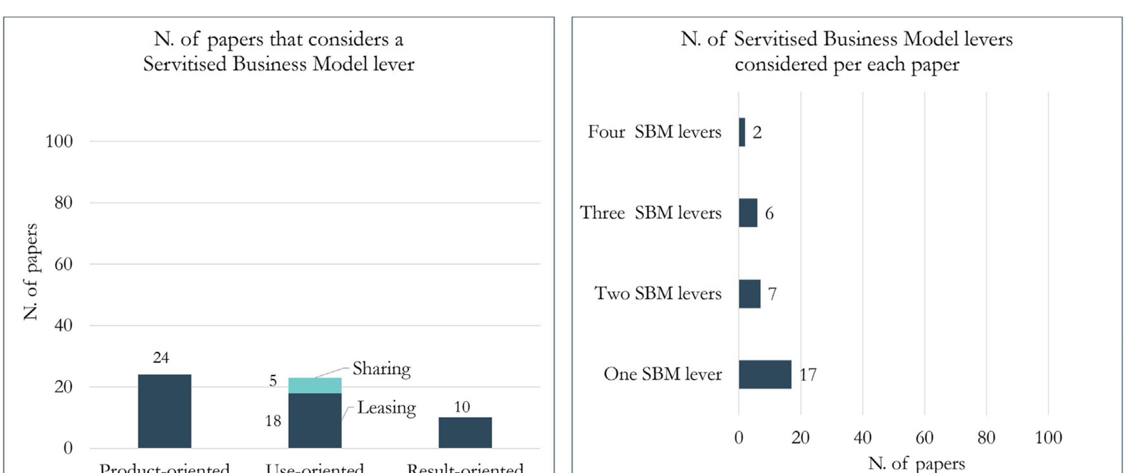

Fig. 11. Servitised Business Models addressed.

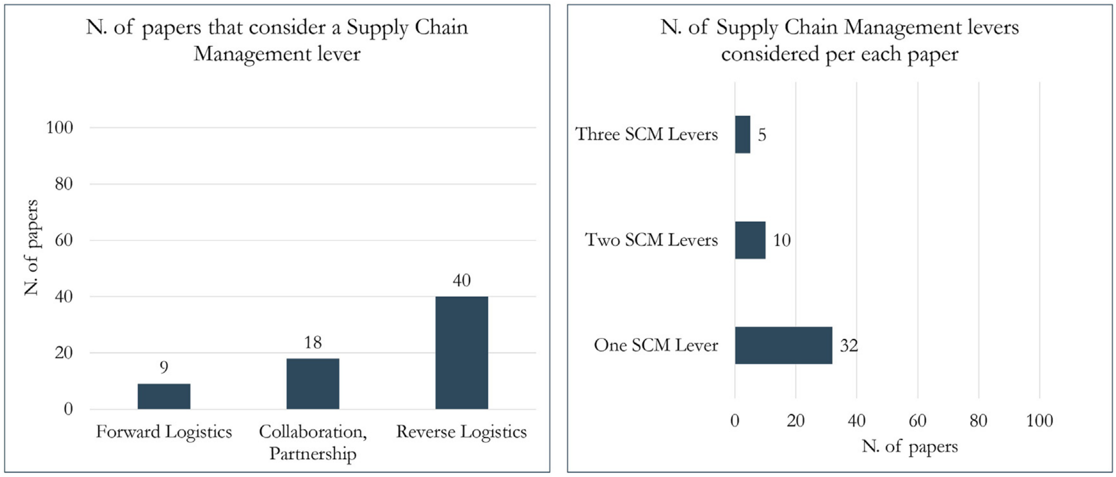

Fig. 12. Supply Chain Management levers addressed.

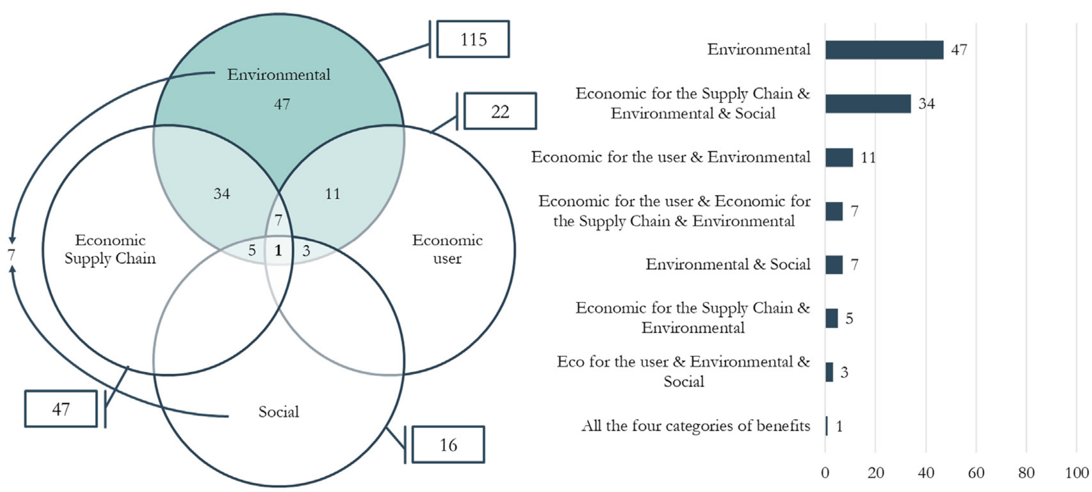

Fig. 13. Number of articles addressing each benefit.

following main economic gains are highlighted: (i.) cost savings achieved by using secondary materials or recovered components into the production of new products (Nelen et al., 2014), e.g. 40–60% lower costs for remanufactured EEE, due to the reuse of most materials and components (Kumar and Putnam, 2008); (ii.) revenue generated from selling recycled materials or recovered components (Wakolbinger et al., 2014); (iii.) revenue generated from selling used or remanufactured products (Quariguasi Frota Neto et al., 2010); (iv.) revenues generated from selling additional services such as maintenance and repair (Lieder et al., 2018; Yang et al., 2009); (v.) the possibility to achieve higher margins, thanks to the offering of high quality and efficient products (Vendrusculo et al., 2009); (vi.) the achievement of a competitive advantage, thanks to a greener image and brand recognition (Kim et al., 2015); (vii.) the minimization of non-compliance risks to regulations (Georgiadis and Besiou, 2010); (viii.) the possibility to further optimize EEE manufacturing and usage due to richer information about product performance (informational value): when EEE are smart, it is possible to evaluate how they have been used throughout their life cycle as well as what should be improved, thus discovering latent design enhancement opportunities (Leitão et al., 2015).

On the other hand, fewer articles (22 out of 115) highlighted how CE can provide **economic benefits for users**. They can be achieved through: (i.) usage savings thanks to the access to high quality and efficient EEE (Deutsch, 2010), such as energy, water and detergent savings from highly efficient washing machines (Saccani et al., 2017); (ii.) usage savings thanks to better users' behaviour during usage (Laitala et al., 2011), e.g. through live feedback mechanisms; (iii.) usage savings generated by smart grids and demand response mechanisms, which can anticipate or delay the usage of the EEE when the electricity prices are low, thus avoiding peaks of energy demand in the system (Nistor et al., 2015); (iv.) lower purchasing price of reused or remanufactured products (Gutowski et al., 2011).

Lastly, only 16 articles out of 115 highlighted how CE can potentially provide **social benefits**, related to: (i.) employment opportunities, since a shift to more skilled design and production methods as well as an increase in repair, maintenance, refurbishment and remanufacturing activities would offset the effect of reduced demand for new products in a CE (M. W. M. O'Connell et al., 2013; Shokohyar and Mansour, 2013); (ii.) an increased access to products or services, since reuse and leasing provides access to good and high quality EEE even for people with low incomes

(Kissling et al., 2012); (iii.) a reduced exposure to toxic materials during EoL (Fiore et al., 2019), by avoiding informal recycling of discarded WEEE that can lead to the contamination of soil, water, air as well as affect human health.

While some areas have been thoroughly investigated – such as environmental benefits and economic benefits for the supply chain – other areas still remain quite unexplored, as in the case of the social benefits and the economic benefits for the users. Only one article simultaneously takes into account all the four benefits, discussing their relations and implications but without quantifying their overall environmental, economic and social impacts (Gnoni et al., 2017). A systemic and holistic perspective in terms of benefits considered has not been observed to date.

4. Discussion

4.1. Relations between levers, enablers and potential benefits

This section assesses and discusses the relations between levers, enablers and benefits. We investigated whether papers addressing a particular enabler also tend to address one specific type of lever (Fig. 14), and the links and mechanisms through which enablers and levers can lead to different types of benefits (Fig. 15).

Digitalization tends to enable especially SBM (11/32 articles, 34%). The joint integration of IoT, cloud platforms, big data and analytics emerged as a strong enabler of SBM based on leasing or pay-per-use (Bressanelli et al., 2018). IoT allows EEE to become smart and connected, enabling their monitoring for billing purposes, thus facilitating the introduction of pay-per-use revenue models. Cloud platforms allow EEE equipped with sensors to be connected for lifecycle data transmission (Yang et al., 2009), facilitating the provision of advanced services such as maintenance and repair. Collecting and analysing big data in the cloud allows companies to learn more about EEE performance during usage, thus improving the service offering (Sundin and Bras, 2005). Digitalization is also related to SCM and circular product design, albeit to a lesser extent (21% and 17%, respectively). IoT installed into EEE can improve EoL activities by providing information about the condition, quality and version of components prior to disassembly (Ilgin and Gupta, 2011). IoT plays a key role in SCM improving the quality and integrity of the information (Garrido-Hidalgo et al., 2020), and promises great advances in the context of reverse logistics to exploit information for a faster and more sustainable collection of WEEE. For instance, RFID (Radio Frequency IDentification) sensors can be used for model recognition, to overcome practical barriers of WEEE identification and sorting, allowing recovery of desired substances such as gold on printed circuit boards or better identification of hazardous materials that must be properly disposed of (M. M.W. O'Connell et al., 2013). IoT and Big Data can finally enable a circular product design, when the information collected throughout the EEE life cycle are used to discover and improve latent design improvement opportunities, e.g. faults on products (Marconi et al., 2019).

Fig. 14 also shows that **government intervention** tends to enable especially circular product design (43/46, 93%). This can be explained by the fact that most papers focused on mandatory regulations, such as the Ecodesign directives in Europe, which force companies to comply with strict requirements about energy efficiency, recyclability and repairability by design (Scur and Barbosa, 2017). On the other side, government intervention enables also SCM and SBM, albeit to a lesser extent (75% and 70%, respectively). Financial incentives for enhancing reverse logistics in the EEE supply chain and the introduction of SBM are often claimed, even though less investigated.

Lastly, we found that **users have an active role** especially in enabling SBM (56%) and circular product design (48%). In fact, literature strongly suggests the consideration of the users' preferences and their changing needs in the design of SBM and circular products (Bocken et al., 2018), also to avoid rebound effects and unintended consequences of circular offerings – e.g., in laundry services, users may start to have their laundry done more often due to an increased convenience, leading to higher resource consumption and costs for the service provider (Kjaer et al., 2019).

EEE literature stressed the need to investigate more deeply the interactions among benefits and CE practices (Rosa et al., 2019). Linking CE levers and enablers to benefits allows better contextualizing how their application can bring environmental, economic and social benefits to the EEE supply chain (Fig. 15). **Digitalization** has been mainly investigated as a means to achieve environmental benefits (19 articles). In fact, many articles highlighted its potential to enable SBM and EEE traceability: both servitisation and traceability promote the collection of EEE at the EoL, reducing waste and the extraction of virgin resources. In addition, digitally enabled SBM are related to the provision of high efficiency EEE, leading to savings on consumables during usage. On the other hand, the links between digitalization and the achievement of economic and social benefits have been much less investigated. **Users** play a critical role in achieving economic benefits for themselves (19 articles

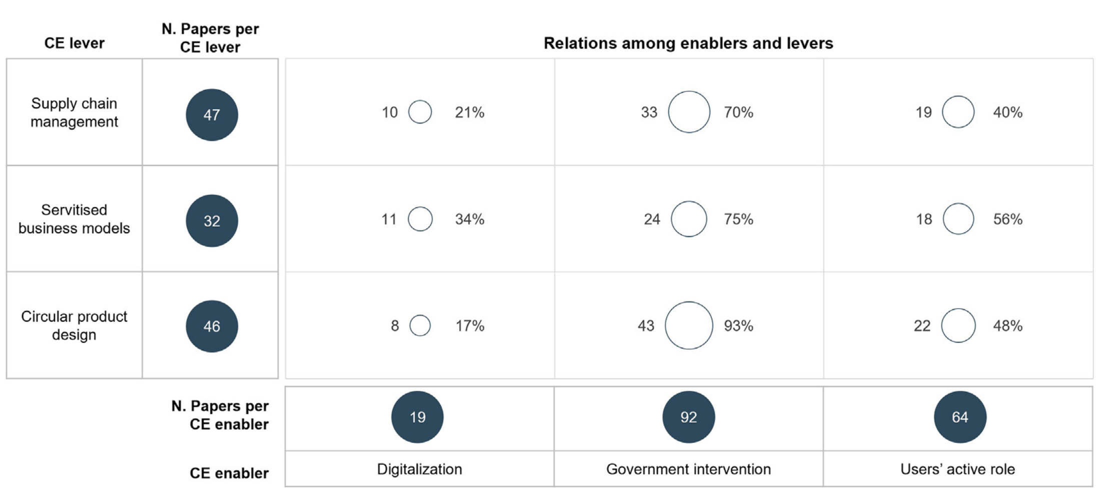

Fig. 14. Relations between CE enablers and levers.

Fig. 15. Relations between CE enablers and levers with benefits.

investigate economic benefits for the users) due to the strong relation between usage behaviour of EEE and their economic impacts. Users who pursue a sustainable behaviour tends to consume less energy and resources, both reducing environmental impact and achieving usage cost savings (e.g., due to a minimized energy consumption). Users who choose to buy a used or remanufactured product may also achieve cost savings through a reduced purchasing price. Not surprisingly, **government intervention** has been often linked to environmental and social benefits (respectively 92 and 14 articles), given the intended purpose of mandatory legislations on EEE, such as the Ecodesign and Extended Producer Responsibility Directives. **Circular product design** levers have been mainly investigated for achieving environmental benefits and economic benefits for the supply chain. In fact, Circular product design reduces the need of extracting virgin resources from the environment (in case of 'reduce' design strategies as durability, upgradability or attachment and trust), and the amount of waste generated (in case of design for disassembly and recycling). Economic benefits, instead, are achieved especially by incorporating secondary (less expensive) materials in the design of EEE. As highlighted before, **SBM** mainly emerged as a lever employed to reduce the stress on the environment, since they entail both the provision of high efficiency EEE and an incentive for their reuse. Lastly, we found that **SCM** have been often linked to environmental and economic benefits for the supply chain, especially due to the role of reverse logistics in both reducing waste and increasing revenues by selling recovered products, components and materials, as in the case of recycling of high-grade waste printed circuit board embedded in EEE (D'Adamo et al., 2019). In summary, all the levers (circular product design, SBM and SCM) have been mainly investigated as a means to achieve environmental benefits or to increase the economic benefits for the supply chain.

4.2. Research agenda

Based on the findings of the literature review and on the discussion about the relations between enablers, levers and benefits, we propose a research agenda for advancing CE research in the EEE supply chain. It consists of eight research directions concerning enabler (2), levers (4) and benefits (2), listed in Table 2.

First, we addressed the role of enablers of CE in the EEE industry (digitalization, government intervention, users' active role). While government interventions and users' role have been investigated in the past, the enabling role of digitalization has been overlooked. In fact, few articles addressed IoT, Big Data and cloud technologies, while no study addressed augmented and virtual reality, blockchain or 3D Printing in the EEE supply chain. This can be partially explained by the emerging role of digitalization in the context of the fourth industrial revolution. Therefore, a first research direction consists in investigating more deeply the role of digitalization in enabling CE in the EEE supply chain, especially regarding the enabling potential of blockchain, 3D Printing, augmented and virtual reality. Moreover, CE enablers have not been investigated in a systemic and holistic perspective so far: digital technologies are rarely investigated together; the combination of government measures is very seldom addressed; and the combined role of users' during purchase, usage and EoL has been rarely analysed. A clear gap emerged from the literature regarding the adoption of a systemic perspective over these enablers. Consequently, a second research direction arises. At a higher level, we recommend the investigation of digitalization, government intervention and users' active role simultaneously, to address their additive and synergistic potential. At a more detailed level, we suggest combining different technologies when researching on digitalization; several regulatory measures when researching on government interventions; all the users' lifecycle stages when researching on users' active role.

Second, companies in the EEE supply chain implement CE by levers that allow redesigning products, business models and supply chains. Research so far has devoted limited attention to the 'reduce' product design strategies (as durability, standardization, upgradability, attachment and trust). In fact, most studies targeted design practices focused on disassembly, reassembly and recycling, while fewer addressed durability, upgradability, standardization, attachment and trust or sustainable behaviours in the product usage. Consequently, the CE hierarchy that advices to prefer Reduce and Reuse (material efficiency through life cycle extension or energy efficiency during usage) over Remanufacture or Recycle strategies is not reflected in literature, based on the popularity of research on the different design levers. Therefore, a third research direction consists in investigating design strategies focused on reduce, such as design for sustainable behaviour, design for durability, standardization, upgradability, attachment and trust. The literature has also devoted limited attention to sharing and result-oriented SBM, even though result-oriented SBM have the greatest CE potential, since product-oriented SBM do not change the incentive to maximize product sales, and use-oriented ones potentially lead to a less careful use thus increasing wear and tear (Kjaer et al., 2019). However, result-oriented are the least investigated SBM in the EEE literature. Thus, a fourth research direction is to carry out more research on result-oriented SBM in the EEE supply chain. In addition - and quite surprisingly - research has devoted limited attention to collaboration as a SCM lever to implement CE in the EEE supply chain. This represents another clear gap in literature, especially considering the important role of collaboration among supply chain actors for implementing CE (Berssaneti et al., 2019). It is very uncommon for a company to be able to get control over all its supply chain to influence also the other actors in transitioning towards CE (Bressanelli et al., 2019). Thus, we recommend, as a fifth research direction, to investigate the potential and the implications of collaboration in the EEE supply chain for the CE. Lastly, CE levers have not been sufficiently investigated in a systemic perspective so far: circular product design, SBM and SCM levers are seldom investigated altogether. For instance, the integration of forward logistics, collaboration and reverse logistics has been rarely addressed as SCM levers. Thus, the sixth research direction suggests to: at a higher level, investigate circular product design, SBM and SCM simultaneously, to leverage

Table 2
Research agenda.

Layer	Findings		Research Agenda
Enablers	Government interventions and users' active role in enabling CE have been well addressed in the past. On the other hand, the enabling role of digitalization has been overlooked: few articles addressed IoT, Big Data and cloud technologies, while no study addressed augmented and virtual reality, blockchain or 3D Printing in the EEE supply chai	1	- Investigate the role of digitalization in enabling CE in the EEE supply chain, especially regarding the enabling potential of blockchain, 3D Printing, augmented and virtual reality
	Lack of a systemic perspective over the CE enablers. Digital technologies are rarely investigated together. The combination of government measures is very seldom addressed. The combined role of users' during purchase, usage and EoL has been rarely investigated	2	- At a higher level: investigate digitalization, government intervention and users' active role simultaneously. At a more detailed level: combine many technologies when researching on digitalization; combine more measures when researching on government intervention; combine all the lifecycle stages when researching on the users' active role
Levers	Research has devoted limited attention to 'reduce' design strategies (durability, standardization, upgradability, attachment and trust)	3	- Investigate design strategies focused on 'reduce' (durability, standardization, upgradability, attachment and trust)
	Research has devoted limited attention to sharing and to result-oriented SBM	4	- Investigate SBM based on result-oriented offering
	Research has devoted limited attention to collaboration among supply chain actors and stakeholders	5	- Investigate the potential and the implications of collaboration in the EEE supply chain for the CE
	CE levers have not been sufficiently investigated in a systemic and holistic perspective: circular design strategies are seldom investigated together; servitised strategies are seldom investigated together; the integration of forward logistics, collaboration and reverse logistics has been rarely addressed	6	- At a higher level, investigate circular product design, SBM and SCM simultaneously. At a more detailed level: combine more design practices if researching on circular design; combine different SBM types if researching on servitisation; combine collaboration, forward and reverse logistics if researching on SCM
Benefits	The application of CE to the EEE supply chain has been mainly focused on environmental impacts and on economic benefits for the supply chain, while few articles covered the social dimension of CE or the economic benefits for the users.	7	- Investigate how CE in general and digitalization in particular can bring social and economic benefits for the users
	Benefits have not been investigated and quantified in a systemic and holistic perspective yet. Whether CE in the EEE industry can (or cannot) contribute to sustainability under a win-win-win strategy still remains an open question	8	- Simultaneously investigate and quantify economic, environmental and social benefits of CE implementation in the EEE supply chain

on their additive potential; at a more detailed level, combine more design practices when researching on circular design, combine different SBM types when researching on servitisation, combine collaboration, forward and reverse logistics when researching on SCM.

Third, research on CE in the EEE supply chain has mainly focused on environmental and economic benefits for the supply chain. Few articles covered the social benefits of CE or the economic benefits for the users. In particular, the link between digitalization and social benefits has been poorly investigated. Literature also neglected how circular product design, SBM and SCM may generate economic benefits to users and social advantages. Considering the intended target of CE to contribute to all the aspects of sustainability, future research is called to fill this gap. Therefore, the seventh research direction is to investigate how CE in general – and digitalization, circular product design, SBM, SCM in particular – can bring social and economic benefits (to users) in the EEE supply chain. Lastly, we found that potential benefits have not been investigated and quantified in a systemic perspective yet, since there is a scarcity of studies that simultaneously assesses economic, environmental and social benefits in the EEE supply chain. This is a relevant gap in the literature, also considering that only by quantifying the impacts it is possible to show the sustainability potential of CE and decide if, for instance, reuse is preferable to recycling for every impact category (Boldoczki et al., 2020). Therefore, whether CE in the EEE industry can (or cannot) contribute to sustainability under a win-win-win strategy still remains an open question. This constitute a clear research gap, which should be addressed in the future. Thus, we recommend to researchers (eighth research direction), to simultaneously investigate and quantify economic, environmental and social benefits of CE implementation in the EEE supply chain.

4.3. Implications for policy-makers and industry

Systematic reviews provide a mean for practitioners to use the evidence of previous research to inform their decisions. The identified benefits represent the starting point for industrials to be involved and act more effectively towards circularity, and can be used also by governments to better plan and act. Through this review, managers and policy-makers can get an overview of CE implementation in the EEE supply chain in terms of enablers, levers and potential benefits. On the basis of these results, we have found several implications for industry and policy-makers.

Policy-makers are advised to focus on governmental interventions such as legislation, financial incentives, eco-labels and especially education campaigns in order to increase the users' acceptance rate of CE solutions, thus leading to environmental and social benefits (as discussed in Section 4.1). To date, governmental interventions tended to enable circular product design by the means of mandatory regulations. From one side, mandatory regulation *pushing* circular product design (e.g., Ecodesign directives) should be aligned with design requirements. From the other side, financial incentives *pulling* the introduction of (i) SBM based on digitalization and (ii) a reverse logistics that prioritises reuse over recycling of EEE should be set. In fact, studies show that WEEE recycling alone is not enough for meeting the yearly demand of most raw materials, even in an ideal scenario in which all the aluminium, iron and copper included in EEE is recycled (Forti et al., 2020). Thus, a combination of levers (circular product design, SBM and SCM) is suggested throughout the EEE supply chain. Given the fact that not all the actors may be willing to voluntarily take part in a CE in the EEE supply chain, regulation should clearly lay out the role and obligations of each stakeholder.

Industry, on the other hand, should reflect on the tendences emerged in Section 4.1 on how CE can be implemented in the EEE supply chain. A first recurrent theme to be exploited is the enabling potential of digitalization – coming from the joint application of IoT, Cloud, Big Data and analytics – to implement SBM. Another key consideration emerged is to follow the users' active role by considering their preferences and changing needs in the design of circular products and business models. Overall, managers in the EEE supply chain are advised to design a roadmap towards CE that consider the combination of all the three levers (circular product design, SBM, SCM), with a prioritization of the different steps. We recognized two recurrent paths. In a *pull* configuration, managers can at first exploit financial incentives focused on digitalization to enable SBM and, when the business model is ready, redesign the product and proceed to configure the supply chain. In a *push* configuration, managers can at first incorporate mandatory regulations and circular design strategies in the design of new products and, when a new circular product is ready, proceed with the redesign of a circular supply chain and the introduction of a SBM. In both configurations, managers are advised to extend the value creation to include also social and economic benefits to users.

4.4. Research limitations

As every piece of research, this study has limitations. Notwithstanding the documentation of the research process to produce a transparent review, the systematization and categorization of the information is affected by researcher bias. To mitigate this issue, the classification criteria described in the Supplementary Material have been adopted. Another limitation is related to the choice to examine only articles published in journals with Impact Factor, which is a way to ensure the quality of the publications analysed, but which exclude other literature that may offer an important contribution to the topic, such as new developments and integrations that are more often found in conference proceedings or in journals without an impact score. Furthermore, it is also important to highlight that there might be a number of rebound effects (i.e., unintended sustainability consequences) connected with the CE implementation in the EEE supply chain – e.g., implementation of digitalization in the EEE industry can lead to enhanced product obsolescence, changes in use patterns and user behaviour, early substitution of devices, etc. These should be investigated in future research, so to ensure a holistic perspective and avoid sub-optimized sustainability performance and backfire effects. Moreover, other enablers and levers, outside the scope of this research and thus not related to digitalization, government intervention, users' role, circular product design, SBM and SCM should be identified and addressed by future research. Finally, future studies should focus on other industries besides the EEE supply chain, to compare the findings, find synergies and potential overlaps.

5. Conclusion

The EEE supply chain has a prominent relevance for the application of CE, but companies are still struggling in understanding and exploiting CE levers and enablers to reach the potential benefits of CE. In order to address the lack of a systemic and holistic perspective in literature, this paper reviewed 115 articles at the intersection of CE and the EEE supply chain to point out CE enablers, levers, and their potential environmental, economic and social benefits.

This article contributes to the accumulation of scientific knowledge on how the application of CE enablers and levers can bring environmental, economic and social benefits to the EEE supply chain. An original research framework has been developed as one of the first attempts to systematize how CE can be introduced in practice. The framework can be seen as a practical tool for contextualizing the transition to a CE. Finally, the paper highlights the main research gaps about enablers, levers and potential benefits in the EEE supply chain. In addition to systematizing CE enablers and levers (RQ1), we drafted a comprehensive list of how the application of CE enablers and levers to the EEE supply chain can bring benefits to the environment, to the supply chain economics, to users and to the society (RQ2). In this domain, the literature has mainly investigated environmental and economic benefits for the supply chain, and there is a need to further investigate how CE in general and digitalization in particular can bring social and economic benefits. We pointed out also the systemic need to investigate and quantify economic, environmental and social benefits simultaneously.

Following those findings, a research agenda with eight research directions has been proposed in Section 4.2, especially regarding: the role of digitalization in enabling CE; design strategies focused on 'reduce'; SBM based on result-oriented offerings; supply chain collaboration in CE endeavours; the social and economic benefits (for users) related to CE in EEE. The research agenda also highlights the need to simultaneously investigate the categories within each layer (i.e., the different types of enablers, levers and benefits) adopting a systemic perspective, to understand their interplay and combined effect.

According to our review, policy-makers are advised to advance mandatory regulations to *push* circular product design (such as Ecodesign directives) and to clearly lay out role and obligations of each stakeholder in the EEE supply chain. They are also advised to design financial incentives to *pull* the introduction of both SBM based on digitalization and a reverse logistics that prioritises reuse over recycling. Managers in the EEE supply chain are advised to design a roadmap towards CE that considers the combination of all the three levers of circular product design, SBM and SCM, following *pull* and *push* configurations to prioritize actions. In both cases, managers are advised to undertake CE approaches leading to social and economic benefits to users.

CRediT authorship contribution statement

Gianmarco Bressanelli: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Daniela C.A. Pigosso:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Nicola Saccani:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Marco Perona:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.126819.

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Viani, C., Vaccari, M., Tudor, T., 2016. Recovering value from used medical instruments: a case study of laryngoscopes in England and Italy. Resour. Conserv. Recycl. 111, 1–9. https://doi.org/10.1016/j.resconrec.2016.03.025.
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Wakolbinger, T., Toyasaki, F., Nowak, T., Nagurney, A., 2014. When and for whom would e-waste be a treasure trove? Insights from a network equilibrium model of e-waste flows. Int. J. Prod. Econ. 154, 263–273. https://doi.org/10.1016/j.ijpe.2014.04.025.
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Yang, X., Moore, P., Chong, S.K., 2009. Intelligent products: from lifecycle data acquisition to enabling product-related services. Comput. Ind. 60, 184–194. https://doi.org/10.1016/j.compind.2008.12.009.

TITLE: MICROSCOPIC OPTICAL MANIPULATION OF THE PHASE TRANSITIONS IN ORGANO-METAL HALIDE PEROVSKITES

Topic number : ***2024_050***

Field : Physics, Optics - Chemistry, Physical chemistry and Chemical Engineering - Material science, Mechanics and Fluids

Subfield: Materials Science

ParisTech School: ESPCI Paris - PSL
Research team : Micro & Nano Characterization (MNC) Group
Research team website:
https://www.espci.psl.eu/recherche/labos/lpem/mnc/index.html
Research lab: LPEM - Laboratoire Physique et d'études des matériaux
Lab location: Paris
Lab website: https://www.lpem.espci.fr/spip.php?rubrique4

Contact point for this topic: CHEN Zhuoying, zhuoying.chen@espci.fr

Advisor 1: Zhuoying CHEN - zhuoying.chen@espci.fr
Advisor 2: Lionel AIGOUY - lionel.aigouy@espci.fr
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Phase-change materials emerge recently as a fascinating topic. Materials that undergo structural phase transitions exhibit significantly different optical, electronic, and thermal properties, which arise from the unique atomic configurations associated with each crystal structure. This topic is challenging because many semiconductors cannot be switched between different phases reversibly without being deteriorated. To this regard, organo-metal halide perovskites, in particular, the family of all-inorganic CsPbI3-xBrx, exhibit interesting near room-temperature perovskite-to-non-perovskite phase transitions, leading to thermochromic behavior occurring at a transition temperature tunable by halide compositions. While the thermally-induced phase transitions in this family of perovskites have been demonstrated, (ref. 1) it remains unexplored whether one can induce such phase transitions optically, for example, by

photothermal means. In addition, manipulating the phase transition down to the nano/micro-scale has not been demonstrated in this family of perovskite materials. This PhD project proposes to investigate, from fundamental views, the possibility of local optical manipulations of the phase transitions and the resultant optically-induced thermochromic behavior of a series of organo-metal halide perovskites thin films. We will focus on the study of light-matter interaction, aiming to boost the capacity of the photothermal effect to achieve optically-induced phase transitions with and without plasmonic nanostructures (examples c.f. our previous work ref. (2-5)). It can be anticipated that through this study we will gain fundamental understanding of how the phase transitions in this family of materials occur at the nano/micro-scale and the optical and photothermal means to control them. References: (1) J. Lin et al., Nature Materials, 17, 261-267 (2018). DOI: 10.1038/s-41563-017-0006-0. (2) Z. Fang et al., Adv. Electronic Mater., 2400249 (2024). DOI: 10.1002/aelm.202400249. (3) C. Xin et al., Materials Today Energy, 22, 100859 (2021). DOI: 10.1016/j.mtener.2021.100859 (4) H. Xiang et al., Energy Technology, 10, 2200757 (2022). DOI: 10.1002/ente.202200757 (5) H. Xiang et al., Small, 14(16), 1704013 (2018). DOI: 10.1002/smll.201704013

Required background of the student:
Solid academic background and a Master Degree on chemistry, material science, or applied physics. Good speaking & writing skills in English. Passionate in scientific experiments.

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Z. Fang et al., Adv. Electronic Mater., 2400249 (2024). DOI: 10.1002/aelm.202400249.

2. C. Xin et al., Materials Today Energy, 22, 100859 (2021). DOI: 10.1016/j.mtener.2021.100859

3. H. Xiang et al., Small, 14(16), 1704013 (2018). DOI: 10.1002/smll.201704013

Figure caption: *(a-b) Phase transitions depending on the composition of a series of Cs-based perovskite halides reported in the literature[1] and the corresponding images showing the thermochromic effect; (c) Results obtained in the LPEM laboratory [2] on the optical manipulation of another type of phase-change materials based on VO2. The established methods [2-5] will be applied in this new project to investigate perovskite halides.*

ParisTech

TITLE: ADVANCED DIALOGUE BETWEEN GRADIENT-ENHANCED PLASTICITY THEORIES AND SMALL-SCALE EXPERIMENTAL TESTS

Topic number : ***2024_051***

Field : Material science, Mechanics and Fluids

Subfield: Mechanics of materials

ParisTech School: Arts et Métiers
Research team : Méthodes Numériques, Instabilités et Vibrations (Numerical Methods, Instabilities and Vibrations)
Research team website:
Research lab: LEM3 - Laboratoire d'étude des microstructures et de mécanique des matériaux
Lab location: Metz
Lab website: https://lem3.univ-lorraine.fr

Contact point for this topic: Mohamed JEBAHI, mohamed.jebahi@ensam.eu

Advisor 1: Mohamed JEBAHI - mohamed.jebahi@ensam.eu
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
With the growing trend towards miniaturization, micro-scale products have become increasingly employed in cutting-edge fields, such as microelectronics and microrobotics. However, as the geometrical size of these products decreases, intrinsic material parameters like grain size and the number of shallow grains remain constant. This leads to significant changes in the mechanical properties of materials. Conventional plasticity theories are unable to account for size effects due to their lack of intrinsic length scales. To address this limitations, gradient-enhanced plasticity approaches have emerged. In this context, the project team has recently developed advanced gradient-enhanced numerical models, which have demonstrated promising results, aligning closely with those derived from dislocation-based mechanics. However,

the application of these models to real-world engineering problems still requires rigorous validation through advanced experimental tests. This project aims to bridge this gap by fostering an advanced dialogue between these numerical models and small-scale experiments. Based on this dialogue, further refinements to the gradient-enhanced models will be proposed, enabling their application to real-world small-scale engineering problems and helping to meet the rising demands of miniaturization-driven industries. The proposed work will make it possible to advance our ability to predict and control size-dependent mechanical behaviors, thus contributing to both scientific progress and technological innovation in miniaturized systems.

Required background of the student:
- Solid background in non-linear solid mechanics and finite element modeling.
- Good analytical and programming skills (e.g., Python, Fortran, C++).
- Excellent English level

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Amouzou-Adoun, Y. A., Jebahi, M., Forest, S., & Fivel, M. (2024). Advanced modeling of higher-order kinematic hardening in strain gradient crystal plasticity based on discrete dislocation dynamics. Journal of the Mechanics and Physics of Solids, 193.

2. Amouzou-Adoun, Y. A., Jebahi, M., Fivel, M., Forest, S., Lecomte, J., Schuman, C., & Abed-Meraim, F. (2023). On elastic gaps in strain gradient plasticity: 3D discrete dislocation dynamics investigation. Acta Materialia, 252, 118920.

3. Jebahi M., & Forest S. (2023). An alternative way to describe thermodynamically-consistent higher-order dissipation within strain gradient plasticity. Journal of the Mechanics and Physics of Solids, 170, 105103.

4. Jebahi M., & Forest S. (2021). Scalar-based strain gradient plasticity theory to model size-dependent kinematic hardening effects. Continuum Mechanics and Thermodynamics, 33, 1223-1245.

5. Jebahi M., Cai L., & Abed-Meraim F. (2020). Strain gradient crystal plasticity model based on generalized non-quadratic defect energy and uncoupled dissipation. International Journal of Plasticity, 126, 102617.

TITLE: STUDY OF THE RESILIENCE OF URBAN ROAD NETWORKS ON CLAY SOILS TO CLIMATE CHANGE USING INTEGRATED MODELLING AND INSTRUMENTATION APPROACHES

Topic number : ***2024_052***

Field : Environment Science and Technology, Sustainable Development, Geosciences

Subfield:

ParisTech School: Arts et Métiers
Research team : Civil and Environmental Engineering Dept. - GT3
Research team website:
https://www.i2m.u-bordeaux.fr/en/Research/Civil-and-Environmental-Engineering
Research lab: I2M - Institut de Mécanique et d'ingénierie
Lab location: Bordeaux
Lab website: https://www.i2m.u-bordeaux.fr

Contact point for this topic: humberto.yanez-godoy@u-bordeaux.fr

Advisor 1: Humberto YANEZ GODOY - humberto.yanez-godoy@u-bordeaux.fr
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Urban networks, particularly road infrastructures, are essential to the functioning of communities. Their failure can disrupt access to vital services. As these infrastructures age and face increasingly stringent operating conditions, their management has become more complex. Decision-makers are seeking solutions to optimize the use of material and financial resources while maintaining an adequate level of service. Although the interdependence of these networks is clear, our understanding of the physical mechanisms governing their behavior remains limited. Furthermore, the impacts of climate change are exacerbating these challenges, highlighting the need to enhance the

resilience of urban infrastructures to withstand extreme events. This thesis project focuses on analyzing the robustness and resilience of urban road networks built on clay soils, which are particularly vulnerable to climate change. The approach combines laboratory experiments and on-site measurements, with data being incorporated into numerical models at two scales: one representing a specific section of the network, and the other a full urban system. The ultimate goal is to leverage the collected data to develop predictive maintenance strategies, which can be integrated into decision-making processes to optimize the management of road infrastructures in an evolving, climate-sensitive environment.

Required background of the student:
The prerequirements for this project include a basic understanding of geotechnical engineering and familiarity with road infrastructure management. Some experience with numerical modeling and simulation tools (e.g. finite element modelling, machine learning, probabilistic modelling) is helpful, along with an interest in learning predictive maintenance strategies. A general awareness of climate change impacts on infrastructure, as well as an openness to working with decision support systems, will be beneficial. Additionally, skills in data collection, analysis, and an interest in risk management and urban network resilience are important but can be developed during the project.

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. F. Stochino, C. Bedon, J. Sagaseta and D. Honfi (2019). Robustness and Resilience of Structures under Extreme Loads. Advances in Civil Engineering, vol. 2019, 4291703.

2. Yáñez-Godoy H., Elachachi S.M. (2023). Spatial structure characterization of the soil surrounding buried water-transmission mains by using a sensor-enabled geotextile. Journal of Pipeline Systems Engineering and Practice, Vol 14, Issue 3. https://doi.org/10.1061/JPSEA2.PSENG-1409.

3. N. Kumar, V. Poonia, B.B. Gupta and M. Kumar Goyal (2021). A novel framework for risk assessment and resilience of critical infrastructure towards climate change. Technological Forecasting & Social Change, vol. 165, 120532.

4. S.A. Argyroudis, S.A. Mitoulis, E. Chatzi, J. W. Baker, I. Brilakis, K. Gkoumas, M. Vousdoukas, W. Hynes, S. Carluccio, O. Keou, D. M. Frangopol, I. Linkov (2022). Digital technologies can enhance climate resilience of critical infrastructure. Climate Risk Management, vol. 35, 100387.

ParisTech

TITLE: EXPERIMENTAL MOLECULAR DYNAMICS - WATCHING INDIVIDUAL POLYMERS MOVING AT INTERFACES

Topic number : ***2024_053***

Field : Chemistry, Physical chemistry and Chemical Engineering

Subfield:

ParisTech School: ESPCI Paris - PSL
Research team : Jean Comtet
Research team website: https://blog.espci.fr/jcomtet/
Research lab: SIMM - Sciences et ingénierie de la matière molle
Lab location: Paris
Lab website: https://www.simm.espci.fr/-Home-.html

Contact point for this topic: jean.comtet@espci.fr

Advisor 1: Jean Comtet - jean.comtet@espci.fr
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Molecular-scale interactions between polymers and solid surfaces govern a large range of processes in soft-matter, from wetting, elastomer and gel friction, down to confined flows in porous media. These situations are typically probed at an ensemble level and described by averaged phenomenological coefficients accounting for the behavior of the interface, e.g. a slip length in the case of the interfacial friction of a polymer melt. However, the molecular foundations behind this averaged vision remain unclear, due to our current inability to experimentally observe the intrinsically nanoscale molecular processes taking place at such interfaces. We aim here to bridge this gap by exploring novel experimental approaches to directly visualize molecular motion in dense polymeric liquid melts at the nanoscale. We will rely in particular on state-of-the-art single-molecule and super-resolution fluorescence microscopy techniques which can be used to localize and track the motion of individual fluorophores with nanoscale resolution and high

temporal resolution. Preliminary results in our group have focused on the interfacial dynamics of flowing polymer solutions, demonstrating the feasibility of our approach for single-macromolecule tracking (Fig. D). Here, we aim to focus on dense polymeric melts (e.g. PDMS molecules), whose relaxation time and viscosity can be tuned over large time-scales through the control of their molecular weight or temperature. A fraction of these molecules will be tagged with a fluorophore (Fig. B), and by selectively imaging the interface with an evanescent wave, we will be able to directly localize their position (Fig. C) and follow their long-term dynamics. A fine control of the molecular-scale interactions between polymer chains and surfaces will be obtained by tuning surface physicochemistry. These single molecule measurements will be coupled with statistical analysis of the dynamics, allowing ultimately for a detailed and fundamental understanding and modelling of macromolecular interactions with solid surfaces. Our measurements will be carried out in a variety of equilibrium and out-of-equilibrium situations, tackling diverse scientific question related to liquid friction, triple line and wetting dynamics or mobility gradients close to solid surfaces.

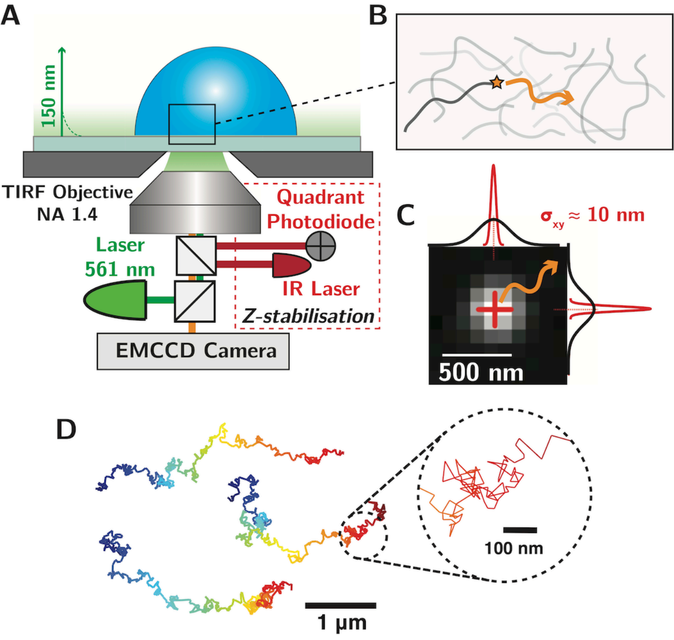
Required background of the student:
Soft Matter, Polymer Physics, Optics

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Direct observation of water mediated single proton transport between hBN surface defects. J Comtet, B Grosjean, E Glushkov, A Avsar, K Watanabe, T Taniguchi, R Vuilleumier, Marie-Laure Bocquet, A Radenovic. Nature Nanotechnology (2020).

2. Liquid-activated quantum emission from native hBN defects for nanofluidic sensing. N Ronceray, Y You, E Glushkov, M Lihter, B Rehl, TH Chen, GH Nam, K Watanabe, T Taniguchi, S Roke, A Keerthi, J Comtet, B Radha, A Radenovic. Nature Materials (2023)

3. Skaug, M. J., Mabry, J. N., & Schwartz, D. K. (2014). Single-molecule tracking of polymer surface diffusion. Journal of the American Chemical Society, 136(4), 1327-1332.


A
150 nm
TIRF Objective
NA 1.4
Quadrant
Photodiode
Laser
561 nm
IR Laser
Z-stabilisation
EMCCD Camera
B
C
$\sigma_{xy} \approx 10$ nm
500 nm
D
100 nm
1 μm

ParisTech

TITLE: ELASTOGRAPHY AND ULTRASONIC IMAGING IN SOFT GRANULAR MATERIALS

Topic number : ***2024_054***

Field : Material science, Mechanics and Fluids

Subfield: Applied Physics, Acoustics

ParisTech School: ESPCI Paris - PSL
Research team : Materials, resonances and interfaces (MRI)
Research team website:
https://www.institut-langevin.espci.fr/materials_resonances_and_interfaces_mri
Research lab: Institut Langevin
Lab location: Paris
Lab website: https://www.institut-langevin.espci.fr

Contact point for this topic: xiaoping.jia@espci.fr

Advisor 1: Xiaoping Jia - xiaoping.jia@espci.fr
Advisor 2: Arnaud Tourin - arnaud.tourin@espci.fr
Advisor 3: Jean-Luc Gennison - jean-luc.gennisson@u-psud.fr
Advisor 4:

Short description of possible research topics for a PhD:
Understanding the microscopic origin of behavior in particulate and particle-fluid systems such as granular materials, foams, and emulsions is of both practical and fundamental importance. In this PhD project, we will investigate the mechanical behavior of an assembly of immersed gel beads (isodense) by ultrasound imaging (transient elastography) and rheology [1,2]. Studying such a soft granular material or suspension is of interest not only for biomedical applications (muscles and tissues) and for geophysical implications (landslides) [3], but is also relevant to the physics of complex systems where the transition from a liquid state to a solid state [4] remains a highly topical issue. In this work, we will first use an ultrafast ultrasound scanner to monitor the low-frequency shear wave within an optically opaque dense gel bead packing generated by an oscillating plate (Fig. 1). We will be particularly interested in nonlinear

response such as shear elastic softening and fracture dynamics [1] as a function of shear amplitude (Fig. 2a). Such transient elastography was originally developed in our laboratory to track tissue motion induced by low-velocity shear waves in the context of medical imaging [2]. In addition, we will use steady and oscillatory shear rheological measurements (Fig. 2b) [5] combined with ultrasonic imaging to monitor the structure change due to plastic rearrangements of particles. Especially, we will investigate the effects of particle shape (e.g., granular dimers/trimers) and/or anisotropic behavior (i.e., force chains) in response to external loading [6]. In the long-term, this research is linked to the search of a possible system for producing artificial skeletal muscles whose mechanical properties can be modified and produce the desired force to dissipate the mechanical energy of an external impact. Inspired by a proposal from Pierre Gilles de Gennes [7] who exploited a temperature-driven nematic/isotropic phase transition to induce a sudden contraction in an artificial muscle, we will also investigate the possibility to modify these soft particle networks by controlled acoustic perturbations. This work will be carried out at the Langevin Institute, ESPCI Paris-PSL, in collaboration with Dr. Jean-Luc GENNISSON at the Laboratoire d'Imagerie Biomédicale Multimodale at Paris-Saclay University. [1] J. Brum, J.-L. Gennisson, M. Fink, A. Tourin & X. Jia, “Drastic slowdown of the Rayleigh-like wave in unjammed granular suspensions”, Phys. Rev. E 84, 020301 (2019) [2] S. Catheline, J.-L. Gennisson, M. Tanter, and M. Fink, “Observation of shock transverse waves in elastic media”, Phys. Rev. Lett. 91, 164301 (2003) [3] P. Johnson and X. Jia, “Nonlinear dynamics, granular media and dynamic earthquake triggering”, Nature 437, 871 (2005) [4] A. J. Liu and S. R. Nagel, “Jamming is not just cool anymore”, Nature 21, 396 (1998) [5] J. Léopoldès and X. Jia, “Probing intermittency and reversibility in a dense granular suspension under shear using multiply scattered ultrasound”, Soft Matter (2020), DOI: 10.1039/D0SM01427C [6] M. Z. Miskin and H. M. Jaeger, Adapting granular materials through artificial evolution”, Nature Materials 12, 326 (2013) [7] P. G. de Gennes, “A semi-fast artificial muscle”, C. R. Acad. Sci. Paris 324, 343 (1997)

Required background of the student:
The student should have a good background in physics, particularly in acoustics and mechanics. The management and interpretation of images generally use the MATLAB and /or Python language with which the candidate should be familiar.

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. J. Brum, J.-L. Gennisson, M. Fink, A. Tourin & X. Jia, “Drastic slowdown of the Rayleigh-like wave in unjammed granular suspensions”, Phys. Rev. E 84, 020301 (2019)

2. P. Johnson and X. Jia, “Nonlinear dynamics, granular media and dynamic earthquake triggering”, Nature 437, 871 (2005)
3. J. Léopoldès and X. Jia, “Probing intermittency and reversibility in a dense granular suspension under shear using multiply scattered ultrasound”, Soft Matter (2020), DOI: 10.1039/D0SM01427C

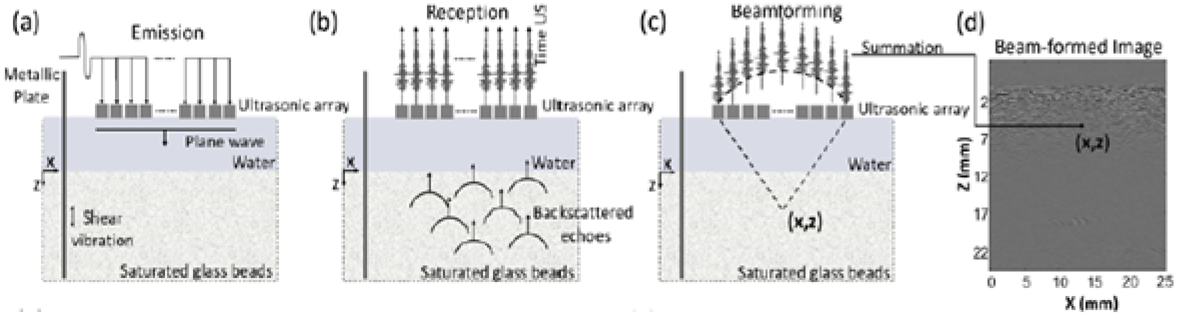


Fig. 1 (a) Ultrasound emission step: all elements in the array emit simultaneously a short pulse centered at 4 MHz, thus generating a pulsed plane ultrasonic wave (b) Ultrasound reception step: the backscattered echoes coming from different locations within the medium are recorded by each element of the transducer array. (c) Beam-forming step: relate the arrival time of an ultrasound echo to a given position within the imaging plane, each point (x, z) in the image is obtained by adding coherently the backscattered signals originating from it (d).

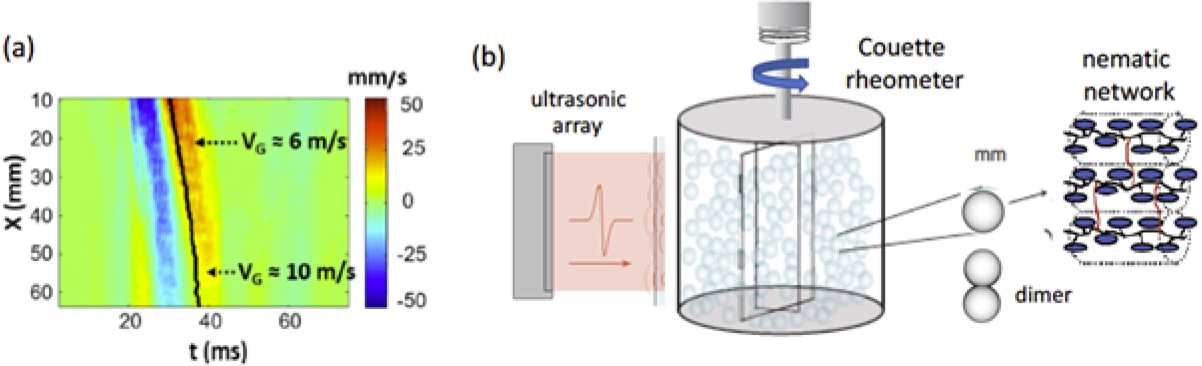


Fig. 2 (a) Particle velocity fields associated with a shear wave propagation inside a granular medium (Fig. 1). (b) The gel bead packing is sheared at constant speed in a Couette-like rheometer and analyzed using ultrasound imaging.

TITLE: WATCHING INTERFACIAL CHARGE DYNAMICS FOLLOWING LIQUID AND SOLID TRIBOELECTRIFICATION

Topic number : ***2024_055***

Field : Energy, Processes

Subfield:

ParisTech School: ESPCI Paris - PSL
Research team :
Research team website: https://blog.espci.fr/jcomtet/
Research lab: SIMM - Sciences et ingénierie de la matière molle
Lab location: Paris
Lab website: https://www.simm.espci.fr/-Home-.html

Contact point for this topic: jean.comtet@espci.fr

Advisor 1: Jean Comtet - jean.comtet@espci.fr
Advisor 2:
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
The universally-known triboelectric effect results in the charging of solid surfaces following mechanical contact. This ubiquitous phenomenon has macroscopic consequences, both mundane and fundamental (tribo-charging leads to dust aggregation, which might be responsible for initial planetary formation [1]). Very recently, triboelectricity has also seen a surge of interest in the context of the development of novel energy harvesting devices with exceptional performances [2]. However, the origin of this surface charging remains fundamentally misunderstood, being indistinctively attributed to the transfer of minute quantities of electrons, ions or matter between surfaces [3]. We demonstrated recently the possibility to map the spatial distribution and temporal evolution of surface charges deposited during liquid triboelectrification, for which charge separation occurs due to the sliding motion of droplets on hydrophobic surfaces. Such spatio-temporal mapping allowed us to evidence the occurrence of spatially heterogenous charging patterns as

well as a peculiarly high mobility of surface trapped charges, giving novel insights on their physicochemical nature. The aim of this PhD is to clarify the role of ion/surface interaction during liquid tribocharging and extend these approaches to the case of solid triboelectrification between insulating dielectric materials, whereby charge separation occurs during frictional sliding. By coupling well-controlled tribological solicitations with spatially and temporally resolved mapping of deposited surface charges, we will attempt to relate the local frictional solicitations to the surface electrification processes, hoping to obtain novel insight on these fundamentally misunderstood electrification processes, with both fundamental and practical implications. [1] T. Steinpilz et al., “Electrical charging overcomes the bouncing barrier in planet formation,” Nature Physics, vol. 16, no. 2, pp. 225–229, 2020. [2] W. Xu et al., “A droplet-based electricity generator with high instantaneous power density,” Nature, vol. 578, no. 7795, pp. 392–396, 2020. [3] D. J. Lacks and T. Shinbrot, “Long-standing and unresolved issues in triboelectric charging,” Nature Review Chemistry, 2019. [4] Li, Xiaomei, et al. "Spontaneous charging affects the motion of sliding drops." Nature Physics 18.6 (2022): 713-719.

Required background of the student:
tribology, soft matter, physics

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. T. Steinpilz et al., “Electrical charging overcomes the bouncing barrier in planet formation,” Nature Physics, vol. 16, no. 2, pp. 225–229, 2020.

2. W. Xu et al., “A droplet-based electricity generator with high instantaneous power density,” Nature, vol. 578, no. 7795, pp. 392–396, 2020.

3. D. J. Lacks and T. Shinbrot, “Long-standing and unresolved issues in triboelectric charging,” Nature Review Chemistry, 2019.

4. Li, Xiaomei, et al. "Spontaneous charging affects the motion of sliding drops." Nature Physics 18.6 (2022): 713-719.

ParisTech

TITLE: MODERATE TRANSHUMANISM, CHATGPT AND EVOLUTION. FINDING THE RIGHT TEMPO

Topic number : ***2024_056***

Field : Design, Industrialization - Information and Communication Science and Technology - Mathematics and their applications

Subfield: Human and Artificial Cognition with Human-computer interaction (HCI) and Designer Responsablility ; http://hdl.handle.net/10985/10398

ParisTech School: Arts et Métiers
Research team : Associate Professor in Assessment and acceptalibility of Technology (AI in Humanities), Professor Simon RICHIR, Head of Innovation and presence team (VR,AR,MR) in LAMPA - ENSAM. Haiwei FU, Doctorant in GenAI + XR. Following Colin Schmidt's University studies in Computational Linguistics (uManchester UK) ('sandwich course' full year in research lab), he was an intern at Paris Polytechnique (Cognitive Science), and a Ph.D. Researcher at the University Sorbonne in Dialogue (France). In his higher role as technology consultant, he worked as a research administrator in Linguistic Technologies for the European Commission, a R&D consultant in Automatic Speech Recog. at the Defence Research Agency Malvern/Oxford. Schmidt was a researcher at Airbus Industries Toulouse. His teaching career started at uGrenoble followed by Assistant Professor at uBesançon. He as an adjunct Professor at UCO-Angers, and notably ENSAM. Currently (since 2003) he is Assoc Research Professor in Social Informatics at Le Mans University as well as a Confirmed researcher in interaction and presence (since 2008) at ENSAM ParisTech in the Arts et Métiers Institute, Presence & Innovation team at LAMPA. Amongst other projects, he is involved in the CNRS. Schmidt (85 publications) is still Expert research evaluator for the European Commission's Cooperations in Sc. & Tech. (COST Actions). Colin SCHMIDT and Simon RICHIR have recently published about he workings of ChatGPT and how affect Society. Cf. http://hdl.handle.net/10985/10398 ,
Research team website: https://lampa.ensam.eu/accueil-lampa-100748.kjsp

Research lab: LAMPA - Laboratoire angevin de mécanique, procédés et innovation
Lab location: Angers
Lab website: In Laval : https://artsetmetiers.fr/fr/institut/laval

Contact point for this topic: SCHMIDT, Colin : Colin.Schmidt@univ-lemans.fr ou Colin.Schmidt@ensam.eu

Advisor 1: Simon RICHIR - Simon.Richir@ensam.eu
Advisor 2: Jayesh Pillai - jay [at] iitb.ac.in (IDC School of Design, Indian Institute of Technology, Powai, Mumbai 400076)
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
The Ph.D. candidate's research will explore the ethical dilemmas posed by contemporary Artificial Intelligences (A.I.) and their impact on society. This will involve a thorough analysis of questions related to privacy, bias, and employment disruption, illustrated through concrete case studies and real-world scenrios in business and industry. But not only. Strategies in industry are evolving due to GenAI. So in addition, the study will investigate how A.I., specifically Generative A.I. and Large Language Models (LLM's) can spur on economic growth in underserved regions. The candidate will provide practical examples of how A.I. technologies can be harnessed to promote economic development in these areas, highlighting the transformative potential (fairness) of A.I. In essence, this research will shed light on the ethical challenges associated with A.I. while showcasing the tangible benefits and innovative possibilities it offers. All of this should be supported by a compelling technological example.

Required background of the student:
Colin Schmidt, Ph.D. M.Phil, MA, B.Sc. is one of the forerunners at the intersection of computer and philosophy. He is an expert in the social and psychological acceptability of technologies and their implications ; the higher levels of cognition are addressed in his works, notably the role of ethics in A.I. and HCI theory.
Required background of the student: A solid understanding of at least some of the following areas: Cognitive Science, Artificial Intelligence, Human-Computer Interaction, Psychological and Philosophical Analysis of Society, and Generative Grammar.

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Schmidt Colin T., Lecossier A., Crubleau P. & Richir S. (2024),

Identifying Confirmed Resemblances in Problem-Solving Engineering in

ChatGPT, Both in the Past and Present, International Conference on Engineering Design ICED in November 2024 in Amsterdam
2. Schmidt Colin T. (2020), Extensions of the Mind. Relating to Data and Others, in Choukou M.-A., Taiar R., ACM Digital Library, https://dl.acm.org/doi/10.1145/3396339.3396402, ISBN: 978-1-4503-7728-7
3. Pillai J, Schmidt C.T. & Richir S. (2013), 'Achieving presence through evoked reality', Consciousness research in Frontiers in psychology vol. 4, 86, ISSN : 1664-1078.
4. Schmidt Colin T. (2019), Have People Lost their Dialogical State of Mind? In Guliciuc V. The 4th Engineering Philosophy & Ethics in Society (EPHES) International Conference, "Artificial Intelligence and Mind","Stefan cel Mare" University of Suceava Romania, October 17-19
5. SCHMIDT C.T. (2008), "Redesigning Man?", Pieter E. VERMAAS, Peter KROES, Andrew LIGHT, Steven A. MOORE, (eds.)Philosophy and Design: From Engineering to Architecture, pp. 209-216: Philosophy of Science section, Springer Science, Dordrecht. ISBN 978-1-4020-6590-3 (Print) 978-1-4020-6591-0

TITLE: EXTENDED REALITY FOR DYNAMIC BLOOD FLOW VISUALIZATION IN HUMAN BRAIN AND STROKE RECURRENCE

Topic number : ***2024_057***

Field : Material science, Mechanics and Fluids - Information and Communication Science and Technology - Life and Health Science and Technology

Subfield:

ParisTech School: Arts et Métiers
Research team : Cardiovascular Technologies and Blood Flow
Research team website: https://lifse.artsetmetiers.fr/themes/theme-technologies-cardiovasculaires-et-ecoulements-sanguins
Research lab: LIFSE - Laboratoire Ingénierie des Fluides Systèmes Energétiques
Lab location: Paris
Lab website: https://lifse.artsetmetiers.fr/

Contact point for this topic: GARBAYA Samir
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Advisor 1: Samir Garbaya - samir.garbaya@ensam.eu
Advisor 2: Sofiane KHELLADI - Sofiane.KHELLADI@ensam.eu
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Intracranial stenosis, also known as intracranial artery stenosis (ICAS), is the narrowing of an artery in the brain, which can be caused by a brain stroke. When blood vessels degrade, nerve cells in the brain, called neurons, are starved of energy, causing them to malfunction or die. The ICAS impedes the blood flow in the brain and could lead to a second stroke. Clinical research studies showed that severe artery stenosis is a predictor of high risk of stroke recurrence [1, 2, 3]. The diagnosis of intracranial stenosis includes a physical exam and a review of the patient's medical history and symptoms. The diagnosis is mainly focused on the area affected by the stroke using magnetic resonance imaging

(MRI) and computed tomography (CT) angiography. The transcranial Doppler (TCD) ultrasound or an angiogram are also used to look exclusively at the blood vessels and blood flow within the body. The approach based on dynamic 3D visualization of fluids such as blood flow in the arteries and tiny vessels [4, 5], high-fidelity representation models and augmented perception are promising for the exploration/understanding of critical pathological situations. Additionally, Blood flow in human body is inherent to physico-chemical properties specific to each patient. Hence, personalized models of artery stenosis are necessary for the accuracy and efficiency of prediction and medical decision making. This PhD project will focus on the development of real-time interactive visualization of artery blood flow using computational fluid dynamics (CFD), interactive computer graphics, extended reality (XR) and digital twin approach. The objective is to identify the risk of stroke occurrence based on better understanding of the hydrodynamics and interactions of the blood in the stenosed artery in the brain of personalized patient. The research work includes geometric data acquisition, 3D modelling of human body organs and dynamic visualization of fluid flow and its interactions with deformable shapes/surfaces. The concept of the digital twin (DT) approach will be developed to monitor [6, 7] and adjust the intracranial blood flow in response to drug administration in severe cases. Based on personalized biodata of patients, this research should lead to the definition of a predictor (personalized digital marker) for the identification and prognosis of Acute ischemic stroke (AIS).

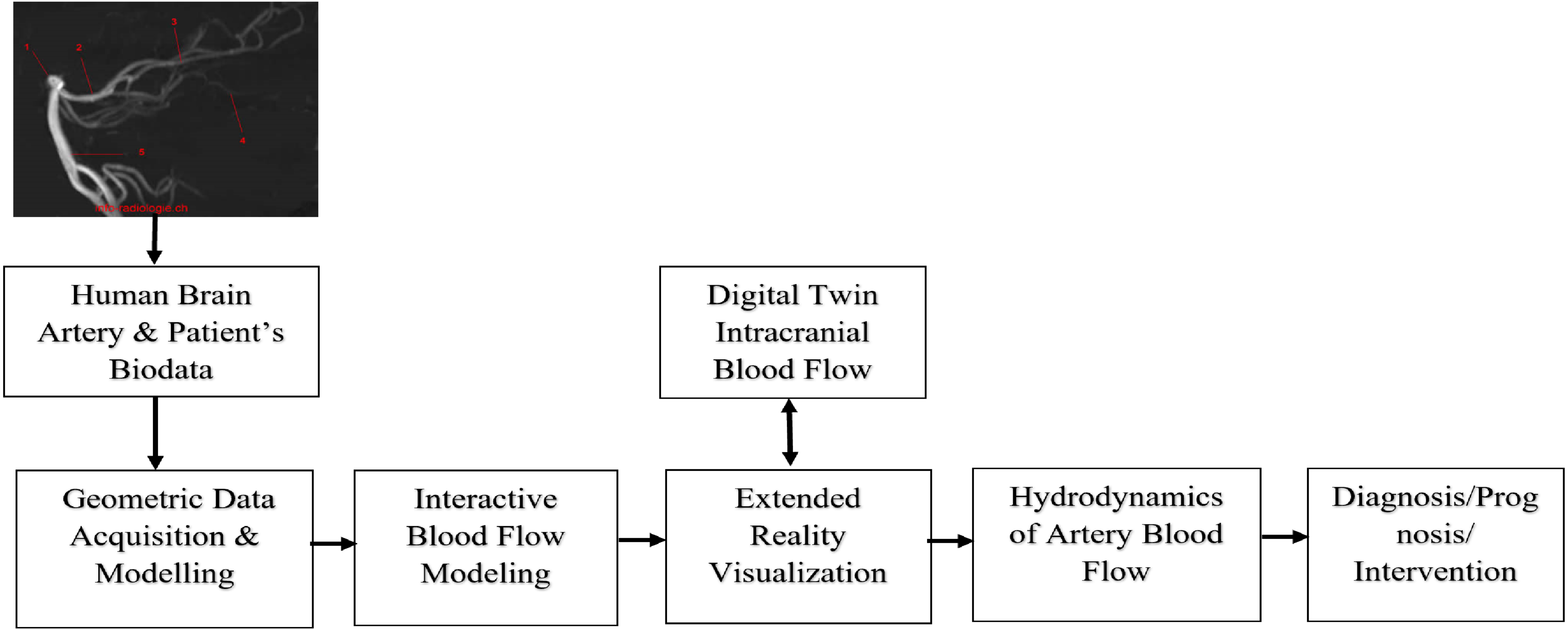
Required background of the student:
Applicants must have completed a Master of Engineering in a discipline related to Mechanical Engineering/Computer Science with good skills in programming in C# and Python, Computational Fluid Dynamics, 3D Computer Graphics and Modelling, Augmented Reality/Virtual reality. Basic knowledge of human anatomy and motivation apply research to neurology will be appreciated.

A list of (5 max.) representative publications of the group: (Related to the research topic)

1. Loïc Corenthy, Vladimir Ortega-González, José M. Espadero-Guillermo, Samir Garbaya, “3D sound for simulation of arthroscopic surgery”, ASME World Conference on Innovative Virtual Reality WINVR 2010, Ames, Iowa, USA, May 2010

2. Maryam Boumrah, Samir Garbaya and Amina Radgui, "Performance Evaluation of Visual Analytics Framework for Monitoring Neuromotor Rehabilitation", In Proceedings of the International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and

Applications, HUCAPP 2024, 27-29 February 2024, Rome, Italy, ISBN: 978-989-758-679-8, DOI: 10.5220/0012575600003660
3. Boumrah, M., Garbaya, S. & Radgui, A. “Real-time visual analytics for in-home medical rehabilitation of stroke patient—systematic review”, Medical & Biological Engineering & Computing (2022). https://doi.org/10.1007/s11517-021-02493-w, ISSN 1741-0444
4. M. Boumrah, S. Garbaya, and A. Radgui, “Real-Time Visual Analytics for Remote Monitoring of Patient’s Health,” WSCG’203 -International Conference in Central Europe on Computer Graphics, Visualization and Computer Vision’2023, Prague, Czech Republic
5. P. Tamayo-Serrano, S. Garbaya, S. Bouakaz and P. Blazevic, "A Game-Based Rehabilitation Therapy for Post-Stroke Patients: An Approach for Improving Patient Motivation and Engagement," in IEEE Systems, Man, and Cybernetics Magazine, vol. 6, no. 4, pp. 54-62, Oct. 2020, doi: 10.1109/MSMC.2020.3002519.



Extended Reality for Dynamic Blood Flow Visualization in Human Brain and Stroke Recurrence

TITLE: DEVELOPMENT OF A DIGITAL TWIN FOR QUALIFICATION OF ADDITIVE MANUFACTURING PARTS

Topic number : ***2024_058***

Field : Design, Industrialization - Design, Industrialization - Information and Communication Science and Technology

Subfield: Industrial Engineering, Information Engineering

ParisTech School: Arts et Métiers
Research team :
Research team website:
Research lab:
Lab location: Metz
Lab website:

Contact point for this topic: ali.siadat@ensam.eu

Advisor 1: Ali SIADAT - ali.siadat@ensam.eu
Advisor 2: Alaa Hassan - alaa.hassan@univ-lorraine.fr
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
The quality of the part fabricated by additive manufacturing (AM) process remains one of the main challenges for the industry. AM processes are typically optimized utilizing offline modelling and monitoring tools and parts are inspected at the end of the process [1]. Various experimental approaches have been proposed to control part quality by establishing its links with process parameters such as speed, temperature and layer thickness [2]. Some research works combine experimental, numerical and statistical approaches in order to predict the part quality [3]. While feedback on some AM process parameters is available (e.g. directed energy deposition) [4], other processes, such as Fused Filament Fabrication (FFF), are not equipped with sensors to provide this information. To address this problem, the digital twin concept is a promising holistic approach for digitalizing the AM process chain like FFF. Its advantages include reducing time-to-market, minimizing

expensive trial and error optimization with physical parts, detecting defects and shortening the path for product qualification [5]. The main objectives of the proposal are: 1. Modification of an FFF 3D printer by integrating heat and speed sensors. 2. Design and implementation of a digital twin approach that combines physics-based models (analytical models, computational models) and data-driven models (empirical data extracted from sensors to observations). 3. Providing a platform for the monitoring and detection of AM part faults by combining theoretical predictions with real-time sensor data, thereby providing a basis for model-based feedforward control in AM.

Required background of the student:
The candidate must have a master degree in industrial, mechatronics or informatics engineering. Skills in Data Analysis and Artificial Intelligence will be appreciated.

A list of (5 max.) representative publications of the group: (Related to the research topic)

P. Stavropoulos, A. Papacharalampoloulos, and K. Tzimanis, “Design and Implementation of a Digital Twin Platform for AM processes,” Procedia CIRP, vol. 104, no. March, pp. 1722–1727, 2021.
Y. Tu, J. A. Arrieta-Escobar, A. Hassan, U. K. uz Zaman, A. Siadat, and G. Yang, “Optimizing Process Parameters of Direct Ink Writing for Dimensional Accuracy of Printed Layers,” 3D Print. Addit. Manuf., Dec. 2021.
Z. Huang, J. Y. Dantan, A. Etienne, M. Rivette, and N. Bonnet, “Geometrical deviation identification and prediction method for additive manufacturing,” Rapid Prototyp. J., 2018.
A. Gaikwad, R. Yavari, M. Montazeri, K. Cole, L. Bian, and P. Rao, “Toward the digital twin of additive manufacturing: Integrating thermal simulations, sensing, and analytics to detect process faults,” IISE Trans., vol. 52, no. 11, pp. 1204–1217, 2020.
S. Krückemeier and R. Anderl, “Concept for Digital Twin Based Virtual Part Inspection for Additive Manufacturing,” Procedia CIRP, vol. 107, no. March, pp. 458–462, 2022.

Title: Computational modeling and analysis for Direct-Ink Writing and Fused Filament Fabrication dual material additive manufacturing

Topic number : ***2024_059***

Field : Material science, Mechanics and Fluids - Material science, Mechanics and Fluids

Subfield: Mechanical Engineering, Material Engineering

ParisTech School: Arts et Métiers
Research team :
Research team website:
Research lab:
Lab location:
Lab website:

Contact point for this topic: ali.siadat@ensam.eu

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Advisor 2: Alaa Hassan - alaa.hassan@univ-lorraine.fr
Advisor 3:
Advisor 4:

Short description of possible research topics for a PhD:
Today, there is a lack of numerical analysis for the multi-material processing that integrates multiple technologies, specifically the simultaneous use of DIW (Direct Ink Writing) and FFF (Fused Filament Fabrication) deposition processes. This analysis must consider key factors such as ink and filament properties, nozzle geometry (shape and size), flow field interactions, multi-nozzle path planning, and material compatibility. Employing numerical simulations prior to experimental testing can significantly reduce both costs and the time required for parallel experimentation. Building numerical model is a pillar for creating a digital twin of this additive manufacturing process. This research aims at proposing a dual-material additive manufacturing approach based on the combined principles of DIW and FFF, along with corresponding numerical simulations. It aims to optimize the selection strategy for the

materials—whether melt or filament—used in additive manufacturing, while also exploring the effects of different parameter settings on material deposition and overall print quality. Additionally, analytical models will be employed to study the extrusion behaviour of materials under various conditions and to establish a correspondence between DIW and FFF technologies. Finally, the accuracy of the model should be validated by constructing an experimental platform aligned with the proposed computational model. To address this problem, the main objectives of the proposal are: 1. Analysis of dual material extrusion process based on DIW and FFF technologies. 2. Develop a numerical simulation model of dual material additive process. 3. Conduct experimental verification of numerical modelling for Tobeca TM-081 DIW-FFF dual material platform

Required background of the student:
The candidate must have a master degree in mechanical or material engineering. Skills in Data Analysis will be appreciated.

A list of (5 max.) representative publications of the group: (Related to the research topic)

S. Gharaie et al., “Direct 3D printing of a two-part silicone resin to fabricate highly stretchable structures,” Prog. Addit. Manuf., vol. 8, no. 6, pp. 1555–1571, 2023, doi: 10.1007/s40964-023-00421-y.
Y. Tu, A. Hassan, J. A. Arrieta-Escobar, U. K. uz Zaman, A. Siadat, and G. Yang, “Modeling and evaluation of freeform extruded filament based on numerical simulation method for direct ink writing,” Int. J. Adv. Manuf. Technol., vol. 120, no. 5–6, pp. 3821–3829, May 2022, doi: 10.1007/s00170-022-08999-3.
T. A. Osswald, J. Puentes, and J. Kattinger, “Fused filament fabrication melting model,” Addit. Manuf., vol. 22, no. October 2017, pp. 51–59, 2018, doi: 10.1016/j.addma.2018.04.030.
A. Pricci, S. M. Al Islam Ovy, G. Stano, G. Percoco, and Y. Tadesse, “Semi-analytical and numerical models to predict the extrusion force for silicone additive manufacturing, as a function of the process parameters,” Addit. Manuf. Lett., vol. 6, no. May, 2023, doi: 10.1016/j.addlet.2023.100147.
T. Cadiou, F. Demoly, and S. Gomes, “A hybrid additive manufacturing platform based on fused filament fabrication and direct ink writing techniques for multi-material 3D printing,” Int. J. Adv. Manuf. Technol., vol. 114, no. 11–12, pp. 3551–3562, Jun. 2021, doi: 10.1007/s00170-021-06891-0.